The OpenGL® Graphics System:
A Specification
(Version 4.0 (Core Profile) - March 11, 2010)

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† The minimum value for each stage is
\[
\text{MAX}_\text{stage}_\text{UNIFORM\_BLOCKS} \times \text{MAX}_\text{UNIFORM\_BLOCK\_SIZE} / 4 + \text{MAX}_\text{stage}_\text{UNIFORM\_COMPONENTS}
\]
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Chapter 1

Introduction

This document describes the OpenGL graphics system: what it is, how it acts, and what is required to implement it. We assume that the reader has at least a rudimentary understanding of computer graphics. This means familiarity with the essentials of computer graphics algorithms as well as familiarity with basic graphics hardware and associated terms.

1.1 Formatting of the OpenGL Specification

1.2 What is the OpenGL Graphics System?

OpenGL (for “Open Graphics Library”) is a software interface to graphics hardware. The interface consists of a set of several hundred procedures and functions that allow a programmer to specify the objects and operations involved in producing high-quality graphical images, specifically color images of three-dimensional objects.

Most of OpenGL requires that the graphics hardware contain a framebuffer. Many OpenGL calls pertain to drawing objects such as points, lines, and polygons, but the way that some of this drawing occurs (such as when antialiasing is enabled) relies on the existence of a framebuffer. Further, some of OpenGL is specifically concerned with framebuffer manipulation.

1.3 Programmer’s View of OpenGL

To the programmer, OpenGL is a set of commands that allow the specification of geometric objects in two or three dimensions, together with commands that control how these objects are rendered into the framebuffer.
1.4 IMPLEMENTOR’S VIEW OF OPENGL

A typical program that uses OpenGL begins with calls to open a window into the framebuffer into which the program will draw. Then, calls are made to allocate a GL context and associate it with the window. Once a GL context is allocated, the programmer is free to issue OpenGL commands. Some calls are used to draw simple geometric objects (i.e. points, line segments, and polygons), while others affect the rendering of these primitives including how they are lit or colored and how they are mapped from the user’s two- or three-dimensional model space to the two-dimensional screen. There are also calls to effect direct control of the framebuffer, such as reading and writing pixels.

1.4 Implementor’s View of OpenGL

To the implementor, OpenGL is a set of commands that affect the operation of graphics hardware. If the hardware consists only of an addressable framebuffer, then OpenGL must be implemented almost entirely on the host CPU. More typically, the graphics hardware may comprise varying degrees of graphics acceleration, from a raster subsystem capable of rendering two-dimensional lines and polygons to sophisticated floating-point processors capable of transforming and computing on geometric data. The OpenGL implementor’s task is to provide the CPU software interface while dividing the work for each OpenGL command between the CPU and the graphics hardware. This division must be tailored to the available graphics hardware to obtain optimum performance in carrying out OpenGL calls.

OpenGL maintains a considerable amount of state information. This state controls how objects are drawn into the framebuffer. Some of this state is directly available to the user: he or she can make calls to obtain its value. Some of it, however, is visible only by the effect it has on what is drawn. One of the main goals of this specification is to make OpenGL state information explicit, to elucidate how it changes, and to indicate what its effects are.

1.5 Our View

We view OpenGL as a pipeline having some programmable stages and some state-driven stages that control a set of specific drawing operations. This model should engender a specification that satisfies the needs of both programmers and implementors. It does not, however, necessarily provide a model for implementation. An implementation must produce results conforming to those produced by the specified methods, but there may be ways to carry out a particular computation that are more efficient than the one specified.
1.6 The Deprecation Model

GL features marked as deprecated in one version of the specification are expected to be removed in a future version, allowing applications time to transition away from use of deprecated features. The deprecation model is described in more detail, together with a summary of the commands and state deprecated from this version of the API, in appendix E.

1.7 Companion Documents

1.7.1 OpenGL Shading Language

This specification should be read together with a companion document titled The OpenGL Shading Language. The latter document (referred to as the OpenGL Shading Language Specification hereafter) defines the syntax and semantics of the programming language used to write vertex and fragment shaders (see sections 2.11 and 3.9). These sections may include references to concepts and terms (such as shading language variable types) defined in the companion document.

OpenGL 4.0 implementations are guaranteed to support version 4.00 of the OpenGL Shading Language. All references to sections of that specification refer to version 4.00. The supported version of the shading language may be queried as described in section 6.1.5.

1.7.2 Window System Bindings

OpenGL requires a companion API to create and manage graphics contexts, windows to render into, and other resources beyond the scope of this Specification. There are several such APIs supporting different operating and window systems.

OpenGL Graphics with the X Window System, also called the “GLX Specification”, describes the GLX API for use of OpenGL in the X Window System. It is primarily directed at Linux and Unix systems, but GLX implementations also exist for Microsoft Windows, MacOS X, and some other platforms where X is available. The GLX Specification is available in the OpenGL Extension Registry (see appendix K).

The WGL API supports use of OpenGL with Microsoft Windows. WGL is documented in Microsoft’s MSDN system, although no full specification exists.

Several APIs exist supporting use of OpenGL with Quartz, the MacOS X window system, including CGL, AGL, and NSOpenGLView. These APIs are documented on Apple’s developer website.

OpenGL 4.0 (Core Profile) - March 11, 2010
The *Khronos Native Platform Graphics Interface* or “EGL Specification” describes the EGL API for use of OpenGL ES on mobile and embedded devices. EGL implementations may be available supporting OpenGL as well. The EGL Specification is available in the Khronos Extension Registry at URL

http://www.khronos.org/registry/egl
Chapter 2

OpenGL Operation

2.1 OpenGL Fundamentals

OpenGL (henceforth, the “GL”) is concerned only with rendering into a framebuffer (and reading values stored in that framebuffer). There is no support for other peripherals sometimes associated with graphics hardware, such as mice and keyboards. Programmers must rely on other mechanisms to obtain user input.

The GL draws primitives subject to a number of selectable modes and shader programs. Each primitive is a point, line segment, or polygon. Each mode may be changed independently; the setting of one does not affect the settings of others (although many modes may interact to determine what eventually ends up in the framebuffer). Modes are set, primitives specified, and other GL operations described by sending commands in the form of function or procedure calls.

Primitives are defined by a group of one or more vertices. A vertex defines a point, an endpoint of an edge, or a corner of a polygon where two edges meet. Data such as positional coordinates, colors, normals, texture coordinates, etc. are associated with a vertex and each vertex is processed independently, in order, and in the same way. The only exception to this rule is if the group of vertices must be clipped so that the indicated primitive fits within a specified region; in this case vertex data may be modified and new vertices created. The type of clipping depends on which primitive the group of vertices represents.

Commands are always processed in the order in which they are received, although there may be an indeterminate delay before the effects of a command are realized. This means, for example, that one primitive must be drawn completely before any subsequent one can affect the framebuffer. It also means that queries and pixel read operations return state consistent with complete execution of all previously invoked GL commands, except where explicitly specified otherwise. In
2.1. **OPENGL FUNDAMENTALS**

In general, the effects of a GL command on either GL modes or the framebuffer must be complete before any subsequent command can have any such effects.

In the GL, data binding occurs on call. This means that data passed to a command are interpreted when that command is received. Even if the command requires a pointer to data, those data are interpreted when the call is made, and any subsequent changes to the data have no effect on the GL (unless the same pointer is used in a subsequent command).

The GL provides direct control over the fundamental operations of 3D and 2D graphics. This includes specification of parameters of application-defined shader programs performing transformation, lighting, texturing, and shading operations, as well as built-in functionality such as antialiasing and texture filtering. It does not provide a means for describing or modeling complex geometric objects. Another way to describe this situation is to say that the GL provides mechanisms to describe how complex geometric objects are to be rendered rather than mechanisms to describe the complex objects themselves.

The model for interpretation of GL commands is client-server. That is, a program (the client) issues commands, and these commands are interpreted and processed by the GL (the server). The server may or may not operate on the same computer as the client. In this sense, the GL is “network-transparent.” A server may maintain a number of GL contexts, each of which is an encapsulation of current GL state. A client may choose to connect to any one of these contexts. Issuing GL commands when the program is not connected to a context results in undefined behavior.

The GL interacts with two classes of framebuffers: window system-provided and application-created. There is at most one window system-provided framebuffer at any time, referred to as the default framebuffer. Application-created framebuffers, referred to as framebuffer objects, may be created as desired. These two types of framebuffer are distinguished primarily by the interface for configuring and managing their state.

The effects of GL commands on the default framebuffer are ultimately controlled by the window system, which allocates framebuffer resources, determines which portions of the default framebuffer the GL may access at any given time, and communicates to the GL how those portions are structured. Therefore, there are no GL commands to initialize a GL context or configure the default framebuffer. Similarly, display of framebuffer contents on a physical display device (including the transformation of individual framebuffer values by such techniques as gamma correction) is not addressed by the GL.

Allocation and configuration of the default framebuffer occurs outside of the GL in conjunction with the window system, using companion APIs described in section 1.7.2.
Allocation and initialization of GL contexts is also done using these companion APIs. GL contexts can typically be associated with different default framebuffers, and some context state is determined at the time this association is performed.

It is possible to use a GL context without a default framebuffer, in which case a framebuffer object must be used to perform all rendering. This is useful for applications needing to perform offscreen rendering.

The GL is designed to be run on a range of graphics platforms with varying graphics capabilities and performance. To accommodate this variety, we specify ideal behavior instead of actual behavior for certain GL operations. In cases where deviation from the ideal is allowed, we also specify the rules that an implementation must obey if it is to approximate the ideal behavior usefully. This allowed variation in GL behavior implies that two distinct GL implementations may not agree pixel for pixel when presented with the same input even when run on identical framebuffer configurations.

Finally, command names, constants, and types are prefixed in the GL (by gl, GL_, and GL, respectively in C) to reduce name clashes with other packages. The prefixes are omitted in this document for clarity.

### 2.1.1 Floating-Point Computation

The GL must perform a number of floating-point operations during the course of its operation. In some cases, the representation and/or precision of such operations is defined or limited; by the OpenGL Shading Language Specification for operations in shaders, and in some cases implicitly limited by the specified format of vertex, texture, or renderbuffer data consumed by the GL. Otherwise, the representation of such floating-point numbers, and the details of how operations on them are performed, is not specified. We require simply that numbers’ floating-point parts contain enough bits and that their exponent fields are large enough so that individual results of floating-point operations are accurate to about 1 part in \(10^5\). The maximum representable magnitude of a floating-point number used to represent positional, normal, or texture coordinates must be at least \(2^{32}\); the maximum representable magnitude for colors must be at least \(2^{10}\). The maximum representable magnitude for all other floating-point values must be at least \(2^{32}\). 

\[
x \cdot 0 = 0 \cdot x = 0 \quad \text{for any non-infinite and non-\text{NaN} } x
\]

\[
x + 0 = 0 + x = x
\]

\[
0^0 = 1
\]

(Occasionally further requirements will be specified.) Most single-precision floating-point formats meet these requirements.

The special values Inf and −Inf encode values with magnitudes too large to be represented; the special value NaN encodes “Not A Number” values resulting from undefined arithmetic operations such as \(\frac{0}{0}\). Implementations are permitted, but not required, to support Inf’s and NaN’s in their floating-point computations.
2.1. OPENGL FUNDAMENTALS

Any representable floating-point value is legal as input to a GL command that requires floating-point data. The result of providing a value that is not a floating-point number to such a command is unspecified, but must not lead to GL interruption or termination. In IEEE arithmetic, for example, providing a negative zero or a denormalized number to a GL command yields predictable results, while providing a NaN or an infinity yields unspecified results.

Some calculations require division. In such cases (including implied divisions required by vector normalizations), a division by zero produces an unspecified result but must not lead to GL interruption or termination.

2.1.2 16-Bit Floating-Point Numbers

A 16-bit floating-point number has a 1-bit sign ($S$), a 5-bit exponent ($E$), and a 10-bit mantissa ($M$). The value $V$ of a 16-bit floating-point number is determined by the following:

$$V = \begin{cases} 
(-1)^S \times 0.0, & E = 0, M = 0 \\
(-1)^S \times 2^{-14} \times \frac{M}{2^{10}}, & E = 0, M \neq 0 \\
(-1)^S \times 2^{E-15} \times (1 + \frac{M}{2^{10}}), & 0 < E < 31 \\
(-1)^S \times \text{Inf}, & E = 31, M = 0 \\
\text{NaN}, & E = 31, M \neq 0
\end{cases}$$

If the floating-point number is interpreted as an unsigned 16-bit integer $N$, then

$$S = \left\lfloor \frac{N \mod 65536}{32768} \right\rfloor$$
$$E = \left\lfloor \frac{N \mod 32768}{1024} \right\rfloor$$
$$M = N \mod 1024.$$

Any representable 16-bit floating-point value is legal as input to a GL command that accepts 16-bit floating-point data. The result of providing a value that is not a floating-point number (such as Inf or NaN) to such a command is unspecified, but must not lead to GL interruption or termination. Providing a denormalized number or negative zero to GL must yield predictable results.

2.1.3 Unsigned 11-Bit Floating-Point Numbers

An unsigned 11-bit floating-point number has no sign bit, a 5-bit exponent ($E$), and a 6-bit mantissa ($M$). The value $V$ of an unsigned 11-bit floating-point number is
determined by the following:

\[
V = \begin{cases} 
0.0, & E = 0, M = 0 \\
2^{-14} \times \frac{M}{64}, & E = 0, M \neq 0 \\
2^{E-15} \times (1 + \frac{M}{32}), & 0 < E < 31 \\
Inf, & E = 31, M = 0 \\
NaN, & E = 31, M \neq 0 
\end{cases}
\]

If the floating-point number is interpreted as an unsigned 11-bit integer \( N \), then

\[
E = \left\lfloor \frac{N}{64} \right\rfloor \\
M = N \mod 64.
\]

When a floating-point value is converted to an unsigned 11-bit floating-point representation, finite values are rounded to the closest representable finite value. While less accurate, implementations are allowed to always round in the direction of zero. This means negative values are converted to zero. Likewise, finite positive values greater than 65024 (the maximum finite representable unsigned 11-bit floating-point value) are converted to 65024. Additionally: negative infinity is converted to zero; positive infinity is converted to positive infinity; and both positive and negative NaN are converted to positive NaN.

Any representable unsigned 11-bit floating-point value is legal as input to a GL command that accepts 11-bit floating-point data. The result of providing a value that is not a floating-point number (such as Inf or NaN) to such a command is unspecified, but must not lead to GL interruption or termination. Providing a denormalized number to GL must yield predictable results.

### 2.1.4 Unsigned 10-Bit Floating-Point Numbers

An unsigned 10-bit floating-point number has no sign bit, a 5-bit exponent \( E \), and a 5-bit mantissa \( M \). The value \( V \) of an unsigned 10-bit floating-point number is determined by the following:

\[
V = \begin{cases} 
0.0, & E = 0, M = 0 \\
2^{-14} \times \frac{M}{32}, & E = 0, M \neq 0 \\
2^{E-15} \times (1 + \frac{M}{32}), & 0 < E < 31 \\
Inf, & E = 31, M = 0 \\
NaN, & E = 31, M \neq 0 
\end{cases}
\]
If the floating-point number is interpreted as an unsigned 10-bit integer \( N \), then

\[
E = \left\lfloor \frac{N}{32} \right\rfloor
\]

\[
M = N \mod 32.
\]

When a floating-point value is converted to an unsigned 10-bit floating-point representation, finite values are rounded to the closest representable finite value. While less accurate, implementations are allowed to always round in the direction of zero. This means negative values are converted to zero. Likewise, finite positive values greater than 64512 (the maximum finite representable unsigned 10-bit floating-point value) are converted to 64512. Additionally: negative infinity is converted to zero; positive infinity is converted to positive infinity; and both positive and negative NaN are converted to positive NaN.

Any representable unsigned 10-bit floating-point value is legal as input to a GL command that accepts 10-bit floating-point data. The result of providing a value that is not a floating-point number (such as \( \text{Inf} \) or \( \text{NaN} \)) to such a command is unspecified, but must not lead to GL interruption or termination. Providing a denormalized number to GL must yield predictable results.

### 2.1.5 Fixed-Point Data Conversions

When generic vertex attributes and pixel color or depth components are represented as integers, they are often (but not always) considered to be normalized. Normalized integer values are treated specially when being converted to and from floating-point values, and are usually referred to as normalized fixed-point. Such values are always either signed or unsigned.

In the remainder of this section, \( b \) denotes the bit width of the fixed-point integer representation. When the integer is one of the types defined in table 2.2, \( b \) is the minimum required bit width of that type. When the integer is a texture or renderbuffer color or depth component (see section 3.8.3), \( b \) is the number of bits allocated to that component in the internal format of the texture or renderbuffer. When the integer is a framebuffer color or depth component (see section 4), \( b \) is the number of bits allocated to that component in the framebuffer. For framebuffer and renderbuffer A components, \( b \) must be at least 2 if the buffer does not contain an A component, or if there is only 1 bit of A in the buffer.

The signed and unsigned fixed-point representations are assumed to be \( b \)-bit binary twos-complement integers and binary unsigned integers, respectively. The signed fixed-point representation may be treated in one of two ways, as discussed below.
2.1. OPENGL FUNDAMENTALS

All the conversions described below are performed as defined, even if the implemented range of an integer data type is greater than the minimum required range.

Conversion from Normalized Fixed-Point to Floating-Point

Unsigned normalized fixed-point integers represent numbers in the range \([0, 1]\). The conversion from an unsigned normalized fixed-point value \(c\) to the corresponding floating-point value \(f\) is defined as

\[
f = \frac{c}{2^b - 1}.
\]  

(2.1)

Signed normalized fixed-point integers represent numbers in the range \([-1, 1]\). The conversion from a signed normalized fixed-point value \(c\) to the corresponding floating-point value \(f\) may be performed in two ways:

\[
f = 2c + 1 \quad \text{or} \quad \frac{2c + 1}{2^b - 1}.
\]  

(2.2)

In this case the full range of the representation is used, so that \(-2^{b-1}\) corresponds to -1.0 and \(2^{b-1} - 1\) corresponds to 1.0. For example, if \(b = 8\), then the integer value -128 corresponds to -1.0 and the value 127 corresponds to 1.0. Note that it is not possible to exactly express 0 in this representation. In general, this representation is used for signed normalized fixed-point parameters in GL commands, such as vertex attribute values.

Alternatively, conversion may be performed using

\[
f = \max \left\{ \frac{c}{2^{b-1} - 1}, -1.0 \right\}.
\]  

(2.3)

In this case only the range \([-2^{b-1} + 1, 2^{b-1} - 1]\) is used to represent signed fixed-point values in the range \([-1, 1]\). For example, if \(b = 8\), then the integer value -127 corresponds to -1.0 and the value 127 corresponds to 1.0. Note that while zero can be exactly expressed in this representation, one value (-128 in the example) is outside the representable range, and must be clamped before use. In general, this representation is used for signed normalized fixed-point texture or framebuffer values.

Everywhere that signed normalized fixed-point values are converted, the equation used is specified.
2.2 GL STATE

Conversion from Floating-Point to Normalized Fixed-Point

The conversion from a floating-point value \( f \) to the corresponding unsigned normalized fixed-point value \( c \) is defined by first clamping \( f \) to the range \([0, 1]\), then computing

\[
f' = f \times (2^b - 1).
\] (2.4)

\( f' \) is then cast to an unsigned binary integer value with exactly \( b \) bits.

The conversion from a floating-point value \( f \) to the corresponding signed normalized fixed-point value \( c \) may be performed in two ways, both beginning by clamping \( f \) to the range \([-1, 1]\):

\[
f' = f \times (2^b - 1) - \frac{1}{2}
\] (2.5)

In general, this conversion is used when querying floating-point state (see section 6) and returning integers.

Alternatively, conversion may be performed using

\[
f' = f \times (2^{b-1} - 1).
\] (2.6)

In general, this conversion is used when specifying signed normalized fixed-point texture or framebuffer values.

After conversion, \( f' \) is then cast to a signed two’s-complement binary integer value with exactly \( b \) bits.

Everywhere that floating-point values are converted to signed normalized fixed-point, the equation used is specified.

2.2 GL State

The GL maintains considerable state. This document enumerates each state variable and describes how each variable can be changed. For purposes of discussion, state variables are categorized somewhat arbitrarily by their function. Although we describe the operations that the GL performs on the framebuffer, the framebuffer is not a part of GL state.

We distinguish two types of state. The first type of state, called GL server state, resides in the GL server. The majority of GL state falls into this category. The second type of state, called GL client state, resides in the GL client. Unless otherwise specified, all state referred to in this document is GL server state; GL client state is specifically identified. Each instance of a GL context implies one...
2.3. GL COMMAND SYNTAX

complete set of GL server state; each connection from a client to a server implies a set of both GL client state and GL server state.

While an implementation of the GL may be hardware dependent, this discussion is independent of the specific hardware on which a GL is implemented. We are therefore concerned with the state of graphics hardware only when it corresponds precisely to GL state.

2.2.1 Shared Object State

It is possible for groups of contexts to share certain state. Enabling such sharing between contexts is done through window system binding APIs such as those described in section 1.7.2. These APIs are responsible for creation and management of contexts, and not discussed further here. More detailed discussion of the behavior of shared objects is included in appendix D. Except as defined in this appendix, all state in a context is specific to that context only.

2.3 GL Command Syntax

GL commands are functions or procedures. Various groups of commands perform the same operation but differ in how arguments are supplied to them. To conveniently accommodate this variation, we adopt a notation for describing commands and their arguments.

GL commands are formed from a name which may be followed, depending on the particular command, by a sequence of characters describing a parameter to the command. If present, a digit indicates the required length (number of values) of the indicated type. Next, a string of characters making up one of the type descriptors from table 2.1 indicates the specific size and data type of parameter values. A final v character, if present, indicates that the command takes a pointer to an array (a vector) of values rather than a series of individual arguments. Two specific examples are:

```c
void Uniform4f( int location, float v0, float v1,
                float v2, float v3 );
```

and

```c
void GetFloatv( enum value, float *data );
```

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2.3. GL COMMAND SYNTAX

<table>
<thead>
<tr>
<th>Type Descriptor</th>
<th>Corresponding GL Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>byte</td>
</tr>
<tr>
<td>s</td>
<td>short</td>
</tr>
<tr>
<td>i</td>
<td>int</td>
</tr>
<tr>
<td>i64</td>
<td>int64</td>
</tr>
<tr>
<td>f</td>
<td>float</td>
</tr>
<tr>
<td>d</td>
<td>double</td>
</tr>
<tr>
<td>ub</td>
<td>ubyte</td>
</tr>
<tr>
<td>us</td>
<td>ushort</td>
</tr>
<tr>
<td>ui</td>
<td>uint</td>
</tr>
<tr>
<td>ui64</td>
<td>uint64</td>
</tr>
</tbody>
</table>

Table 2.1: Correspondence of command suffix type descriptors to GL argument types. Refer to table 2.2 for definitions of the GL types.

These examples show the ANSI C declarations for these commands. In general, a command declaration has the form

\[
\text{rtype Name}\{\epsilon 1234}\{\epsilon b s i i64 f d ub us ui ui64\}\{\epsilon v\} \\
(\{args ,\} T arg1 , \ldots , T argN [, args] ) ;
\]

\text{rtype} is the return type of the function. The braces (\{\}) enclose a series of type descriptors (see table 2.1), of which one is selected. \(\epsilon\) indicates no type descriptor. The arguments enclosed in brackets ([args ,] and [, args]) may or may not be present. The \(N\) arguments \(arg1\) through \(argN\) have type \(T\), which corresponds to one of the type descriptors indicated in table 2.1 (if there are no letters, then the arguments’ type is given explicitly). If the final character is not \(v\), then \(N\) is given by the digit 1, 2, 3, or 4 (if there is no digit, then the number of arguments is fixed). If the final character is \(v\), then only \(arg1\) is present and it is an array of \(N\) values of the indicated type.

For example,

```c
void Uniform\{1234\}{if}( int location, T value ) ;
```

indicates the eight declarations

```c
void Uniform1i( int location, int value ) ;
```

---

\(^1\)The declarations shown in this document apply to ANSI C. Languages such as C++ and Ada that allow passing of argument type information admit simpler declarations and fewer entry points.
2.4 Basic GL Operation

Figure 2.1 shows a schematic diagram of the GL. Commands enter the GL on the left. Some commands specify geometric objects to be drawn while others control how the objects are handled by the various stages. Commands are effectively sent through a processing pipeline.

The first stage operates on geometric primitives described by vertices: points, line segments, and polygons. In this stage vertices may be transformed and lit, followed by assembly into geometric primitives, which may optionally be used by the next stage, geometry shading, to generate new primitives. The final resulting primitives are clipped to a viewing volume in preparation for the next stage, rasterization. The rasterizer produces a series of framebuffer addresses and values using a two-dimensional description of a point, line segment, or polygon. Each fragment so produced is fed to the next stage that performs operations on individual fragments before they finally alter the framebuffer. These operations include conditional updates into the framebuffer based on incoming and previously stored depth values (to effect depth buffering), blending of incoming fragment colors with stored colors, as well as masking and other logical operations on fragment values.

Finally, values may also be read back from the framebuffer or copied from one portion of the framebuffer to another. These transfers may include some type of decoding or encoding.

This ordering is meant only as a tool for describing the GL, not as a strict rule of how the GL is implemented, and we present it only as a means to organize the various operations of the GL. Objects such as curved surfaces, for instance, may be transformed before they are converted to polygons.
### Table 2.2: GL data types

GL types are not C types. Thus, for example, GL type `int` is referred to as `GLint` outside this document, and is not necessarily equivalent to the C type `int`. An implementation may use more bits than the number indicated in the table to represent a GL type. Correct interpretation of integer values outside the minimum range is not required, however.

`ptrbits` is the number of bits required to represent a pointer type; in other words, types `intptr`, `sizeiptr`, and `sync` must be sufficiently large as to store any address.

<table>
<thead>
<tr>
<th>GL Type</th>
<th>Minimum Bit Width</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>boolean</td>
<td>1</td>
<td>Boolean</td>
</tr>
<tr>
<td>byte</td>
<td>8</td>
<td>Signed twos complement binary integer</td>
</tr>
<tr>
<td>ubyte</td>
<td>8</td>
<td>Unsigned binary integer</td>
</tr>
<tr>
<td>char</td>
<td>8</td>
<td>Characters making up strings</td>
</tr>
<tr>
<td>short</td>
<td>16</td>
<td>Signed twos complement binary integer</td>
</tr>
<tr>
<td>ushort</td>
<td>16</td>
<td>Unsigned binary integer</td>
</tr>
<tr>
<td>int</td>
<td>32</td>
<td>Signed twos complement binary integer</td>
</tr>
<tr>
<td>uint</td>
<td>32</td>
<td>Unsigned binary integer</td>
</tr>
<tr>
<td>int64</td>
<td>64</td>
<td>Signed twos complement binary integer</td>
</tr>
<tr>
<td>uint64</td>
<td>64</td>
<td>Unsigned binary integer</td>
</tr>
<tr>
<td>sizei</td>
<td>32</td>
<td>Non-negative binary integer size</td>
</tr>
<tr>
<td>enum</td>
<td>32</td>
<td>Enumerated binary integer value</td>
</tr>
<tr>
<td>intptr</td>
<td><code>ptrbits</code></td>
<td>Signed twos complement binary integer</td>
</tr>
<tr>
<td>sizeiptr</td>
<td><code>ptrbits</code></td>
<td>Non-negative binary integer size</td>
</tr>
<tr>
<td>sync</td>
<td><code>ptrbits</code></td>
<td>Sync object handle (see section 5.3)</td>
</tr>
<tr>
<td>bitfield</td>
<td>32</td>
<td>Bit field</td>
</tr>
<tr>
<td>half</td>
<td>16</td>
<td>Half-precision floating-point value encoded in an unsigned scalar</td>
</tr>
<tr>
<td>float</td>
<td>32</td>
<td>Floating-point value</td>
</tr>
<tr>
<td>clampf</td>
<td>32</td>
<td>Floating-point value clamped to [0, 1]</td>
</tr>
<tr>
<td>double</td>
<td>64</td>
<td>Floating-point value</td>
</tr>
<tr>
<td>clampd</td>
<td>64</td>
<td>Floating-point value clamped to [0, 1]</td>
</tr>
</tbody>
</table>
2.4. BASIC GL OPERATION

Figure 2.1. Block diagram of the GL.

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2.5 GL Errors

The GL detects only a subset of those conditions that could be considered errors. This is because in many cases error checking would adversely impact the performance of an error-free program.

The command

```c
enum GetError( void );
```

is used to obtain error information. Each detectable error is assigned a numeric code. When an error is detected, a flag is set and the code is recorded. Further errors, if they occur, do not affect this recorded code. When `GetError` is called, the code is returned and the flag is cleared, so that a further error will again record its code. If a call to `GetError` returns `NO_ERROR`, then there has been no detectable error since the last call to `GetError` (or since the GL was initialized).

To allow for distributed implementations, there may be several flag-code pairs. In this case, after a call to `GetError` returns a value other than `NO_ERROR` each subsequent call returns the non-zero code of a distinct flag-code pair (in unspecified order), until all non-`NO_ERROR` codes have been returned. When there are no more non-`NO_ERROR` error codes, all flags are reset. This scheme requires some positive number of pairs of a flag bit and an integer. The initial state of all flags is cleared and the initial value of all codes is `NO_ERROR`.

Table 2.3 summarizes GL errors. Currently, when an error flag is set, results of GL operation are undefined only if `OUT_OF_MEMORY` has occurred. In other cases, the command generating the error is ignored so that it has no effect on GL state or framebuffer contents. If the generating command returns a value, it returns zero. If the generating command modifies values through a pointer argument, no change is made to these values. These error semantics apply only to GL errors, not to system errors such as memory access errors. This behavior is the current behavior; the action of the GL in the presence of errors is subject to change.

Several error generation conditions are implicit in the description of every GL command:

- If a command that requires an enumerated value is passed a symbolic constant that is not one of those specified as allowable for that command, the error `INVALID_ENUM` is generated. This is the case even if the argument is a pointer to a symbolic constant, if the value pointed to is not allowable for the given command.

- If a negative number is provided where an argument of type `sizei` or `sizeiptr` is specified, the error `INVALID_VALUE` is generated.
### 2.6 Primitives and Vertices

In the GL, most geometric objects are drawn by specifying a series of generic attribute sets using `DrawArrays` or one of the other drawing commands defined in section 2.8.3. Points, lines, polygons, and a variety of related geometric objects (see section 2.6.1) can be drawn in this way.

Each vertex is specified with one or more generic vertex attributes. Each attribute is specified with one, two, three, or four scalar values. Generic vertex attributes can be accessed from within vertex shaders (section 2.11) and used to compute values for consumption by later processing stages.

The methods by which generic attributes are sent to the GL, as well as how attributes are used by vertex shaders to generate vertices mapped to the two-dimensional screen, are discussed later.

Before vertex shader execution, the state required by a vertex is its generic vertex attributes. Vertex shader execution processes vertices producing a homogeneous vertex position and any varying outputs explicitly written by the vertex shader.

Figure 2.2 shows the sequence of operations that builds a *primitive* (point, line segment, or polygon) from a sequence of vertices. After a primitive is formed, it is clipped to a viewing volume. This may alter the primitive by altering vertex attributes.

---

<table>
<thead>
<tr>
<th>Error</th>
<th>Description</th>
<th>Offending command ignored?</th>
</tr>
</thead>
<tbody>
<tr>
<td>INVALID_ENUM</td>
<td>enum argument out of range</td>
<td>Yes</td>
</tr>
<tr>
<td>INVALID_VALUE</td>
<td>Numeric argument out of range</td>
<td>Yes</td>
</tr>
<tr>
<td>INVALID_OPERATION</td>
<td>Operation illegal in current state</td>
<td>Yes</td>
</tr>
<tr>
<td>INVALID_FRAMEBUFFER_OPERATION</td>
<td>Framebuffer object is not complete</td>
<td>Yes</td>
</tr>
<tr>
<td>OUT_OF_MEMORY</td>
<td>Not enough memory left to execute command</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Table 2.3: Summary of GL errors

- If memory is exhausted as a side effect of the execution of a command, the error `OUT_OF_MEMORY` may be generated.

Otherwise, errors are generated only for conditions that are explicitly described in this specification.
2.6. PRIMITIVES AND VERTICES

Figure 2.2. Vertex processing and primitive assembly.
coordinates and varying vertex shader outputs. In the case of line and polygon primitives, clipping may insert new vertices into the primitive. The vertices defining a primitive to be rasterized have varying outputs associated with them.

### 2.6.1 Primitive Types

A sequence of vertices is passed to the GL using **DrawArrays** or one of the other drawing commands defined in section 2.8.3. There is no limit to the number of vertices that may be specified, other than the size of the vertex arrays. The *mode* parameter of these commands determines the type of primitives to be drawn using the vertices. The types, and the corresponding *mode* parameters, are:

**Points**

A series of individual points may be specified with *mode* **POINTS**. Each vertex defines a separate point.

**Line Strips**

A series of one or more connected line segments may be specified with *mode** **LINE_STRIP**. In this case, the first vertex specifies the first segment’s start point while the second vertex specifies the first segment’s endpoint and the second segment’s start point. In general, the *i*th vertex (for *i* > 1) specifies the beginning of the *i*th segment and the end of the *(i−1)*st. The last vertex specifies the end of the last segment. If only one vertex is specified, then no primitive is generated.

The required state consists of the processed vertex produced from the last vertex that was sent (so that a line segment can be generated from it to the current vertex), and a boolean flag indicating if the current vertex is the first vertex.

**Line Loops**

Line loops may be specified with *mode** **LINE_LOOP**. Loops are the same as line strips except that a final segment is added from the final specified vertex to the first vertex. The required state consists of the processed first vertex, in addition to the state required for line strips.

**Separate Lines**

Individual line segments, each specified by a pair of vertices, may be specified with *mode** **LINES**. The first two vertices passed define the first segment, with subsequent pairs of vertices each defining one more segment. If the number of specified vertices is odd, then the last one is ignored. The state required is the same as for line strips but it is used differently: a processed vertex holding the first vertex of the current segment, and a boolean flag indicating whether the current vertex is odd or even (a segment start or end).
2.6. PRIMITIVES AND VERTICES

Triangle Strips

A triangle strip is a series of triangles connected along shared edges, and may be specified with mode \texttt{TRIANGLE_STRIP}. In this case, the first three vertices define the first triangle (and their order is significant). Each subsequent vertex defines a new triangle using that point along with two vertices from the previous triangle. If fewer than three vertices are specified, no primitive is produced. See figure 2.3.

The required state consists of a flag indicating if the first triangle has been completed, two stored processed vertices, (called vertex A and vertex B), and a one bit pointer indicating which stored vertex will be replaced with the next vertex. The pointer is initialized to point to vertex A. Each successive vertex toggles the pointer. Therefore, the first vertex is stored as vertex A, the second stored as vertex B, the third stored as vertex A, and so on. Any vertex after the second one sent forms a triangle from vertex A, vertex B, and the current vertex (in that order).

Triangle Fans

A triangle fan is the same as a triangle strip with one exception: each vertex after the first always replaces vertex B of the two stored vertices. A triangle fan may be specified with mode \texttt{TRIANGLE_FAN}.

Separate Triangles

Separate triangles are specified with mode \texttt{TRIANGLES}. In this case,

\[ 3i + \]
2.6. PRIMITIVES AND VERTICES

![Diagram of lines with adjacency and line strips with adjacency]

Figure 2.4. Lines with adjacency (a) and line strips with adjacency (b). The vertices connected with solid lines belong to the main primitives; the vertices connected by dashed lines are the adjacent vertices that may be used in a geometry shader.

1st, 3i + 2nd, and 3i + 3rd vertices (in that order) determine a triangle for each i = 0, 1, . . . , n − 1, where there are 3n + k vertices drawn. k is either 0, 1, or 2; if k is not zero, the final k vertices are ignored. For each triangle, vertex A is vertex 3i and vertex B is vertex 3i + 1. Otherwise, separate triangles are the same as a triangle strip.

**Lines with Adjacency**

Lines with adjacency are independent line segments where each endpoint has a corresponding adjacent vertex that can be accessed by a geometry shader (section 2.13). If a geometry shader is not active, the adjacent vertices are ignored. They are generated with mode `LINES_ADJACENCY`.

A line segment is drawn from the 4i + 2nd vertex to the 4i + 3rd vertex for each i = 0, 1, . . . , n − 1, where there are 4n + k vertices passed. k is either 0, 1, 2, or 3; if k is not zero, the final k vertices are ignored. For line segment i, the 4i + 1st and 4i + 4th vertices are considered adjacent to the 4i + 2nd and 4i + 3rd vertices, respectively (see figure 2.4).

**Line Strips with Adjacency**
2.6. PRIMITIVES AND VERTICES

Line strips with adjacency are similar to line strips, except that each line segment has a pair of adjacent vertices that can be accessed by a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored. They are generated with mode \texttt{LINE\_STRIP\_ADJACENCY}.

A line segment is drawn from the $i + 2$nd vertex to the $i + 3$rd vertex for each $i = 0, 1, \ldots, n - 1$, where there are $n + 3$ vertices passed. If there are fewer than four vertices, all vertices are ignored. For line segment $i$, the $i + 1$st and $i + 4$th vertex are considered adjacent to the $i + 2$nd and $i + 3$rd vertices, respectively (see figure 2.4).

**Triangles with Adjacency**

Triangles with adjacency are similar to separate triangles, except that each triangle edge has an adjacent vertex that can be accessed by a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored. They are generated with mode \texttt{TRIANGLES\_ADJACENCY}.

The $6i + 1$st, $6i + 3$rd, and $6i + 5$th vertices (in that order) determine a triangle for each $i = 0, 1, \ldots, n - 1$, where there are $6n + k$ vertices passed. $k$ is either $0, 1, 2, 3, 4, \text{ or } 5$; if $k$ is non-zero, the final $k$ vertices are ignored. For triangle $i$, the $i + 2$nd, $i + 4$th, and $i + 6$th vertices are considered adjacent to edges from the $i + 1$st to the $i + 3$rd, from the $i + 3$rd to the $i + 5$th, and from the $i + 5$th to the $i + 1$st.
Triangle Strips with Adjacency

Triangle strips with adjacency are similar to triangle strips, except that each line triangle edge has an adjacent vertex that can be accessed by a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored. They are generated with mode \texttt{TRIANGLE_STRIP_ADJACENCY}.

In triangle strips with adjacency, \( n \) triangles are drawn where there are \( 2(n + 2) + k \) vertices passed. \( k \) is either 0 or 1; if \( k \) is 1, the final vertex is ignored. If there are fewer than 6 vertices, the entire primitive is ignored. Table 2.4 describes the vertices and order used to draw each triangle, and which vertices are considered adjacent to each edge of the triangle (see figure 2.6).
2.6. **PRIMITIVES AND VERTICES**

<table>
<thead>
<tr>
<th>Primitive</th>
<th>Primitive Vertices</th>
<th>Adjacent Vertices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
<td>2nd</td>
</tr>
<tr>
<td>only ((i = 0, n = 1))</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>first ((i = 0))</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>middle ((i \text{ odd}))</td>
<td>(2i + 3)</td>
<td>(2i + 1)</td>
</tr>
<tr>
<td>middle ((i \text{ even}))</td>
<td>(2i + 1)</td>
<td>(2i + 3)</td>
</tr>
<tr>
<td>last ((i = n - 1, i \text{ odd}))</td>
<td>(2i + 3)</td>
<td>(2i + 1)</td>
</tr>
<tr>
<td>last ((i = n - 1, i \text{ even}))</td>
<td>(2i + 1)</td>
<td>(2i + 3)</td>
</tr>
</tbody>
</table>

Table 2.4: Triangles generated by triangle strips with adjacency. Each triangle is drawn using the vertices whose numbers are in the 1st, 2nd, and 3rd columns under *primitive vertices*, in that order. The vertices in the 1/2, 2/3, and 3/1 columns under *adjacent vertices* are considered adjacent to the edges from the first to the second, from the second to the third, and from the third to the first vertex of the triangle, respectively. The six rows correspond to six cases: the first and only triangle \((i = 0, n = 1)\), the first triangle of several \((i = 0, n > 0)\), “odd” middle triangles \((i = 1,3, 5 \ldots)\), “even” middle triangles \((i = 2, 4, 6 \ldots)\), and special cases for the last triangle, when \(i\) is either even or odd. For the purposes of this table, the first vertex passed is numbered 1 and the first triangle is numbered 0.

**Separate Patches**

A patch is an ordered collection of vertices used for primitive tessellation (section 2.12). The vertices comprising a patch have no implied geometric ordering. The vertices of a patch are used by tessellation shaders and a fixed-function tessellator to generate new point, line, or triangle primitives. Separate patches are generated with mode **PATCHES**.

Each patch in the series has a fixed number of vertices, which is specified by calling

```c
void PatchParameteri( enum pname, int value );
```

with `pname` set to **PATCH_VERTICES**. The error **INVALID_VALUE** is generated if `value` is less than or equal to zero or is greater than the implementation-dependent maximum patch size (the value of **MAX_PATCH_VERTICES**). The patch size is initially three vertices.

If the number of vertices in a patch is given by \(v\), the \(vi + 1\)st through \(vi + v\)th vertices (in that order) determine a patch for each \(i = 0, 1, \ldots n - 1\), where there are \(vn + k\) vertices. \(k\) is in the range \([0, v - 1]\); if \(k\) is not zero, the final \(k\) vertices are ignored.
2.7. VERTEX SPECIFICATION

General Considerations For Polygon Primitives

Depending on the current state of the GL, a polygon primitive generated from a drawing command with mode TRIANGLE_FAN, TRIANGLE_STRIP, TRIANGLES, TRIANGLES_ADJACENCY, or TRIANGLE_STRIP_ADJACENCY may be rendered in one of several ways, such as outlining its border or filling its interior. The order of vertices in such a primitive is significant in polygon rasterization and fragment shading (see sections 3.6.1 and 3.9.2).

2.7 Vertex Specification

Vertex shaders (see section 2.11) access an array of 4-component generic vertex attributes. The first slot of this array is numbered 0, and the size of the array is specified by the implementation-dependent constant MAX_VERTEX_ATTRIBS.

Current generic attribute values define generic attributes for a vertex when a vertex array defining that data is not enabled, as described in section 2.8. The current values of a generic shader attribute declared as a floating-point scalar, vector, or matrix may be changed at any time by issuing one of the commands

\[
\begin{align*}
\text{void \hspace{2mm} VertexAttrib{1234}\{\text{sfd}\}(\text{uint} \ \text{index, T values});} \\
\text{void \hspace{2mm} VertexAttrib{123}\{\text{sfd}\}v(\text{uint} \ \text{index, const T values);}} \\
\text{void \hspace{2mm} VertexAttrib4\{\text{bsifd ub us ui}\}v(\text{uint} \ \text{index, const T values);}} \\
\text{void \hspace{2mm} VertexAttrib4Nub(\text{uint} \ \text{index, T values);}} \\
\text{void \hspace{2mm} VertexAttrib4N\{\text{bsi ub us ui}\}v(\text{uint} \ \text{index, const T values);}}
\end{align*}
\]

The VertexAttrib4N* commands specify fixed-point values that are converted to a normalized \([0, 1]\) or \([-1, 1]\) range as described in equations 2.1 and 2.2, respectively, while the other commands specify values that are converted directly to the internal floating-point representation.

The resulting value(s) are loaded into the generic attribute at slot index, whose components are named x, y, z, and w. The VertexAttrib1* family of commands sets the x coordinate to the provided single argument while setting y and z to 0 and w to 1. Similarly, VertexAttrib2* commands set x and y to the specified values, z to 0 and w to 1; VertexAttrib3* commands set x, y, and z, with w set to 1, and VertexAttrib4* commands set all four coordinates.

The VertexAttrib* entry points may also be used to load shader attributes declared as a floating-point matrix. Each column of a matrix takes up one generic
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4-component attribute slot out of the MAX_VERTEX_ATTRIBS available slots. Matrices are loaded into these slots in column major order. Matrix columns are loaded in increasing slot numbers.

The resulting attribute values are undefined if the base type of the shader attribute at slot index is not floating-point (e.g. is signed or unsigned integer). To load current values of a generic shader attribute declared as a signed or unsigned scalar or vector, use the commands

```c
voidVertexAttribI{1234}{i ui}(uint index, T values);
voidVertexAttribI{1234}{i ui}v(uint index, const T values);
voidVertexAttribI4{bs ubus}v(uint index, const T values);
```

These commands specify values that are extended to full signed or unsigned integers, then loaded into the generic attribute at slot index in the same fashion as described above.

The resulting attribute values are undefined if the base type of the shader attribute at slot index is floating-point; if the base type is integer and unsigned integer values are supplied (the VertexAttribI*ui, VertexAttribI*us, and VertexAttribI*ub commands); or if the base type is unsigned integer and signed integer values are supplied (the VertexAttribI*i, VertexAttribI*s, and VertexAttribI*b commands).

Vertex data may be stored as packed components within a larger natural type. Such data may be specified using

```c
voidVertexAttribP{1234}ui(uint index, enum type, boolean normalized, uint value);
voidVertexAttribP{1234}uiv(uint index, enum type, boolean normalized, const uint *value);
```

These commands specify up to four attribute component values, packed into a single natural type as described in section 2.8.2, and load it into the generic attribute at slot index. The type parameter must be INT_2_10_10_10_REV or UNSIGNED_INT_2_10_10_10_REV, specifying signed or unsigned data respectively. The first one (x), two (x, y), three (x, y, z), or four (x, y, z, w) components of the packed data are consumed by VertexAttribP1ui, VertexAttribP2ui, VertexAttribP3ui, and VertexAttribP4ui, respectively. Data specified by VertexAttribP* will be converted to floating point by normalizing if normalized is TRUE, and converted directly to floating point otherwise. For VertexAttribP*uiv, value contains the address of a single uint containing the packed attribute components.

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The error INVALID_VALUE is generated by VertexAttrib* if index is greater than or equal to MAX_VERTEX_ATTRIBS.

The state required to support vertex specification consists of the value of MAX_VERTEX_ATTRIBS four-component vectors to store generic vertex attributes.

The initial values for all generic vertex attributes are (0.0, 0.0, 0.0, 1.0).

2.8 Vertex Arrays

Vertex data is placed into arrays that are stored in the server’s address space (described in section 2.9). Blocks of data in these arrays may then be used to specify multiple geometric primitives through the execution of a single GL command. The client may specify up to the value of MAX_VERTEX_ATTRIBS arrays to store one or more generic vertex attributes. The commands

```c
void VertexAttribPointer(uint index, int size, enum type,
    boolean normalized, sizei stride, const
    *pointer);
void VertexAttribIPointer(uint index, int size, enum type,
    size stride, const void *pointer);
```

describe the locations and organizations of these arrays. For each command, type specifies the data type of the values stored in the array. size indicates the number of values per vertex that are stored in the array as well as their component ordering. Table 2.5 indicates the allowable values for size and type (when present). For type the values BYTE, SHORT, INT, FLOAT, HALF_FLOAT, and DOUBLE indicate types byte, short, int, float, half, and double, respectively; the values UNSIGNED_BYTE, UNSIGNED_SHORT, and UNSIGNED_INT indicate types ubyte, ushort, and uint, respectively; and the values INT_2_10_10_10_REV and UNSIGNED_INT_2_10_10_10_REV, indicating respectively four signed or unsigned elements packed into a single uint, both correspond to the term packed in that table.

An INVALID_VALUE error is generated if size is not one of the values allowed in table 2.5 for the corresponding command.

An INVALID_OPERATION error is generated under any of the following conditions:

- size is BGRA and type is not UNSIGNED_BYTE, INT_2_10_10_10_10_REV or UNSIGNED_INT_2_10_10_10_10_REV;
- type is INT_2_10_10_10_10_REV or UNSIGNED_INT_2_10_10_10_10_REV, and size is neither 4 or BGRA;

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<table>
<thead>
<tr>
<th>Command</th>
<th>Sizes and Component Ordering</th>
<th>Integer Handling</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>VertexAttribPointer</td>
<td>1, 2, 3, 4, BGRA</td>
<td>flag</td>
<td>byte, ubyte, short, ushort, int, uint, float, half, double, packed</td>
</tr>
<tr>
<td>VertexAttribI Pointer</td>
<td>1, 2, 3, 4</td>
<td>integer</td>
<td>byte, ubyte, short, ushort, int, uint</td>
</tr>
</tbody>
</table>

Table 2.5: Vertex array sizes (values per vertex) and data types. The “Integer Handling” column indicates how fixed-point data types are handled: “integer” means that they remain as integer values, and “flag” means that they are either converted to floating-point directly, or converted by normalizing to $[0, 1]$ (for unsigned types) or $[-1, 1]$ (for signed types), depending on the setting of the normalized flag in VertexAttribPointer. If size is BGRA, vertex array values are always normalized, irrespective of the “normalize” table entry. packed is not a GL type, but indicates commands accepting multiple components packed into a single uint.

- for VertexAttribPointer only, size is BGRA and normalized is FALSE;
- any of the *Pointer commands specifying the location and organization of vertex array data are called while zero is bound to the ARRAY_BUFFER buffer object binding point (see section 2.9.6), and the pointer argument is not NULL.

The index parameter in the VertexAttribPointer and VertexAttribI Pointer commands identifies the generic vertex attribute array being described. The error INVALID_VALUE is generated if index is greater than or equal to the value of MAX_VERTEX_ATTRIBS. Generic attribute arrays with integer type arguments can be handled in one of three ways: converted to float by normalizing to $[0, 1]$ or $[-1, 1]$ as described in equations 2.1 and 2.2, respectively; converted directly to float, or left as integers. Data for an array specified by VertexAttribPointer will be converted to floating-point by normalizing if normalized is TRUE, and converted directly to floating-point otherwise. Data for an array specified by VertexAttribI Pointer will always be left as integer values; such data are referred to as pure integers.

The one, two, three, or four values in an array that correspond to a single vertex comprise an array element. When size is BGRA, it indicates four values. The
values within each array element are stored sequentially in memory. However, if
\( \text{size} \) is BGRA, the first, second, third, and fourth values of each array element are
taken from the third, second, first, and fourth values in memory respectively. If
\( \text{stride} \) is specified as zero, then array elements are stored sequentially as well. The
error INVALID_VALUE is generated if \( \text{stride} \) is negative. Otherwise pointers to the
\( i \)th and \( (i + 1) \)st elements of an array differ by \( \text{stride} \) basic machine units (typi-
cally unsigned bytes), the pointer to the \( (i + 1) \)st element being greater. For each
call, \( \text{pointer} \) specifies the offset within a buffer of the first value of the first
element of the array being specified.

An individual generic vertex attribute array is enabled or disabled by calling
one of

\[
\begin{align*}
\text{void } &\text{EnableVertexAttribArray( uint index );} \\
\text{void } &\text{DisableVertexAttribArray( uint index );}
\end{align*}
\]

where \( \text{index} \) identifies the generic vertex attribute array to enable or disable. The
error INVALID_VALUE is generated if \( \text{index} \) is greater than or equal to MAX_VERTEX_ATTRIBS.

The command

\[
\text{void } \text{VertexAttribDivisor( uint index, uint divisor );}
\]

modifies the rate at which generic vertex attributes advance when rendering multi-
ple instances of primitives in a single draw call. If \( \text{divisor} \) is zero, the attribute at
slot \( \text{index} \) advances once per vertex. If \( \text{divisor} \) is non-zero, the attribute advances
once per \( \text{divisor} \) instances of the set(s) of vertices being rendered. An attribute is
referred to as instanced if its \( \text{divisor} \) value is non-zero.

An INVALID_VALUE error is generated if \( \text{index} \) is greater than or equal to the
value of MAX_VERTEX_ATTRIBS.

2.8.1 Transferring Array Elements

When an array element \( i \) is transferred to the GL by DrawArrays, DrawElements,
or the other Draw* commands described below, each generic attribute is expanded
to four components. If \( \text{size} \) is one then the \( x \) component of the attribute is specified
by the array; the \( y \), \( z \), and \( w \) components are implicitly set to 0, 0, and 1, respec-
tively. If \( \text{size} \) is two then the \( x \) and \( y \) components of the attribute are specified by
the array; the \( z \) and \( w \) components are implicitly set to 0 and 1, respectively. If \( \text{size} \)
is three then \( x \), \( y \), and \( z \) are specified, and \( w \) is implicitly set to 1. If \( \text{size} \) is four
then all components are specified.

Primitive restarting is enabled or disabled by calling one of the commands.
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void Enable( enum target );

and

void Disable( enum target );

with target PRIMITIVE_RESTART. The command

void PrimitiveRestartIndex( uint index );

specifies a vertex array element that is treated specially when primitive restarting is enabled. This value is called the primitive restart index. When one of the Draw* commands transfers a set of generic attribute array elements to the GL, if the index within the vertex arrays corresponding to that set is equal to the primitive restart index, then the GL does not process those elements as a vertex. Instead, it is as if the drawing command ended with the immediately preceding transfer, and another drawing command is immediately started with the same parameters, but only transferring the immediately following element through the end of the originally specified elements.

When one of the *BaseVertex drawing commands specified in section 2.8.3 is used, the primitive restart comparison occurs before the basevertex offset is added to the array index.

2.8.2 Packed Vertex Data Formats

UNSIGNED_INT_2_10_10_10_REV and INT_2_10_10_10_REV vertex data formats describe packed, 4 component formats stored in a single 32-bit word.

For the UNSIGNED_INT_2_10_10_10_REV vertex data format, the first \( x \), second \( y \), and third \( z \) components are represented as 10-bit unsigned integer values and the fourth \( w \) component is represented as a 2-bit unsigned integer value.

For the INT_2_10_10_10_REV vertex data format, the \( x \), \( y \) and \( z \) components are represented as 10-bit signed two’s complement integer values and the \( w \) component is represented as a 2-bit signed two’s complement integer value.

The normalized value is used to indicate whether to normalize the data to \([0, 1]\) (for unsigned types) or \([-1, 1]\) (for signed types). During normalization, the conversion rules specified in equations 2.1 and 2.2 are followed.

Tables 2.6 and 2.7 describe how these components are laid out in a 32-bit word.
2.8. VERTEX ARRAYS

Table 2.6: Packed component layout for non-BGRA formats. Bit numbers are indicated for each component.

Table 2.7: Packed component layout for BGRA format. Bit numbers are indicated for each component.

2.8.3 Drawing Commands

The command

```c
void DrawArraysOneInstance( enum mode, int first,
sizei count, int instance );
```

does not exist in the GL, but is used to describe functionality in the rest of this section. This command constructs a sequence of geometric primitives by transferring elements `first` through `first + count - 1` of each enabled array to the GL. `mode` specifies what kind of primitives are constructed, as defined in section 2.6.1. If `mode` is not a valid primitive type, an INVALID_ENUM error is generated. If `count` is negative, an INVALID_VALUE error is generated.

If an array corresponding to a generic attribute required by a vertex shader is not enabled, then the corresponding element is taken from the current generic attribute state (see section 2.7).

If an array corresponding to a generic attribute required by a vertex shader is enabled, the corresponding current generic attribute value is undefined after the execution of `DrawArraysOneInstance`.

Specifying `first < 0` results in undefined behavior. Generating the error INVALID_VALUE is recommended in this case.

The command

```c
void DrawArrays( enum mode, int first, sizei count );
```

is equivalent to the command sequence
DrawArraysOneInstance(mode, first, count, 0);

The internal counter instanceID is a 32-bit integer value which may be read by a vertex shader as gl_InstanceID, as described in section 2.11.8. The value of this counter is always zero, except as noted below.

The command

```c
void DrawArraysInstanced(enum mode, int first, sizei count, sizei primcount);
```

behaves identically to DrawArrays except that primcount instances of the range of elements are executed, the value of instanceID advances for each iteration, and the instanced elements advance per instance depending on the value of the divisor for that vertex attribute set with VertexAttribDivisor. It has the same effect as:

```c
if (mode or count is invalid)
    generate appropriate error
else {
    for (i = 0; i < primcount; i++) {
        instanceID = i;
        DrawArraysOneInstance(mode, first, count, i);
    }
    instanceID = 0;
}
```

The command

```c
void DrawArraysIndirect(enum mode, const void *indirect);
```

has the same effect as:

```c
typedef struct {
    uint count;
    uint primCount;
    uint first;
    uint reservedMustBeZero;
} DrawArraysIndirectCommand;

DrawArraysIndirectCommand *cmd =
    (DrawArraysIndirectCommand *)indirect;
DrawArraysInstanced(mode, cmd->first, cmd->count, cmd->primCount);
```
Unlike DrawArraysInstanced, first is unsigned and cannot cause an error. Results are undefined if reservedMustBeZero is non-zero, but must not lead to GL interruption or termination.

All elements of DrawArraysIndirectCommand are tightly packed 32 bit values.

The command

```c
void MultiDrawArrays( enum mode, const int *first,
                       const sizei *count, sizei primcount );
```

behaves identically to DrawArraysInstanced except that primcount separate ranges of elements are specified instead, all elements are treated as though they are not instanced, and the value of instanceID stays at 0. It has the same effect as:

```c
if (mode is invalid)
generate appropriate error
else {
    for (i = 0; i < primcount; i++) {
        if (count[i] > 0)
            DrawArraysOneInstance (mode, first[i], count[i], 0);
    }
}
```

The command

```c
void DrawElementsOneInstance( enum mode, sizei count,
                           enum type, const void *indices );
```

does not exist in the GL, but is used to describe functionality in the rest of this section. This command constructs a sequence of geometric primitives by successively transferring the count elements whose indices are stored in the currently bound element array buffer (see section 2.9.7) at the offset defined by indices to the GL. The ith element transferred by DrawElementsOneInstance will be taken from element indices[i] of each enabled array. type must be one of UNSIGNED_BYTE, UNSIGNED_SHORT, or UNSIGNED_INT, indicating that the index values are of GL type ubyte, ushort, or uint respectively. mode specifies what kind of primitives are constructed, as defined in section 2.6.1.

If an array corresponding to a generic attribute required by a vertex shader is not enabled, then the corresponding element is taken from the current generic attribute state (see section 2.7).
If an array corresponding to a generic attribute required by a vertex shader is enabled, the corresponding current generic attribute value is undefined after the execution of DrawElementsOneInstance.

The command

```c
void DrawElements( enum mode, sizei count, enum type,
    const void *indices );
```

behaves identically to DrawElementsOneInstance with the instance parameter set to zero; the effect of calling

```c
DrawElements( mode, count, type, indices );
```

is equivalent to the command sequence:

```c
if ( mode, count or type is invalid)
genenerate appropriate error
else
    DrawElementsOneInstance( mode, count, type, indices, 0 );
```

The command

```c
void DrawElementsInstanced( enum mode, sizei count,
    enum type, const void *indices, sizei primcount );
```

behaves identically to DrawElements except that `primcount` instances of the set of elements are executed, the value of `instanceID` advances between each set, and the instance advances between each set. It has the same effect as:

```c
if ( mode, count, or type is invalid)
genenerate appropriate error
else {
    for (int i = 0; i < primcount; i++) {
        instanceID = i;
        DrawElementsOneInstance( mode, count, type, indices, i );
    }
    instanceID = 0;
}
```

The command

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void MultiDrawElements(enum mode, const sizei *count, enum type, const void **indices, sizei primcount);

behaves identically to DrawElementsInstanced except that primcount separate sets of elements are specified instead, all elements are treated as though they are not instanced, and the value of instanceID stays at 0. It has the same effect as:

```c
if (mode, count, or type is invalid)
    generate appropriate error
else {
    for (int i = 0; i < primcount; i++)
        DrawElementsOneInstance(mode, count[i], type, indices[i], 0);
}
```

The command

```c
void DrawRangeElements( enum mode, uint start, uint end, sizei count, enum type, const void *indices );
```

is a restricted form of DrawElements. mode, count, type, and indices match the corresponding arguments to DrawElements, with the additional constraint that all index values identified by indices must lie between start and end inclusive.

Implementations denote recommended maximum amounts of vertex and index data, which may be queried by calling GetIntegerv with the symbolic constants MAX_ELEMENTS_VERTICES and MAX_ELEMENTS_INDICES. If end − start + 1 is greater than the value of MAX_ELEMENTS_VERTICES, or if count is greater than the value of MAX_ELEMENTS_INDICES, then the call may operate at reduced performance. There is no requirement that all vertices in the range [start, end] be referenced. However, the implementation may partially process unused vertices, reducing performance from what could be achieved with an optimal index set.

The error INVALID_VALUE is generated if end < start. Invalid mode, count, or type parameters generate the same errors as would the corresponding call to DrawElements. It is an error for index values other than the primitive restart index to lie outside the range [start, end], but implementations are not required to check for this. Such indices will cause implementation-dependent behavior.

The commands

```c
void DrawElementsBaseVertex( enum mode, sizei count, enum type, const void *indices, int basevertex );
```
2.8. VERTEX ARRAYS

```c
void DrawRangeElementsBaseVertex( enum mode, uint start, uint end, sizei count, enum type, const void *indices, int basevertex );
void DrawElementsInstancedBaseVertex( enum mode, sizei count, enum type, const void *indices, sizei primcount, int basevertex );
```

are equivalent to the commands with the same base name (without the BaseVertex suffix), except that the \( i \)th element transferred by the corresponding draw call will be taken from element \( \text{indices}[i] + \text{basevertex} \) of each enabled array. If the resulting value is larger than the maximum value representable by \( \text{type} \), it should behave as if the calculation were upconverted to 32-bit unsigned integers (with wrapping on overflow conditions). The operation is undefined if the sum would be negative and should be handled as described in section 2.9.4. For DrawRangeElementsBaseVertex, the index values must lie between \( \text{start} \) and \( \text{end} \) inclusive, prior to adding the \( \text{basevertex} \) offset. Index values lying outside the range \( [\text{start}, \text{end}] \) are treated in the same way as DrawRangeElements.

The command

```c
void DrawElementsIndirect( enum mode, enum type, const void *indirect );
```

has the same effect as:

```c
typedef struct {
    uint count;
    uint primCount;
    uint firstIndex;
    int baseVertex;
    uint reservedMustBeZero;
} DrawElementsIndirectCommand;
```

```c
if (no element array buffer is bound) {
    generate appropriate error
} else {
    DrawElementsIndirectCommand *cmd = (DrawElementsIndirectCommand *)indirect;

    DrawElementsInstancedBaseVertex(mode, cmd->count, type, cmd->firstIndex * size-of-type,
```
If no element array buffer is bound, an INVALID_OPERATION error is generated. Results are undefined if reservedMustBeZero is non-zero, but must not lead to GL interruption or termination.

All elements of `DrawElementsIndirectCommand` are tightly packed.

The command

```c
void MultiDrawElementsBaseVertex( enum mode, const sizei *count, enum type, const void **indices,
sizei primcount, const int *basevertex );
```

behaves identically to `DrawElementsBaseVertex`, except that `primcount` separate lists of elements are specified instead. It has the same effect as:

```c
for (int i = 0; i < primcount; i++)
if (count[i] > 0)
    DrawElementsBaseVertex( mode, count[i], type, indices[i], basevertex[i] );
```

If the number of supported generic vertex attributes (the value of `MAX_VERTEX_ATTRIBS`) is \( n \), then the state required to implement vertex arrays consists of \( n \) boolean values, \( n \) memory pointers, \( n \) integer stride values, \( n \) symbolic constants representing array types, \( n \) integers representing values per element, \( n \) boolean values indicating normalization, \( n \) boolean values indicating whether the attribute values are pure integers, \( n \) integers representing vertex attribute divisors, and an unsigned integer representing the restart index.

In the initial state, the boolean values are each false, the memory pointers are each `NULL`, the strides are each zero, the array types are each `FLOAT`, the integers representing values per element are each four, the normalized and pure integer flags are each false, the divisors are each zero, and the restart index is zero.

### 2.9 Buffer Objects

Vertex array data are stored in high-performance server memory. GL buffer objects provide a mechanism that clients can use to allocate, initialize, and render from such memory.

The command

```c
cmd->primCount, cmd->baseVertex);
```
2.9. BUFFER OBJECTS

<table>
<thead>
<tr>
<th>Target name</th>
<th>Purpose</th>
<th>Described in section(s)</th>
</tr>
</thead>
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<td>Vertex attributes</td>
<td>2.9.6</td>
</tr>
<tr>
<td>COPY_READ_BUFFER</td>
<td>Buffer copy source</td>
<td>2.9.5</td>
</tr>
<tr>
<td>COPY_WRITE_BUFFER</td>
<td>Buffer copy destination</td>
<td>2.9.5</td>
</tr>
<tr>
<td>DRAW_INDIRECT_BUFFER</td>
<td>Indirect command arguments</td>
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</tr>
<tr>
<td>ELEMENT_ARRAY_BUFFER</td>
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<tr>
<td>PIXEL_PACK_BUFFER</td>
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<td>PIXEL_UNPACK_BUFFER</td>
<td>Texture data source</td>
<td>3.7</td>
</tr>
<tr>
<td>TEXTURE_BUFFER</td>
<td>Texture data buffer</td>
<td>3.8.7</td>
</tr>
<tr>
<td>TRANSFORM_FEEDBACK_BUFFER</td>
<td>Transform feedback buffer</td>
<td>2.17</td>
</tr>
<tr>
<td>UNIFORM_BUFFER</td>
<td>Uniform block storage</td>
<td>2.11.4</td>
</tr>
</tbody>
</table>

Table 2.8: Buffer object binding targets.

```c
void GenBuffers( sizei n, uint *buffers );
```

returns \( n \) previously unused buffer object names in `buffers`. These names are marked as used, for the purposes of `GenBuffers` only, but they acquire buffer state only when they are first bound with `BindBuffer` (see below), just as if they were unused.

Buffer objects are deleted by calling

```c
void DeleteBuffers( sizei n, const uint *buffers );
```

`buffers` contains \( n \) names of buffer objects to be deleted. After a buffer object is deleted it has no contents, and its name is again unused. Unused names in `buffers` are silently ignored, as is the value zero.

2.9.1 Creating and Binding Buffer Objects

A buffer object is created by binding a name returned by `GenBuffers` to a buffer target. The binding is effected by calling

```c
void BindBuffer( enum target, uint buffer );
```

`target` must be one of the targets listed in table 2.8. If the buffer object named `buffer` has not been previously bound, the GL creates a new state vector, initialized with a zero-sized memory buffer and comprising the state values listed in table 2.9.
2.9. BUFFER OBJECTS

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Initial Value</th>
<th>Legal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUFFER_SIZE</td>
<td>int64</td>
<td>0</td>
<td>any non-negative integer</td>
</tr>
<tr>
<td>BUFFER_USAGE</td>
<td>enum</td>
<td>STATIC_DRAW</td>
<td>STREAM_DRAW, STREAM_READ, STATIC_DRAW, STREAM_COPY, STATIC_DRAW, STATIC_READ, STATIC_COPY, DYNAMIC_DRAW, DYNAMIC_READ, DYNAMIC_COPY</td>
</tr>
<tr>
<td>BUFFER_ACCESS</td>
<td>enum</td>
<td>READ_WRITE</td>
<td>READ_ONLY, WRITE_ONLY, READ_WRITE</td>
</tr>
<tr>
<td>BUFFER_ACCESS_FLAGS</td>
<td>int</td>
<td>0</td>
<td>See section 2.9.3</td>
</tr>
<tr>
<td>BUFFER_MAPPED</td>
<td>boolean</td>
<td>FALSE</td>
<td>TRUE, FALSE</td>
</tr>
<tr>
<td>BUFFER_MAP_POINTER</td>
<td>void*</td>
<td>NULL</td>
<td>address</td>
</tr>
<tr>
<td>BUFFER_MAP_OFFSET</td>
<td>int64</td>
<td>0</td>
<td>any non-negative integer</td>
</tr>
<tr>
<td>BUFFER_MAP_LENGTH</td>
<td>int64</td>
<td>0</td>
<td>any non-negative integer</td>
</tr>
</tbody>
</table>

Table 2.9: Buffer object parameters and their values.

Buffer objects created by binding a name returned by GenBuffers to any of the valid targets are formally equivalent, but the GL may make different choices about storage location and layout based on the initial binding.

BindBuffer may also be used to bind an existing buffer object. If the bind is successful no change is made to the state of the newly bound buffer object, and any previous binding to target is broken.

BindBuffer fails and an INVALID_OPERATION error is generated if buffer is not zero or a name returned from a previous call to GenBuffers, or if such a name has since been deleted with DeleteBuffers.

While a buffer object is bound, GL operations on the target to which it is bound affect the bound buffer object, and queries of the target to which a buffer object is bound return state from the bound object. Operations on the target also affect any other bindings of that object.

If a buffer object is deleted while it is bound, all bindings to that object in the current context (i.e. in the thread that called DeleteBuffers) are reset to zero. Bindings to that buffer in other contexts and other threads are not affected, but attempting to use a deleted buffer in another thread produces undefined results, including but not limited to possible GL errors and rendering corruption. Using a deleted buffer in another context or thread may not, however, result in program termination.
Initially, each buffer object target is bound to zero. There is no buffer object corresponding to the name zero, so client attempts to modify or query buffer object state for a target bound to zero generate an INVALID_OPERATION error.

### Binding Buffer Objects to Indexed Targets

Buffer objects may be bound to *indexed* targets by calling one of the commands

```c
void BindBufferRange( enum target, uint index,
                      uint buffer, intptr offset, sizeiptr size );
void BindBufferBase( enum target, uint index, uint buffer );
```

*target* must be TRANSFORM_FEEDBACK_BUFFER or UNIFORM_BUFFER. Additional language specific to each target is included in sections referred to for each target in table 2.8.

Each *target* represents an indexed array of buffer object binding points, as well as a single general binding point that can be used by other buffer object manipulation functions (e.g. BindBuffer, MapBuffer). Both commands bind the buffer object named by *buffer* to both the general binding point, and to the binding point in the array given by *index*. The error INVALID_VALUE is generated if *index* is greater than or equal to the number of *target*-specific indexed binding points.

For **BindBufferRange**, *offset* specifies a starting offset into the buffer object *buffer*, and *size* specifies the amount of data that can be read from the buffer object while used as an indexed target. Both *offset* and *size* are in basic machine units. The error INVALID_VALUE is generated if *size* is less than or equal to zero or if *offset + size* is greater than the value of BUFFER_SIZE. Additional errors may be generated if *offset* violates *target*-specific alignment requirements.

**BindBufferBase** is equivalent to calling **BindBufferRange** with *offset* zero and *size* equal to the size of *buffer*.

### 2.9.2 Creating Buffer Object Data Stores

The data store of a buffer object is created and initialized by calling

```c
voidBufferData( enum target, sizeiptr size, const void *data, enum usage );
```

with *target* set to one of the targets listed in table 2.8, *size* set to the size of the data store in basic machine units, and *data* pointing to the source data in client memory. If *data* is non-null, then the source data is copied to the buffer object’s data store. If *data* is null, then the contents of the buffer object’s data store are undefined.
usage is specified as one of nine enumerated values, indicating the expected application usage pattern of the data store. The values are:

STREAM_DRAW The data store contents will be specified once by the application, and used at most a few times as the source for GL drawing and image specification commands.

STREAM_READ The data store contents will be specified once by reading data from the GL, and queried at most a few times by the application.

STREAM_COPY The data store contents will be specified once by reading data from the GL, and used at most a few times as the source for GL drawing and image specification commands.

STATIC_DRAW The data store contents will be specified once by the application, and used many times as the source for GL drawing and image specification commands.

STATIC_READ The data store contents will be specified once by reading data from the GL, and queried many times by the application.

STATIC_COPY The data store contents will be specified once by reading data from the GL, and used many times as the source for GL drawing and image specification commands.

DYNAMIC_DRAW The data store contents will be respecified repeatedly by the application, and used many times as the source for GL drawing and image specification commands.

DYNAMIC_READ The data store contents will be respecified repeatedly by reading data from the GL, and queried many times by the application.

DYNAMIC_COPY The data store contents will be respecified repeatedly by reading data from the GL, and used many times as the source for GL drawing and image specification commands.

usage is provided as a performance hint only. The specified usage value does not constrain the actual usage pattern of the data store. BufferData deletes any existing data store, and sets the values of the buffer object’s state variables as shown in table 2.10.

Clients must align data elements consistent with the requirements of the client platform, with an additional base-level requirement that an offset within a buffer to a datum comprising \( N \) basic machine units be a multiple of \( N \).
<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUFFER_SIZE</td>
<td>size</td>
</tr>
<tr>
<td>BUFFER_USAGE</td>
<td>usage</td>
</tr>
<tr>
<td>BUFFER_ACCESS</td>
<td>READ_WRITE</td>
</tr>
<tr>
<td>BUFFER_ACCESS_FLAGS</td>
<td>0</td>
</tr>
<tr>
<td>BUFFER_MAPPED</td>
<td>FALSE</td>
</tr>
<tr>
<td>BUFFER_MAP_POINTER</td>
<td>NULL</td>
</tr>
<tr>
<td>BUFFER_MAP_OFFSET</td>
<td>0</td>
</tr>
<tr>
<td>BUFFER_MAP_LENGTH</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.10: Buffer object initial state.

If the GL is unable to create a data store of the requested size, the error `OUT_OF_MEMORY` is generated.

To modify some or all of the data contained in a buffer object’s data store, the client may use the command

```c
void BufferSubData( enum target, intptr offset, sizeiptr size, const void *data );
```

with `target` set to one of the targets listed in table 2.8. `offset` and `size` indicate the range of data in the buffer object that is to be replaced, in terms of basic machine units. `data` specifies a region of client memory `size` basic machine units in length, containing the data that replace the specified buffer range. An `INVALID_VALUE` error is generated if `offset` or `size` is less than zero or if `offset + size` is greater than the value of `BUFFER_SIZE`. An `INVALID_OPERATION` error is generated if any part of the specified buffer range is mapped with `MapBufferRange` or `MapBuffer` (see section 2.9.3).

### 2.9.3 Mapping and Unmapping Buffer Data

All or part of the data store of a buffer object may be mapped into the client’s address space by calling

```c
void *MapBufferRange( enum target, intptr offset, sizeiptr length, bitfield access );
```

with `target` set to one of the targets listed in table 2.8. `offset` and `length` indicate the range of data in the buffer object that is to be mapped, in terms of basic machine units.
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units. *access* is a bitfield containing flags which describe the requested mapping. These flags are described below.

If no error occurs, a pointer to the beginning of the mapped range is returned once all pending operations on that buffer have completed, and may be used to modify and/or query the corresponding range of the buffer, according to the following flag bits set in *access*:

- **MAP_READ_BIT** indicates that the returned pointer may be used to read buffer object data. No GL error is generated if the pointer is used to query a mapping which excludes this flag, but the result is undefined and system errors (possibly including program termination) may occur.

- **MAP_WRITE_BIT** indicates that the returned pointer may be used to modify buffer object data. No GL error is generated if the pointer is used to modify a mapping which excludes this flag, but the result is undefined and system errors (possibly including program termination) may occur.

Pointer values returned by **MapBufferRange** may not be passed as parameter values to GL commands. For example, they may not be used to specify array pointers, or to specify or query pixel or texture image data; such actions produce undefined results, although implementations may not check for such behavior for performance reasons.

Mappings to the data stores of buffer objects may have nonstandard performance characteristics. For example, such mappings may be marked as uncacheable regions of memory, and in such cases reading from them may be very slow. To ensure optimal performance, the client should use the mapping in a fashion consistent with the values of **BUFFER_USAGE** and *access*. Using a mapping in a fashion inconsistent with these values is liable to be multiple orders of magnitude slower than using normal memory.

The following optional flag bits in *access* may be used to modify the mapping:

- **MAP_INVALIDATE_RANGE_BIT** indicates that the previous contents of the specified range may be discarded. Data within this range are undefined with the exception of subsequently written data. No GL error is generated if subsequent GL operations access unwritten data, but the result is undefined and system errors (possibly including program termination) may occur. This flag may not be used in combination with **MAP_READ_BIT**.

- **MAP_INVALIDATE_BUFFER_BIT** indicates that the previous contents of the entire buffer may be discarded. Data within the entire buffer are undefined with the exception of subsequently written data. No GL error is generated if
2.9. BUFFER OBJECTS

Table 2.11: Buffer object state set by MapBufferRange.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUFFER_ACCESS</td>
<td>Depends on access$^1$</td>
</tr>
<tr>
<td>BUFFER_ACCESS_FLAGS</td>
<td>access</td>
</tr>
<tr>
<td>BUFFER_MAPPED</td>
<td>TRUE</td>
</tr>
<tr>
<td>BUFFER_MAP_POINTER</td>
<td>pointer to the data store</td>
</tr>
<tr>
<td>BUFFER_MAP_OFFSET</td>
<td>offset</td>
</tr>
<tr>
<td>BUFFER_MAP_LENGTH</td>
<td>length</td>
</tr>
</tbody>
</table>

$^1$ BUFFER_ACCESS is set to READ_ONLY, WRITE_ONLY, or READ_WRITE if access
& (MAP_READ_BIT|MAP_WRITE_BIT) is respectively MAP_READ_BIT, MAP_WRITE_BIT, or MAP_READ_BIT|MAP_WRITE_BIT.

subsequent GL operations access unwritten data, but the result is undefined and system errors (possibly including program termination) may occur. This flag may not be used in combination with MAP_READ_BIT.

- MAP_FLUSH_EXPLICIT_BIT indicates that one or more discrete subranges of the mapping may be modified. When this flag is set, modifications to each subrange must be explicitly flushed by calling FlushMappedBufferRange. No GL error is set if a subrange of the mapping is modified and not flushed, but data within the corresponding subrange of the buffer are undefined. This flag may only be used in conjunction with MAP_WRITE_BIT. When this option is selected, flushing is strictly limited to regions that are explicitly indicated with calls to FlushMappedBufferRange prior to unmap; if this option is not selected UnmapBuffer will automatically flush the entire mapped range when called.

- MAP_UNSYNCHRONIZED_BIT indicates that the GL should not attempt to synchronize pending operations on the buffer prior to returning from MapBufferRange. No GL error is generated if pending operations which source or modify the buffer overlap the mapped region, but the result of such previous and any subsequent operations is undefined.

A successful MapBufferRange sets buffer object state values as shown in table 2.11.

Errors

If an error occurs, MapBufferRange returns a NULL pointer.
An **INVALID_VALUE** error is generated if *offset* or *length* is negative, if *offset + length* is greater than the value of *BUFFER_SIZE*, or if *access* has any bits set other than those defined above.

An **INVALID_OPERATION** error is generated for any of the following conditions:

- The buffer is already in a mapped state.
- Neither **MAP_READ_BIT** nor **MAP_WRITE_BIT** is set.
- **MAP_READ_BIT** is set and any of **MAP_INVALIDATE_RANGE_BIT**, **MAP_INVALIDATE_BUFFER_BIT**, or **MAP_UNSYNCHRONIZED_BIT** is set.
- **MAP_FLUSH_EXPLICIT_BIT** is set and **MAP_WRITE_BIT** is not set.

An **OUT_OF_MEMORY** error is generated if **MapBufferRange** fails because memory for the mapping could not be obtained.

No error is generated if memory outside the mapped range is modified or queried, but the result is undefined and system errors (possibly including program termination) may occur.

The entire data store of a buffer object can be mapped into the client’s address space by calling

```c
void *MapBuffer( enum target, enum access );
```

**MapBuffer** is equivalent to calling **MapBufferRange** with the same *target*, *offset* of zero, *length* equal to the value of *BUFFER_SIZE*, and the *access* bitfield value passed to **MapBufferRange** equal to

- **MAP_READ_BIT**, if *mbaccess* is **READ_ONLY**
- **MAP_WRITE_BIT**, if *mbaccess* is **WRITE_ONLY**
- **MAP_READ_BIT | MAP_WRITE_BIT**, if *mbaccess* is **READ_WRITE**

and *mbaccess* is the value of the *access* enum parameter passed to **MapBuffer**.

**INVALID_ENUM** is generated if *access* is not one of the values described above. Other errors are generated as described above for **MapBufferRange**.

If a buffer is mapped with the **MAP_FLUSH_EXPLICIT_BIT** flag, modifications to the mapped range may be indicated by calling

```c
void FlushMappedBufferRange( enum target, intptr offset, sizeiptr length );
```

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with target set to one of the targets listed in table 2.8. offset and length indicate a modified subrange of the mapping, in basic machine units. The specified subrange to flush is relative to the start of the currently mapped range of buffer. 
FlushMappedBufferRange may be called multiple times to indicate distinct subranges of the mapping which require flushing.

Errors

An INVALID_VALUE error is generated if offset or length is negative, or if offset + length exceeds the size of the mapping.

An INVALID_OPERATION error is generated if zero is bound to target.

An INVALID_OPERATION error is generated if the buffer bound to target is not mapped, or is mapped without the MAP_FLUSH_EXPLICIT_BIT flag.

Unmapping Buffers

After the client has specified the contents of a mapped buffer range, and before the data in that range are dereferenced by any GL commands, the mapping must be relinquished by calling

    boolean UnmapBuffer( enum target );

with target set to one of the targets listed in table 2.8. Unmapping a mapped buffer object invalidates the pointer to its data store and sets the object’s BUFFER_MAPPED, BUFFER_MAP_POINTER, BUFFER_ACCESS_FLAGS, BUFFER_MAP_OFFSET, and BUFFER_MAP_LENGTH state variables to the initial values shown in table 2.10.

UnmapBuffer returns TRUE unless data values in the buffer’s data store have become corrupted during the period that the buffer was mapped. Such corruption can be the result of a screen resolution change or other window system-dependent event that causes system heaps such as those for high-performance graphics memory to be discarded. GL implementations must guarantee that such corruption can occur only during the periods that a buffer’s data store is mapped. If such corruption has occurred, UnmapBuffer returns FALSE, and the contents of the buffer’s data store become undefined.

If the buffer data store is already in the unmapped state, UnmapBuffer returns FALSE, and an INVALID_OPERATION error is generated. However, unmapping that occurs as a side effect of buffer deletion or reinitialization is not an error.

Effects of Mapping Buffers on Other GL Commands

Most, but not all GL commands will detect attempts to read data from a mapped buffer object. When such an attempt is detected, an INVALID_OPERATION error
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will be generated. Any command which does not detect these attempts, and per-
forms such an invalid read, has undefined results and may result in GL interruption
or termination.

2.9.4 Effects of Accessing Outside Buffer Bounds

Most, but not all GL commands operating on buffer objects will detect attempts to
read from or write to a location in a bound buffer object at an offset less than zero,
or greater than or equal to the buffer’s size. When such an attempt is detected, a
GL error will be generated. Any command which does not detect these attempts,
and performs such an invalid read or write, has undefined results, and may result
in GL interruption or termination.

2.9.5 Copying Between Buffers

All or part of the data store of a buffer object may be copied to the data store of
another buffer object by calling

```c
void *CopyBufferSubData( enum readtarget,
    enum writetarget, intptr readoffset, intptr writeoffset,
    sizeiptr size );
```

with `readtarget` and `writetarget` each set to one of the targets listed in table 2.8.
While any of these targets may be used, the `COPY_READ_BUFFER` and `COPY-
WRITE_BUFFER` targets are provided specifically for copies, so that they can be
done without affecting other buffer binding targets that may be in use. `writeoffset`
and `size` specify the range of data in the buffer object bound to `writetarget` that is
to be replaced, in terms of basic machine units. `readoffset` and `size` specify the
range of data in the buffer object bound to `readtarget` that is to be copied to the
corresponding region of `writetarget`.

An `INVALID_VALUE` error is generated if any of `readoffset`, `writeoffset`, or `size`
are negative, if `readoffset + size` exceeds the size of the buffer object bound to
`readtarget`, or if `writeoffset + size` exceeds the size of the buffer object bound to
`writetarget`.

An `INVALID_VALUE` error is generated if the same buffer object is bound to
both `readtarget` and `writetarget`, and the ranges `[readoffset, readoffset+size]` and
`[writeoffset, writeoffset+size]` overlap.

An `INVALID_OPERATION` error is generated if zero is bound to `readtarget` or
`writetarget`.

An `INVALID_OPERATION` error is generated if the buffer objects bound to
either `readtarget` or `writetarget` are mapped.

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2.9.6 Vertex Arrays in Buffer Objects

Blocks of vertex array data are stored in buffer objects with the same format and layout options described in section 2.8. A buffer object binding point is added to the client state associated with each vertex array type. The commands that specify the locations and organizations of vertex arrays copy the buffer object name that is bound to ARRAY_BUFFER to the binding point corresponding to the vertex array of the type being specified. For example, the VertexAttribPointer command copies the value of ARRAY_BUFFER_BINDING (the queriable name of the buffer binding corresponding to the target ARRAY_BUFFER) to the client state variable VERTEX_ATTRIB_ARRAY_BUFFER_BINDING for the specified index.

Rendering commands DrawArrays, and the other drawing commands defined in section 2.8.3 operate as previously defined, where data for enabled generic attribute arrays are sourced from buffer objects. When an array is sourced from a buffer object, the pointer value of that array is used to compute an offset, in basic machine units, into the data store of the buffer object. This offset is computed by subtracting a null pointer from the pointer value, where both pointers are treated as pointers to basic machine units.

If any enabled array’s buffer binding is zero when DrawArrays or one of the other drawing commands defined in section 2.8.3 is called, the result is undefined.

2.9.7 Array Indices in Buffer Objects

Blocks of array indices are stored in buffer objects in the formats described by the type parameter of DrawElements (see section 2.8.3).

A buffer object is bound to ELEMENT_ARRAY_BUFFER by calling BindBuffer with target set to ELEMENT_ARRAY_BUFFER, and buffer set to the name of the buffer object. If no corresponding buffer object exists, one is initialized as defined in section 2.9. DrawElements, DrawRangeElements, and DrawElementsInstanced source their indices from the buffer object whose name is bound to ELEMENT_ARRAY_BUFFER, using their indices parameters as offsets into the buffer object in the same fashion as described in section 2.9.6. DrawElementsBaseVertex, DrawRangeElementsBaseVertex, and DrawElementsInstancedBaseVertex also source their indices from that buffer object, adding the basevertex offset to the appropriate vertex index as a final step before indexing into the vertex buffer; this does not affect the calculation of the base pointer for the index array. Finally, MultiDrawElements and MultiDrawElementsBaseVertex also source their indices from that buffer object, using its indices parameter as a pointer to an array of pointers that represent offsets into the buffer object. If zero is bound to
2.10. VERTEX ARRAY OBJECTS

ELEMENT_ARRAY_BUFFER, the result of these drawing commands is undefined.

In some cases performance will be optimized by storing indices and array data in separate buffer objects, and by creating those buffer objects with the corresponding binding points.

2.9.8 Indirect Commands in Buffer Objects

Arguments to **DrawArraysIndirect** and **DrawElementsIndirect** commands are stored in buffer objects in the formats described in section 2.8.3 for the **DrawArraysIndirectCommand** and **DrawElementsIndirectCommand** structures, respectively.

A buffer object is bound to **DRAW_INDIRECT_BUFFER** by calling **BindBuffer** with **target** set to **DRAW_INDIRECT_BUFFER**, and **buffer** set to the name of the buffer object. If no corresponding buffer object exists, one is initialized as defined in section 2.9.

**DrawArraysIndirect** and **DrawElementsIndirect** source their arguments from the buffer object whose name is bound to **DRAW_INDIRECT_BUFFER**, using their **indirect** parameters as offsets into the buffer object in the same fashion as described in section 2.9.6. An **INVALID_OPERATION** error is generated if these commands source data beyond the end of the buffer object, or if **indirect** is not aligned to a multiple of the size, in basic machine units, of **uint**.

If zero is bound to **DRAW_INDIRECT_BUFFER**, the result of these drawing commands is undefined.

2.9.9 Buffer Object State

The state required to support buffer objects consists of binding names for each of the buffer targets in table 2.8, and for each of the indexed buffer targets in section 2.9.1. Additionally, each vertex array has an associated binding so there is a buffer object binding for each of the vertex attribute arrays. The initial values for all buffer object bindings is zero.

The state of each buffer object consists of a buffer size in basic machine units, a usage parameter, an access parameter, a mapped boolean, two integers for the offset and size of the mapped region, a pointer to the mapped buffer (**NULL** if unmapped), and the sized array of basic machine units for the buffer data.

2.10 Vertex Array Objects

The buffer objects that are to be used by the vertex stage of the GL are collected together to form a vertex array object. All state related to the definition of data
used by the vertex processor is encapsulated in a vertex array object.

The command

```c
void GenVertexArrays( sizei n, uint *arrays );
```

returns \( n \) previous unused vertex array object names in `arrays`. These names are marked as used, for the purposes of `GenVertexArrays` only, but they acquire array state only when they are first bound.

Vertex array objects are deleted by calling

```c
void DeleteVertexArrays( sizei n, const uint *arrays );
```

`arrays` contains \( n \) names of vertex array objects to be deleted. Once a vertex array object is deleted it has no contents and its name is again unused. If a vertex array object that is currently bound is deleted, the binding for that object reverts to zero and the default vertex array becomes current. Unused names in `arrays` are silently ignored, as is the value zero.

A vertex array object is created by binding a name returned by `GenVertexArrays` with the command

```c
void BindVertexArray( uint array );
```

`array` is the vertex array object name. The resulting vertex array object is a new state vector, comprising all the state values listed in tables 6.5 and 6.6.

`BindVertexArray` may also be used to bind an existing vertex array object. If the bind is successful no change is made to the state of the bound vertex array object, and any previous binding is broken.

The currently bound vertex array object is used for all commands which modify vertex array state, such as `VertexAttribPointer` and `EnableVertexAttribArray`; all commands which draw from vertex arrays, such as `DrawArrays` and `DrawElements`; and all queries of vertex array state (see chapter 6).

`BindVertexArray` fails and an INVALID_OPERATION error is generated if `array` is not zero or a name returned from a previous call to `GenVertexArrays`, or if such a name has since been deleted with `DeleteVertexArrays`.

### 2.11 Vertex Shaders

Vertex shaders describe the operations that occur on vertex values and their associated data.
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A vertex shader is an array of strings containing source code for the operations that are meant to occur on each vertex that is processed. The language used for vertex shaders is described in the OpenGL Shading Language Specification.

To use a vertex shader, shader source code is first loaded into a shader object and then compiled. One or more vertex shader objects are then attached to a program object. A program object is then linked, which generates executable code from all the compiled shader objects attached to the program. When a linked program object is used as the current program object, the executable code for the vertex shaders it contains is used to process vertices.

In addition to vertex shaders, tessellation control shaders, tessellation evaluation shaders, geometry shaders and fragment shaders can be created, compiled, and linked into program objects. Tessellation control and evaluation shaders are used to control the operation of the tessellator, and are described in section 2.12. Geometry shaders affect the processing of primitives assembled from vertices (see section 2.13). Fragment shaders affect the processing of fragments during rasterization (see section 3.9). A single program object can contain all of vertex, tessellation control, tessellation evaluation, geometry, and fragment shaders.

When the program object currently in use includes a vertex shader, its vertex shader is considered active and is used to process vertices. If the program object has no vertex shader, or no program object is currently in use, the results of vertex shader execution are undefined.

A vertex shader can reference a number of variables as it executes. Vertex attributes are the per-vertex values specified in section 2.7. Uniforms are per-program variables that are constant during program execution. Samplers are a special form of uniform used for texturing (section 3.8). Varying variables hold the results of vertex shader execution that are used later in the pipeline. Each of these variable types is described in more detail below.

2.11.1 Shader Objects

The source code that makes up a program that gets executed by one of the programmable stages is encapsulated in one or more shader objects.

The name space for shader objects is the unsigned integers, with zero reserved for the GL. This name space is shared with program objects. The following sections define commands that operate on shader and program objects by name. Commands that accept shader or program object names will generate the error INVALID_VALUE if the provided name is not the name of either a shader or program object and INVALID_OPERATION if the provided name identifies an object that is not the expected type.

To create a shader object, use the command
2.11. VERTEX SHADERS

```c
uint CreateShader(enum type);
```

The shader object is empty when it is created. The `type` argument specifies the type of shader object to be created. For vertex shaders, `type` must be `VERTEX_SHADER`. A non-zero name that can be used to reference the shader object is returned. If an error occurs, zero will be returned.

The command

```c
void ShaderSource(uint shader, sizei count, const char **string, const int *length);
```

loads source code into the shader object named `shader`. `string` is an array of `count` pointers to optionally null-terminated character strings that make up the source code. The `length` argument is an array with the number of characters in each string (the string length). If an element in `length` is negative, its accompanying string is null-terminated. If `length` is `NULL`, all strings in the `string` argument are considered null-terminated. The `ShaderSource` command sets the source code for the `shader` to the text strings in the `string` array. If `shader` previously had source code loaded into it, the existing source code is completely replaced. Any length passed in excludes the null terminator in its count.

The strings that are loaded into a shader object are expected to form the source code for a valid shader as defined in the OpenGL Shading Language Specification.

Once the source code for a shader has been loaded, a shader object can be compiled with the command

```c
void CompileShader(uint shader);
```

Each shader object has a boolean status, `COMPILE_STATUS`, that is modified as a result of compilation. This status can be queried with `GetShaderiv` (see section 6.1.12). This status will be set to `TRUE` if `shader` was compiled without errors and is ready for use, and `FALSE` otherwise. Compilation can fail for a variety of reasons as listed in the OpenGL Shading Language Specification. If `CompileShader` failed, any information about a previous compile is lost. Thus a failed compile does not restore the old state of `shader`.

Changing the source code of a shader object with `ShaderSource` does not change its compile status or the compiled shader code.

Each shader object has an information log, which is a text string that is overwritten as a result of compilation. This information log can be queried with `GetShaderInfoLog` to obtain more information about the compilation attempt (see section 6.1.12).
An INVALID_OPERATION error is generated if shader is not the name of a valid shader object generated by CreateShader.

The command

```c
void CompileShader( uint shader );
```

is equivalent to

```c
CompileShaderInclude (shader, 0, NULL, NULL).
```

Shader objects can be deleted with the command

```c
void DeleteShader( uint shader );
```

If shader is not attached to any program object, it is deleted immediately. Otherwise, shader is flagged for deletion and will be deleted when it is no longer attached to any program object. If an object is flagged for deletion, its boolean status bit DELETE_STATUS is set to true. The value of DELETE_STATUS can be queried with GetShaderiv (see section 6.1.12). DeleteShader will silently ignore the value zero.

### 2.11.2 Program Objects

The shader objects that are to be used by the programmable stages of the GL are collected together to form a program object. The programs that are executed by these programmable stages are called executables. All information necessary for defining an executable is encapsulated in a program object. A program object is created with the command

```c
uint CreateProgram( void );
```

Program objects are empty when they are created. A non-zero name that can be used to reference the program object is returned. If an error occurs, zero will be returned.

To attach a shader object to a program object, use the command

```c
void AttachShader( uint program, uint shader );
```

The error INVALID_OPERATION is generated if shader is already attached to program.

Shader objects may be attached to program objects before source code has been loaded into the shader object, or before the shader object has been compiled. Multiple shader objects of the same type may be attached to a single program object, and a single shader object may be attached to more than one program object.

To detach a shader object from a program object, use the command
void DetachShader(uint program, uint shader);

The error INVALID_OPERATION is generated if shader is not attached to program. If shader has been flagged for deletion and is not attached to any other program object, it is deleted.

In order to use the shader objects contained in a program object, the program object must be linked. The command

void LinkProgram(uint program);

will link the program object named program. Each program object has a boolean status, LINK_STATUS, that is modified as a result of linking. This status can be queried with GetProgramiv (see section 6.1.12). This status will be set to TRUE if a valid executable is created, and FALSE otherwise.

Linking can fail for a variety of reasons as specified in the OpenGL Shading Language Specification, as well as any of the following reasons:

- One or more of the shader objects attached to program are not compiled successfully.
- More active uniform or active sampler variables are used in program than allowed (see sections 2.11.4, 2.11.6, and 2.13.3).
- The program object contains objects to form a tessellation control shader (see section 2.12.1), and
  - the program contains no objects to form a vertex shader;
  - the output patch vertex count is not specified in any compiled tessellation control shader object; or
  - the output patch vertex count is specified differently in multiple tessellation control shader objects.
- The program object contains objects to form a tessellation evaluation shader (see section 2.12.3), and
  - the program contains no objects to form a vertex shader;
  - the tessellation primitive mode is not specified in any compiled tessellation evaluation shader object; or
  - the tessellation primitive mode, spacing, vertex order, or point mode is specified differently in multiple tessellation evaluation shader objects.
• The program object contains objects to form a geometry shader (see section 2.13), and
  
  – the program contains no objects to form a vertex shader;
  
  – the input primitive type, output primitive type, or maximum output vertex count is not specified in any compiled geometry shader object; or
  
  – the input primitive type, output primitive type, or maximum output vertex count is specified differently in multiple geometry shader objects.

If LinkProgram failed, any information about a previous link of that program object is lost. Thus, a failed link does not restore the old state of program. Each program object has an information log that is overwritten as a result of a link operation. This information log can be queried with GetProgramInfoLog to obtain more information about the link operation or the validation information (see section 6.1.12).

If a valid executable is created, it can be made part of the current rendering state with the command

```c
void UseProgram(uint program);
```

This command will install the executable code as part of current rendering state if the program object program contains valid executable code, i.e. has been linked successfully. If UseProgram is called with program set to 0, then the current rendering state refers to an invalid program object, and the results of vertex and fragment shader execution are undefined. However, this is not an error. If program has not been successfully linked, the error INVALID_OPERATION is generated and the current rendering state is not modified.

While a program object is in use, applications are free to modify attached shader objects, compile attached shader objects, attach additional shader objects, and detach shader objects. These operations do not affect the link status or executable code of the program object.

If the program object that is in use is re-linked successfully, the LinkProgram command will install the generated executable code as part of the current rendering state if the specified program object was already in use as a result of a previous call to UseProgram.

If that program object that is in use is re-linked unsuccessfully, the link status will be set to FALSE, but existing executable and associated state will remain part of the current rendering state until a subsequent call to UseProgram removes it from use. After such a program is removed from use, it can not be made part of the current rendering state until it is successfully re-linked.

Program objects can be deleted with the command
void DeleteProgram(uint program);

If program is not the current program for any GL context, it is deleted immediately. Otherwise, program is flagged for deletion and will be deleted when it is no longer the current program for any context. When a program object is deleted, all shader objects attached to it are detached. DeleteProgram will silently ignore the value zero.

2.11.3 Vertex Attributes

Vertex shaders can define named attribute variables, which are bound to the generic vertex attributes that are set by VertexAttrib*. This binding can be specified by the application before the program is linked, or automatically assigned by the GL when the program is linked.

When an attribute variable declared as a float, vec2, vec3 or vec4 is bound to a generic attribute index i, its value(s) are taken from the x, (x, y), (x, y, z), or (x, y, z, w) components, respectively, of the generic attribute i. When an attribute variable is declared as a mat2, mat3x2 or mat4x2, its matrix columns are taken from the (x, y) components of generic attributes i and i + 1 (mat2), from attributes i through i + 2 (mat3x2), or from attributes i through i + 3 (mat4x2). When an attribute variable is declared as a mat2x3, mat3 or mat4x3, its matrix columns are taken from the (x, y, z) components of generic attributes i and i + 1 (mat2x3), from attributes i through i + 2 (mat3), or from attributes i through i + 3 (mat4x3). When an attribute variable is declared as a mat2x4, mat3x4 or mat4, its matrix columns are taken from the (x, y, z, w) components of generic attributes i and i + 1 (mat2x4), from attributes i through i + 2 (mat3x4), or from attributes i through i + 3 (mat4).

A generic attribute variable is considered active if it is determined by the compiler and linker that the attribute may be accessed when the shader is executed. Attribute variables that are declared in a vertex shader but never used will not count against the limit. In cases where the compiler and linker cannot make a conclusive determination, an attribute will be considered active. A program object will fail to link if the number of active vertex attributes exceeds MAX_VERTEX_ATTRIBS.

To determine the set of active vertex attributes used by a program, and to determine their types, use the command:

void GetActiveAttrib(uint program, uint index, 
sizei bufSize, sizei *length, int *size, enum *type, 
char *name );
This command provides information about the attribute selected by *index*. An *index* of 0 selects the first active attribute, and an *index* of `ACTIVE_ATTRIBUTES` - 1 selects the last active attribute. The value of `ACTIVE_ATTRIBUTES` can be queried with `GetProgramiv` (see section 6.1.12). If *index* is greater than or equal to `ACTIVE_ATTRIBUTES`, the error `INVALID_VALUE` is generated. Note that *index* simply identifies a member in a list of active attributes, and has no relation to the generic attribute that the corresponding variable is bound to.

The parameter *program* is the name of a program object for which the command `LinkProgram` has been issued in the past. It is not necessary for *program* to have been linked successfully. The link could have failed because the number of active attributes exceeded the limit.

The name of the selected attribute is returned as a null-terminated string in *name*. The actual number of characters written into *name*, excluding the null terminator, is returned in *length*. If *length* is NULL, no length is returned. The maximum number of characters that may be written into *name*, including the null terminator, is specified by *bufSize*. The returned attribute name must be the name of a generic attribute. The length of the longest attribute name in *program* is given by `ACTIVE_ATTRIBUTE_MAX_LENGTH`, which can be queried with `GetProgramiv` (see section 6.1.12).

For the selected attribute, the type of the attribute is returned into *type*. The size of the attribute is returned into *size*. The value in *size* is in units of the type returned in *type*. The type returned can be any of the types whose “Attrib” column is checked in table 2.12.

If an error occurred, the return parameters *length*, *size*, *type* and *name* will be unmodified.

This command will return as much information about active attributes as possible. If no information is available, *length* will be set to zero and *name* will be an empty string. This situation could arise if `GetActiveAttrib` is issued after a failed link.

After a program object has been linked successfully, the bindings of attribute variable names to indices can be queried. The command

```c
int GetAttribLocation(uint program, const char *name);
```

returns the generic attribute index that the attribute variable named *name* was bound to when the program object named *program* was last linked. *name* must be a null-terminated string. If *name* is active and is an attribute matrix, `GetAttribLocation` returns the index of the first column of that matrix. If *program* has not been successfully linked, the error `INVALID_OPERATION` is generated. If *name* is not an active attribute, or if an error occurs, -1 will be returned.
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The binding of an attribute variable to a generic attribute index can also be specified explicitly. The command

```c
void BindAttribLocation( uint program, uint index, const char *name );
```

determines that the attribute variable named `name` in program `program` should be bound to generic vertex attribute `index` when the program is next linked. If `name` was bound previously, its assigned binding is replaced with `index`. `name` must be a null-terminated string. The error `INVALID_VALUE` is generated if `index` is equal or greater than `MAX_VERTEX_ATTRIBS`. `BindAttribLocation` has no effect until the program is linked. In particular, it doesn’t modify the bindings of active attribute variables in a program that has already been linked.

When a program is linked, any active attributes without a binding specified either through `BindAttribLocation` or explicitly set within the shader text will automatically be bound to vertex attributes by the GL. Such bindings can be queried using the command `GetAttribLocation`. `LinkProgram` will fail if the assigned binding of an active attribute variable would cause the GL to reference a nonexistent generic attribute (one greater than or equal to the value of `MAX_VERTEX_ATTRIBS`). `LinkProgram` will fail if the attribute bindings assigned by `BindAttribLocation` do not leave enough space to assign a location for an active matrix attribute or an active attribute array, both of which require multiple contiguous generic attributes. If an active attribute has a binding explicitly set within the shader text and a different binding assigned by `BindAttribLocation`, the assignment in the shader text is used.

`BindAttribLocation` may be issued before any vertex shader objects are attached to a program object. Hence it is allowed to bind any name to an index, including a name that is never used as an attribute in any vertex shader object. Assigned bindings for attribute variables that do not exist or are not active are ignored.

The values of generic attributes sent to generic attribute index `i` are part of current state. If a new program object has been made active, then these values will be tracked by the GL in such a way that the same values will be observed by attributes in the new program object that are also bound to index `i`.

It is possible for an application to bind more than one attribute name to the same location. This is referred to as aliasing. This will only work if only one of the aliased attributes is active in the executable program, or if no path through the shader consumes more than one attribute of a set of attributes aliased to the same location. A link error can occur if the linker determines that every path through the shader consumes multiple aliased attributes, but implementations are not required to generate an error in this case. The compiler and linker are allowed to assume that
2.11. VERTEX SHADERS

no aliasing is done, and may employ optimizations that work only in the absence of aliasing.

2.11.4 Uniform Variables

Shaders can declare named uniform variables, as described in the OpenGL Shading Language Specification. Values for these uniforms are constant over a primitive, and typically they are constant across many primitives. Uniforms are program object-specific state. They retain their values once loaded, and their values are restored whenever a program object is used, as long as the program object has not been re-linked. A uniform is considered active if it is determined by the compiler and linker that the uniform will actually be accessed when the executable code is executed. In cases where the compiler and linker cannot make a conclusive determination, the uniform will be considered active.

Sets of uniforms can be grouped into uniform blocks. The values of each uniform in such a set are extracted from the data store of a buffer object corresponding to the uniform block. OpenGL Shading Language syntax serves to delimit named blocks of uniforms that can be backed by a buffer object. These are referred to as named uniform blocks, and are assigned a uniform block index. Uniforms that are declared outside of a named uniform block are said to be part of the default uniform block. Default uniform blocks have no name or uniform block index. Like uniforms, uniform blocks can be active or inactive. Active uniform blocks are those that contain active uniforms after a program has been compiled and linked.

The amount of storage available for uniform variables in the default uniform block accessed by a vertex shader is specified by the value of the implementation-dependent constant MAX_VERTEX_UNIFORM_COMPONENTS. The total amount of combined storage available for uniform variables in all uniform blocks accessed by a vertex shader (including the default uniform block) is specified by the value of the implementation-dependent constant MAX_COMBINED_VERTEX_UNIFORM_COMPONENTS. These values represent the numbers of individual floating-point, integer, or boolean values that can be held in uniform variable storage for a vertex shader. A uniform matrix with single- or double-precision components will consume no more than $4 \times \min(r, c)$ or $8 \times \min(r, c)$ uniform components, respectively. A scalar or vector uniform with double-precision components will consume no more than $2n$ components, where $n$ is 1 for scalars, and the component count for vectors. A link error is generated if an attempt is made to utilize more than the space available for vertex shader uniform variables.

When a program is successfully linked, all active uniforms belonging to the program object’s default uniform block are initialized as defined by the version of the OpenGL Shading Language used to compile the program. A successful link
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will also generate a location for each active uniform in the default uniform block. The values of active uniforms in the default uniform block can be changed using this location and the appropriate Uniform* command (see below). These locations are invalidated and new ones assigned after each successful re-link.

Similarly, when a program is successfully linked, all active uniforms belonging to the program’s named uniform blocks are assigned offsets (and strides for array and matrix type uniforms) within the uniform block according to layout rules described below. Uniform buffer objects provide the storage for named uniform blocks, so the values of active uniforms in named uniform blocks may be changed by modifying the contents of the buffer object using commands such as BufferData, BufferSubData, MapBuffer, and UnmapBuffer. Uniforms in a named uniform block are not assigned a location and may not be modified using the Uniform* commands. The offsets and strides of all active uniforms belonging to named uniform blocks of a program object are invalidated and new ones assigned after each successful re-link.

To find the location within a program object of an active uniform variable associated with the default uniform block, use the command

\[
\text{int GetUniformLocation( uint program, const char *name );}
\]

This command will return the location of uniform variable name if it is associated with the default uniform block. name must be a null-terminated string, without white space. The value -1 will be returned if name does not correspond to an active uniform variable name in program, or if name is associated with a named uniform block.

If program has not been successfully linked, the error INVALID_OPERATION is generated. After a program is linked, the location of a uniform variable will not change, unless the program is re-linked.

A valid name cannot be a structure, an array of structures, or any portion of a single vector or a matrix. In order to identify a valid name, the ".", "(dot) and "[]" operators can be used in name to specify a member of a structure or element of an array.

The first element of a uniform array is identified using the name of the uniform array appended with "[0]". Except if the last part of the string name indicates a uniform array, then the location of the first element of that array can be retrieved by either using the name of the uniform array, or the name of the uniform array appended with "[0]".

Named uniform blocks, like uniforms, are identified by name strings. Uniform block indices corresponding to uniform block names can be queried by calling

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```c
uint GetUniformBlockIndex( uint program, const char *uniformBlockName );
```

`program` is the name of a program object for which the command `LinkProgram`
has been issued in the past. It is not necessary for `program` to have been linked
successfully. The link could have failed because the number of active uniforms
exceeded the limit.

`uniformBlockName` must contain a null-terminated string specifying the name
of a uniform block.

`GetUniformBlockIndex` returns the uniform block index for the uniform block
named `uniformBlockName` of `program`. If `uniformBlockName` does not identify an
active uniform block of `program`, or an error occurred, then `INVALID_INDEX` is
returned. The indices of the active uniform blocks of a program are assigned in
consecutive order, beginning with zero.

An active uniform block’s name string can be queried from its uniform block
index by calling

```c
void GetActiveUniformBlockName( uint program, 
    uint uniformBlockIndex, sizei bufSize, sizei *length, 
    char *uniformBlockName );
```

`program` is the name of a program object for which the command `LinkProgram`
has been issued in the past. It is not necessary for `program` to have been linked
successfully. The link could have failed because the number of active uniforms
exceeded the limit.

`uniformBlockIndex` must be an active uniform block index of `program`, in the
range zero to the value of `ACTIVE_UNIFORM_BLOCKS` - 1. The value of `ACTIVE_-
UNIFORM_BLOCKS` can be queried with `GetProgramiv` (see section 6.1.12). If
`uniformBlockIndex` is greater than or equal to the value of `ACTIVE_UNIFORM_-
BLOCKS`, the error `INVALID_VALUE` is generated.

The string name of the uniform block identified by `uniformBlockIndex` is re-
turned into `uniformBlockName`. The name is null-terminated. The actual number
of characters written into `uniformBlockName`, excluding the null terminator, is re-
turned in `length`. If `length` is NULL, no length is returned.

`bufSize` contains the maximum number of characters (including the null termi-
nator) that will be written back to `uniformBlockName`.

If an error occurs, nothing will be written to `uniformBlockName` or `length`.

Information about an active uniform block can be queried by calling

```c
void GetActiveUniformBlockiv( uint program, 
    uint uniformBlockIndex, enum pname, int *params );
```
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`program` is the name of a program object for which the command `LinkProgram` has been issued in the past. It is not necessary for `program` to have been linked successfully. The link could have failed because the number of active uniforms exceeded the limit.

`uniformBlockIndex` is an active uniform block index of `program`. If `uniformBlockIndex` is greater than or equal to the value of `ACTIVE_UNIFORM_BLOCKS`, or is not the index of an active uniform block in `program`, the error `INVALID_VALUE` is generated.

If no error occurs, the uniform block parameter(s) specified by `pname` are returned in `params`. Otherwise, nothing will be written to `params`.

If `pname` is `UNIFORM_BLOCK_BINDING`, then the index of the uniform buffer binding point last selected by the uniform block specified by `uniformBlockIndex` for `program` is returned. If no uniform block has been previously specified, zero is returned.

If `pname` is `UNIFORM_BLOCK_DATA_SIZE`, then the implementation-dependent minimum total buffer object size, in basic machine units, required to hold all active uniforms in the uniform block identified by `uniformBlockIndex` is returned. It is neither guaranteed nor expected that a given implementation will arrange uniform values as tightly packed in a buffer object. The exception to this is the `std140` uniform block layout, which guarantees specific packing behavior and does not require the application to query for offsets and strides. In this case the minimum size may still be queried, even though it is determined in advance based only on the uniform block declaration (see “Standard Uniform Block Layout” in section 2.11.4).

The total amount of buffer object storage available for any given uniform block is subject to an implementation-dependent limit. The maximum amount of available space, in basic machine units, can be queried by calling `GetIntegerv` with the constant `MAX_UNIFORM_BLOCK_SIZE`. If the amount of storage required for a uniform block exceeds this limit, a program may fail to link.

If `pname` is `UNIFORM_BLOCK_NAME_LENGTH`, then the total length (including the null terminator) of the name of the uniform block identified by `uniformBlockIndex` is returned.

If `pname` is `UNIFORM_BLOCK_ACTIVE_UNIFORMS`, then the number of active uniforms in the uniform block identified by `uniformBlockIndex` is returned.

If `pname` is `UNIFORM_BLOCK_ACTIVE_UNIFORM_INDICES`, then a list of the active uniform indices for the uniform block identified by `uniformBlockIndex` is returned. The number of elements that will be written to `params` is the value of `UNIFORM_BLOCK_ACTIVE_UNIFORMS` for `uniformBlockIndex`.

If `pname` is `UNIFORM_BLOCK_REFERENCED_BY_VERTEX_SHADER`, `UNIFORM_BLOCK_REFERENCED_BY_TESS_CONTROL_SHADER`, `UNIFORM_BLOCK_REFERENCED_BY_TESS_EVALUATION_SHADER`, `UNIFORM_BLOCK_REFERENCED_BY_GEOMETRY_SHADER`, `UNIFORM_BLOCK_REFERENCED_BY_FRAGMENT_SHADER`, or `UNIFORM_BLOCK_REFERENCED_BY_COMPUTE_SHADER`, then the number of uniforms referenced by the corresponding shader stage is returned.
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BLOCK_REFERENCED_BY_TESS_EVALUATION_SHADER, UNIFORM_BLOCK_REFERENCED_BY_GEOMETRY_SHADER, or UNIFORM_BLOCK_REFERENCED_BY_FRAGMENT_SHADER, then a boolean value indicating whether the uniform block identified by uniformBlockIndex is referenced by the vertex, tessellation control, tessellation evaluation, geometry, or fragment programming stages of program, respectively, is returned.

Each active uniform, whether in a named uniform block or in the default block, is assigned an index when a program is linked. Indices are assigned in consecutive order, beginning with zero. The indices assigned to a set of uniforms in a program may be queried by calling

```c
void GetUniformIndices( uint program,
                        sizei uniformCount, const char **uniformNames,
                        uint *uniformIndices );
```

program is the name of a program object for which the command LinkProgram has been issued in the past. It is not necessary for program to have been linked successfully. The link could have failed because the number of active uniforms exceeded the limit.

uniformCount indicates both the number of elements in the array of names uniformNames and the number of indices that may be written to uniformIndices.

uniformNames contains a list of uniformCount name strings identifying the uniform names to be queried for indices. For each name string in uniformNames, the index assigned to the active uniform of that name will be written to the corresponding element of uniformIndices. If a string in uniformNames is not the name of an active uniform, the value INVALID_INDEX will be written to the corresponding element of uniformIndices.

If an error occurs, nothing is written to uniformIndices.

The name of an active uniform may be queried from the corresponding uniform index by calling

```c
void GetActiveUniformName( uint program,
                          uint uniformIndex, sizei bufSize, sizei *length,
                          char *uniformName );
```

program is the name of a program object for which the command LinkProgram has been issued in the past. It is not necessary for program to have been linked successfully. The link could have failed because the number of active uniforms exceeded the limit.
uniformIndex must be an active uniform index of the program program, in the range zero to the value of ACTIVE_UNIFORMS - 1. The value of ACTIVE_UNIFORMS can be queried with GetProgramiv. If uniformIndex is greater than or equal to the value of ACTIVE_UNIFORMS, the error INVALID_VALUE is generated.

The name of the uniform identified by uniformIndex is returned as a null-terminated string in uniformName. The actual number of characters written into uniformName, excluding the null terminator, is returned in length. If length is NULL, no length is returned. The maximum number of characters that may be written into uniformName, including the null terminator, is specified by bufSize. The returned uniform name can be the name of built-in uniform state as well. The complete list of built-in uniform state is described in section 7.5 of the OpenGL Shading Language Specification. The length of the longest uniform name in program is given by the value of ACTIVE_UNIFORM_MAX_LENGTH, which can be queried with GetProgramiv.

If GetActiveUniformName is not successful, nothing is written to length or uniformName.

Each uniform variable, declared in a shader, is broken down into one or more strings using the "." (dot) and "[]" operators, if necessary, to the point that it is legal to pass each string back into GetUniformLocation, for default uniform block uniform names, or GetUniformIndices, for named uniform block uniform names.

Information about active uniforms can be obtained by calling either

```c
void GetActiveUniform( uint program, uint index,  
   sizei bufSize, sizei *length, int *size, enum *type,  
   char *name );
```

or

```c
void GetActiveUniformsiv( uint program,  
   sizei uniformCount, const uint *uniformIndices,  
   enum pname, int *params );
```

program is the name of a program object for which the command LinkProgram has been issued in the past. It is not necessary for program to have been linked successfully. The link could have failed because the number of active uniforms exceeded the limit.

These commands provide information about the uniform or uniforms selected by index or uniformIndices, respectively. In GetActiveUniform, an index of 0 selects the first active uniform, and an index of the value of ACTIVE_UNIFORMS - 1 selects the last active uniform. In GetActiveUniformsiv, uniformIndices is an
array of such active uniform indices. If any index is greater than or equal to the value of \texttt{ACTIVE\_UNIFORMS}, the error \texttt{INVALID\_VALUE} is generated.

For the selected uniform, \texttt{GetActiveUniform} returns the uniform name as a null-terminated string in \texttt{name}. The actual number of characters written into \texttt{name}, excluding the null terminator, is returned in \texttt{length}. If \texttt{length} is \texttt{NULL}, no length is returned. The maximum number of characters that may be written into \texttt{name}, including the null terminator, is specified by \texttt{bufSize}. The returned uniform name can be the name of built-in uniform state as well. The complete list of built-in uniform state is described in section 7.5 of the OpenGL Shading Language Specification. The length of the longest uniform name in \texttt{program} is given by \texttt{ACTIVE\_UNIFORM\_MAX\_LENGTH}.

Each uniform variable, declared in a shader, is broken down into one or more strings using the "." (dot) and "[]" operators, if necessary, to the point that it is legal to pass each string back into \texttt{GetUniformLocation}, for default uniform block uniform names, or \texttt{GetUniformIndices}, for named uniform block uniform names.

For the selected uniform, \texttt{GetActiveUniform} returns the type of the uniform into \texttt{type} and the size of the uniform is into \texttt{size}. The value in \texttt{size} is in units of the uniform type, which can be any of the type name tokens in table 2.12, corresponding to OpenGL Shading Language type keywords also shown in that table.

If one or more elements of an array are active, \texttt{GetActiveUniform} will return the name of the array in \texttt{name}, subject to the restrictions listed above. The type of the array is returned in \texttt{type}. The \texttt{size} parameter contains the highest array element index used, plus one. The compiler or linker determines the highest index used. There will be only one active uniform reported by the GL per uniform array.

\texttt{GetActiveUniform} will return as much information about active uniforms as possible. If no information is available, \texttt{length} will be set to zero and \texttt{name} will be an empty string. This situation could arise if \texttt{GetActiveUniform} is issued after a failed link.

If an error occurs, nothing is written to \texttt{length}, \texttt{size}, \texttt{type}, or \texttt{name}.

<table>
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<th>Type Name Token</th>
<th>Keyword</th>
<th>Attrib</th>
<th>Xfb</th>
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### OpenGL Shading Language Type Tokens (continued)

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2.11. VERTEX SHADERS

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Table 2.12: OpenGL Shading Language type tokens returned by GetActiveUniform and GetActiveUniformsiv, and corresponding shading language keywords declaring each such type. Types whose “Attrib” column are marked may be declared as vertex attributes (see section 2.11.3). Types whose “Xfb” column are marked may be the types of variable returned by transform feedback (see section 2.11.7).

For GetActiveUniformsiv, uniformCount indicates both the number of elements in the array of indices uniformIndices and the number of parameters written to params upon successful return. pname identifies a property of each uniform in uniformIndices that should be written into the corresponding element of params. If an error occurs, nothing will be written to params.

If pname is UNIFORM_TYPE, then an array identifying the types of the uniforms specified by the corresponding array of uniformIndices is returned. The returned types can be any of the values in table 2.12.

If pname is UNIFORM_SIZE, then an array identifying the size of the uniforms specified by the corresponding array of uniformIndices is returned. The sizes returned are in units of the type returned by a query of UNIFORM_TYPE. For active uniforms that are arrays, the size is the number of active elements in the array; for all other uniforms, the size is one.
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If `pname` is UNIFORM_NAME_LENGTH, then an array identifying the length, including the terminating null character, of the uniform name strings specified by the corresponding array of `uniformIndices` is returned.

If `pname` is UNIFORM_BLOCK_INDEX, then an array identifying the uniform block index of each of the uniforms specified by the corresponding array of `uniformIndices` is returned. The index of a uniform associated with the default uniform block is -1.

If `pname` is UNIFORM_OFFSET, then an array of uniform buffer offsets is returned. For uniforms in a named uniform block, the returned value will be its offset, in basic machine units, relative to the beginning of the uniform block in the buffer object data store. For uniforms in the default uniform block, -1 will be returned.

If `pname` is UNIFORM_ARRAY_STRIDE, then an array identifying the stride between elements, in basic machine units, of each of the uniforms specified by the corresponding array of `uniformIndices` is returned. The stride of a uniform associated with the default uniform block is -1. Note that this information only makes sense for uniforms that are arrays. For uniforms that are not arrays, but are declared in a named uniform block, an array stride of zero is returned.

If `pname` is UNIFORM_MATRIX_STRIDE, then an array identifying the stride between columns of a column-major matrix or rows of a row-major matrix, in basic machine units, of each of the uniforms specified by the corresponding array of `uniformIndices` is returned. The matrix stride of a uniform associated with the default uniform block is -1. Note that this information only makes sense for uniforms that are matrices. For uniforms that are not matrices, but are declared in a named uniform block, a matrix stride of zero is returned.

If `pname` is UNIFORM_IS_ROW_MAJOR, then an array identifying whether each of the uniforms specified by the corresponding array of `uniformIndices` is a row-major matrix or not is returned. A value of one indicates a row-major matrix, and a value of zero indicates a column-major matrix, a matrix in the default uniform block, or a non-matrix.

Loading Uniform Variables In The Default Uniform Block

To load values into the uniform variables of the default uniform block of the program object that is currently in use, use the commands

```c
void Uniform{1234}{ifd}( int location, T value );
void Uniform{1234}{ifd}v( int location, sizei count, const T value );
void Uniform{1234}ui( int location, T value );
```

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The given values are loaded into the default uniform block uniform variable location identified by location.

The Uniform\*f\{v\} commands will load count sets of one to four floating-point values into a uniform location defined as a float, a floating-point vector, an array of floats, or an array of floating-point vectors.

The Uniform\*d\{v\} commands will load count sets of one to four double-precision floating-point values into a uniform location defined as a double, a double vector, or an array of double scalars or vectors.

The Uniform\*i\{v\} commands will load count sets of one to four integer values into a uniform location defined as a sampler, an integer, an integer vector, an array of samplers, an array of integers, or an array of integer vectors. Only the Uniform1i\{v\} commands can be used to load sampler values (see below).

The Uniform\*ui\{v\} commands will load count sets of one to four unsigned integer values into a uniform location defined as an unsigned integer, an unsigned integer vector, an array of unsigned integers or an array of unsigned integer vectors.

The UniformMatrix\{234\}\{fd\}\{v\} and UniformMatrix\{2x3,3x2,2x4,4x2,3x4,4x3\}\{fd\}\{v\} commands will load count $2 \times 2$, $3 \times 3$, or $4 \times 4$ matrices (corresponding to 2, 3, or 4 in the command name) of single- or double-precision floating-point values, respectively, into a uniform location defined as a matrix or an array of matrices. If transpose is FALSE, the matrix is specified in column major order, otherwise in row major order.

The UniformMatrix\{2x3,3x2,2x4,4x2,3x4,4x3\}\{fv\} and UniformMatrix\{2x3,3x2,2x4,4x2,3x4,4x3\}\{dv\} commands will load count $2 \times 3$, $3 \times 2$, $2 \times 4$, $4 \times 2$, $3 \times 4$, or $4 \times 3$ matrices (corresponding to the numbers in the command name) of single- or double-precision floating-point values, respectively, into a uniform location defined as a matrix or an array of matrices. The first number in the command name is the number of columns; the second is the number of rows. For example, UniformMatrix2x4fv is used to load a single-precision matrix consisting of two columns and four rows. If transpose is FALSE, the matrix is specified in column major order, otherwise in row major order.

When loading values for a uniform declared as a boolean, a boolean vector, an array of booleans, or an array of boolean vectors, the Uniform\*i\{v\}, Uni-
2.11. VERTEX SHADERS

\texttt{form\*ui\{v\}}, and \texttt{Uniform\*f\{v\}} set of commands can be used to load boolean values. Type conversion is done by the GL. The uniform is set to \texttt{FALSE} if the input value is 0 or 0.0f, and set to \texttt{TRUE} otherwise. The \texttt{Uniform\*} command used must match the size of the uniform, as declared in the shader. For example, to load a uniform declared as a \texttt{bvec2}, any of the \texttt{Uniform2\{if ui\} star} commands may be used. An \texttt{INVALID\_OPERATION} error will be generated if an attempt is made to use a non-matching \texttt{Uniform\*} command. In this example using \texttt{Uniform1iv} would generate an error.

For all other uniform types the \texttt{Uniform\*} command used must match the size and type of the uniform, as declared in the shader. No type conversions are done. For example, to load a uniform declared as a \texttt{vec4}, \texttt{Uniform4f\{v\}} must be used, and to load a uniform declared as a \texttt{dmat3}, \texttt{UniformMatrix3dv} must be used. An \texttt{INVALID\_OPERATION} error will be generated if an attempt is made to use a non-matching \texttt{Uniform\*} command.

When loading \(N\) elements starting at an arbitrary position \(k\) in a uniform declared as an array, elements \(k\) through \(k + N - 1\) in the array will be replaced with the new values. Values for any array element that exceeds the highest array element index used, as reported by \texttt{GetActiveUniform}, will be ignored by the GL.

If the value of \texttt{location} is -1, the \texttt{Uniform\*} commands will silently ignore the data passed in, and the current uniform values will not be changed.

If any of the following conditions occur, an \texttt{INVALID\_OPERATION} error is generated by the \texttt{Uniform\*} commands, and no uniform values are changed:

- if the size indicated in the name of the \texttt{Uniform\*} command used does not match the size of the uniform declared in the shader,
- if the uniform declared in the shader is not of type boolean and the type indicated in the name of the \texttt{Uniform\*} command used does not match the type of the uniform,
- if \texttt{count} is greater than one, and the uniform declared in the shader is not an array variable,
- if no variable with a location of \texttt{location} exists in the program object currently in use and \texttt{location} is not -1, or
- if there is no program object currently in use.

\textbf{Uniform Blocks}

The values of uniforms arranged in named uniform blocks are extracted from buffer object storage. The mechanisms for placing individual uniforms in a buffer object...
and connecting a uniform block to an individual buffer object are described below.

There is a set of implementation-dependent maximums for the number of active uniform blocks used by each shader. If the number of uniform blocks used by any shader in the program exceeds its corresponding limit, the program will fail to link. The limits for vertex, tessellation control, tessellation evaluation, geometry, and fragment shaders can be obtained by calling `GetIntegerv` with `pname` values of `MAX_VERTEX_UNIFORM_BLOCKS`, `MAX_TESS_CONTROL_UNIFORM_BLOCKS`, `MAX_TESS_EVALUATION_UNIFORM_BLOCKS`, `MAX_GEOMETRY_UNIFORM_BLOCKS`, and `MAX_FRAGMENT_UNIFORM_BLOCKS`, respectively.

Additionally, there is an implementation-dependent limit on the sum of the number of active uniform blocks used by each shader of a program. If a uniform block is used by multiple shaders, each such use counts separately against this combined limit. The combined uniform block use limit can be obtained by calling `GetIntegerv` with a `pname` of `MAX_COMBINED_UNIFORM_BLOCKS`.

When a named uniform block is declared by multiple shaders in a program, it must be declared identically in each shader. The uniforms within the block must be declared with the same names and types, and in the same order. If a program contains multiple shaders with different declarations for the same named uniform block differs between shader, the program will fail to link.

**Uniform Buffer Object Storage**

When stored in buffer objects associated with uniform blocks, uniforms are represented in memory as follows:

- Members of type `bool` are extracted from a buffer object by reading a single `uint`-typed value at the specified offset. All non-zero values correspond to true, and zero corresponds to false.
- Members of type `int` are extracted from a buffer object by reading a single `int`-typed value at the specified offset.
- Members of type `uint` are extracted from a buffer object by reading a single `uint`-typed value at the specified offset.
- Members of type `float` are extracted from a buffer object by reading a single `float`-typed value at the specified offset.
- Members of type `double` are extracted from a buffer object by reading a single `double`-typed value at the specified offset.
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- Vectors with \( N \) elements with basic data types of \( \text{bool, int, uint, float,} \) or \( \text{double} \) are extracted as \( N \) values in consecutive memory locations beginning at the specified offset, with components stored in order with the first (X) component at the lowest offset. The GL data type used for component extraction is derived according to the rules for scalar members above.

- Column-major matrices with \( C \) columns and \( R \) rows (using the type \( \text{mat}C\times R \), or simply \( \text{mat}C \) if \( C = R \)) are treated as an array of \( C \) floating-point column vectors, each consisting of \( R \) components. The column vectors will be stored in order, with column zero at the lowest offset. The difference in offsets between consecutive columns of the matrix will be referred to as the column stride, and is constant across the matrix. The column stride, \( \text{UNIFORM\_MATRIX\_STRIDE} \), is an implementation-dependent value and may be queried after a program is linked.

- Row-major matrices with \( C \) columns and \( R \) rows (using the type \( \text{mat}C\times R \), or simply \( \text{mat}C \) if \( C = R \)) are treated as an array of \( R \) floating-point row vectors, each consisting of \( C \) components. The row vectors will be stored in order, with row zero at the lowest offset. The difference in offsets between consecutive rows of the matrix will be referred to as the row stride, and is constant across the matrix. The row stride, \( \text{UNIFORM\_MATRIX\_STRIDE} \), is an implementation-dependent value and may be queried after a program is linked.

- Arrays of scalars, vectors, and matrices are stored in memory by element order, with array member zero at the lowest offset. The difference in offsets between each pair of elements in the array in basic machine units is referred to as the array stride, and is constant across the entire array. The array stride, \( \text{UNIFORM\_ARRAY\_STRIDE} \), is an implementation-dependent value and may be queried after a program is linked.

Standard Uniform Block Layout

By default, uniforms contained within a uniform block are extracted from buffer storage in an implementation-dependent manner. Applications may query the offsets assigned to uniforms inside uniform blocks with query functions provided by the GL.

The \text{layout} qualifier provides shaders with control of the layout of uniforms within a uniform block. When the \text{std140} layout is specified, the offset of each uniform in a uniform block can be derived from the definition of the uniform block by applying the set of rules described below.
If a uniform block is declared in multiple shaders linked together into a single program, the link will fail unless the uniform block declaration, including layout qualifier, are identical in all such shaders.

When using the \texttt{std140} storage layout, structures will be laid out in buffer storage with its members stored in monotonically increasing order based on their location in the declaration. A structure and each structure member have a base offset and a base alignment, from which an aligned offset is computed by rounding the base offset up to a multiple of the base alignment. The base offset of the first member of a structure is taken from the aligned offset of the structure itself. The base offset of all other structure members is derived by taking the offset of the last basic machine unit consumed by the previous member and adding one. Each structure member is stored in memory at its aligned offset. The members of a top-level uniform block are laid out in buffer storage by treating the uniform block as a structure with a base offset of zero.

1. If the member is a scalar consuming $N$ basic machine units, the base alignment is $N$.

2. If the member is a two- or four-component vector with components consuming $N$ basic machine units, the base alignment is $2N$ or $4N$, respectively.

3. If the member is a three-component vector with components consuming $N$ basic machine units, the base alignment is $4N$.

4. If the member is an array of scalars or vectors, the base alignment and array stride are set to match the base alignment of a single array element, according to rules (1), (2), and (3), and rounded up to the base alignment of a vec4. The array may have padding at the end; the base offset of the member following the array is rounded up to the next multiple of the base alignment.

5. If the member is a column-major matrix with $C$ columns and $R$ rows, the matrix is stored identically to an array of $C$ column vectors with $R$ components each, according to rule (4).

6. If the member is an array of $S$ column-major matrices with $C$ columns and $R$ rows, the matrix is stored identically to a row of $S \times C$ column vectors with $R$ components each, according to rule (4).

7. If the member is a row-major matrix with $C$ columns and $R$ rows, the matrix is stored identically to an array of $R$ row vectors with $C$ components each, according to rule (4).
8. If the member is an array of \( S \) row-major matrices with \( C \) columns and \( R \) rows, the matrix is stored identically to a row of \( S \times R \) row vectors with \( C \) components each, according to rule (4).

9. If the member is a structure, the base alignment of the structure is \( N \), where \( N \) is the largest base alignment value of any of its members, and rounded up to the base alignment of a vec4. The individual members of this sub-structure are then assigned offsets by applying this set of rules recursively, where the base offset of the first member of the sub-structure is equal to the aligned offset of the structure. The structure may have padding at the end; the base offset of the member following the sub-structure is rounded up to the next multiple of the base alignment of the structure.

10. If the member is an array of \( S \) structures, the \( S \) elements of the array are laid out in order, according to rule (9).

**Uniform Buffer Object Bindings**

The value an active uniform inside a named uniform block is extracted from the data store of a buffer object bound to one of an array of uniform buffer binding points. The number of binding points can be queried using `GetIntegerv` with the constant `MAX_UNIFORM_BUFFER_BINDINGS`.

Regions of buffer objects are bound as storage for uniform blocks by calling one of the commands `BindBufferRange` or `BindBufferBase` (see section 2.9.1) with `target` set to `UNIFORM_BUFFER`. In addition to the general errors described in section 2.9.1, `BindBufferRange` will generate an `INVALID_VALUE` error if `index` is greater than or equal to the value of `MAX_UNIFORM_BUFFER_BINDINGS`, or if `offset` is not a multiple of the implementation-dependent alignment requirement (the value of `UNIFORM_BUFFER_OFFSET_ALIGNMENT`).

Each of a program’s active uniform blocks has a corresponding uniform buffer object binding point. This binding point can be assigned by calling:

```c
void UniformBlockBinding( uint program,
                         uint uniformBlockIndex, uint uniformBlockBinding );
```

`program` is a name of a program object for which the command `LinkProgram` has been issued in the past.

An `INVALID_VALUE` error is generated if `uniformBlockIndex` is not an active uniform block index of `program`, or if `uniformBlockBinding` is greater than or equal to the value of `MAX_UNIFORM_BUFFER_BINDINGS`.

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If successful, UniformBlockBinding specifies that program will use the data store of the buffer object bound to the binding point uniformBlockBinding to extract the values of the uniforms in the uniform block identified by uniformBlockIndex.

When executing shaders that access uniform blocks, the binding point corresponding to each active uniform block must be populated with a buffer object with a size no smaller than the minimum required size of the uniform block (the value of UNIFORM_BLOCK_DATA_SIZE). For binding points populated by BindBufferRange, the size in question is the value of the size parameter. If any active uniform block is not backed by a sufficiently large buffer object, the results of shader execution are undefined, and may result in GL interruption or termination. Shaders may be executed to process the primitives and vertices specified by vertex array commands (see section 2.8).

When a program object is linked or re-linked, the uniform buffer object binding point assigned to each of its active uniform blocks is reset to zero.

### 2.11.5 Subroutine Uniform Variables

Subroutine uniform variables are similar to uniform variables, except they are context state rather than program state. Having subroutine uniforms be context state allows them to have different values if the program is used in multiple contexts simultaneously. There is a set of subroutine uniforms for each shader stage.

The command

```c
int GetSubroutineUniformLocation( uint program, 
    enum shadertype, const char *name );
```

will return the location of the subroutine uniform variable name in the shader stage of type shadertype attached to program, with behavior otherwise identical to GetUniformLocation. The value -1 will be returned if name is not the name of an active subroutine uniform. Active subroutine locations are assigned using consecutive integers in the range from zero to the value of ACTIVE_SUBROUTINE_UNIFORM_LOCATIONS minus one for the shader stage. There is an implementation-dependent limit on the number of active subroutine uniform locations in each shader stage; a program will fail to link if the number of subroutine uniform locations required is greater than the value of MAX_SUBROUTINE_UNIFORM_LOCATIONS. If program has not been successfully linked, the error INVALID_OPERATION will be generated. For active subroutine uniforms declared as arrays, the declared array elements are assigned consecutive locations.

Each function in a shader associated with a subroutine type is considered an active subroutine, unless the compiler conclusively determines that the function
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could never be assigned to an active subroutine uniform. Each active subroutine will be assigned an unsigned integer subroutine index that is unique to the shader stage. This index can be queried with the command

\[
\text{uint \ GetSubroutineIndex( uint } \text{program, enum shadertype, }
\text{const char } \ast \text{name }) ;
\]

where \( \text{name} \) is the null-terminated name of a function in the shader stage of type \text{shadertype} attached to \text{program}. Subroutine indices are assigned using consecutive integers in the range from zero to the value of \text{ACTIVE_SUBROUTINES} minus one for the shader stage. The value \text{INVALID_INDEX} will be returned if \text{name} is not the name of an active subroutine in the shader stage. After the program has been linked, the subroutine index will not change unless the program is re-linked.

There is an implementation-dependent limit on the number of active subroutines in each shader stage; a program will fail to link if the number of subroutines is greater than the maximum subroutine count, (the value of \text{MAX_SUBROUTINES}).

Information about active subroutine uniforms can be obtained by calling

\[
\text{void \ GetActiveSubroutineUniformiv( uint } \text{program,}
\text{enum shadertype, uint index, enum pname, int } \ast \text{values }) ;
\]

\[
\text{void \ GetActiveSubroutineUniformName( uint } \text{program,}
\text{enum shadertype, uint index, sizei bufsize, sizei } \ast \text{length, char } \ast \text{name }) ;
\]

\text{program} and \text{shadertype} specify the program and shader stage. \text{index} must be an active subroutine uniform index in the range from zero to the value of \text{ACTIVE_SUBROUTINE_UNIFORMS} minus one for the shader stage. If \text{index} is greater than or equal to the value of \text{ACTIVE_SUBROUTINE_UNIFORMS}, the error \text{INVALID_VALUE} is generated.

For \text{GetActiveSubroutineUniformiv}, \text{pname} identifies a property of the active subroutine uniform being queried. If \text{pname} is \text{NUM_COMPATIBLE_SUBROUTINES}, a single integer indicating the number of subroutines that can be assigned to the uniform is returned in \text{values}. If \text{pname} is \text{COMPATIBLE_SUBROUTINES}, an array of integers is returned in \text{values}, with each integer specifying the index of an active subroutine that can be assigned to the selected subroutine uniform. The number of integers returned is the same as the value returned for \text{NUM_COMPATIBLE_SUBROUTINES}. If \text{pname} is \text{UNIFORM_SIZE}, a single integer is returned in \text{values}. If the selected subroutine uniform is an array, the declared size of the array is returned; otherwise, one is returned. If \text{pname} is \text{UNIFORM_NAME_LENGTH}, a single integer specifying the length of the subroutine uniform name (including the terminating null character) is returned in \text{values}.
For `GetActiveSubroutineUniformLocation`, the uniform name is returned as a null-terminated string in `name`. The actual number of characters written into `name`, excluding the null terminator is returned in `length`. If `length` is NULL, no length is returned. The maximum number of characters that may be written into `name`, including the null terminator, is specified by `bufsize`. The length of the longest subroutine uniform name in `program` and `shadertype` is given by the value of `ACTIVE_SUBROUTINE_UNIFORM_MAX_LENGTH`, which can be queried with `GetProgramStageiv`.

The name of an active subroutine can be queried given its subroutine index with the command:

```c
void GetActiveSubroutineUniformLocation( uint program,
                                         enum shadertype, uint index, sizei bufsize,
                                         sizei *length, char *name );
```

`program` and `shadertype` specify the program and shader stage. `index` must be an active subroutine index in the range from zero to the value of `ACTIVE_SUBROUTINES` minus one for the shader stage. If `index` is greater than or equal to the value of `ACTIVE_SUBROUTINES`, the error `INVALID_VALUE` is generated. The name of the selected subroutine is returned as a null-terminated string in `name`. The actual number of characters written into `name`, excluding the null terminator, is returned in `length`. If `length` is NULL, no length is returned. The maximum number of characters that may be written into `name`, including the null terminator, is specified by `bufsize`. The length of the longest subroutine name in `program` and `shadertype` is given by the value of `ACTIVE_SUBROUTINE_MAX_LENGTH`, which can be queried with `GetProgramStageiv`.

The command

```c
void UniformSubroutinesuiv( enum shadertype, sizei count,
                             const uint *indices );
```

will load all active subroutine uniforms for shader stage `shadertype` with subroutine indices from `indices`, storing `indices[i]` into the uniform at location `i`. If `count` is not equal to the value of `ACTIVE_SUBROUTINE_UNIFORM_LOCATIONS` for the program currently in use at shader stage `shadertype`, or if any value in `indices` is greater than or equal to the value of `ACTIVE_SUBROUTINES` for the shader stage, the error `INVALID_VALUE` is generated. If, for any subroutine index being loaded to a particular uniform location, the function corresponding to the subroutine index was not associated (as defined in Section 6.1.2 of the OpenGL Shading Language Specification) with the type of the subroutine variable at that location, then the error

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INVALID_OPERATION is generated. If no program is active, the error INVALID_OPERATION is generated.

Each subroutine uniform must have at least one subroutine to assign to the uniform. A program will fail to link if any stage has one or more subroutine uniforms that has no subroutine associated with the subroutine type of the uniform.

When UseProgram is called, the subroutine uniforms for all shader stages are reset to arbitrarily chosen default functions with compatible subroutine types.

2.11.6 Samplers

Samplers are special uniforms used in the OpenGL Shading Language to identify the texture object used for each texture lookup. The value of a sampler indicates the texture image unit being accessed. Setting a sampler’s value to $i$ selects texture image unit number $i$. The values of $i$ range from zero to the implementation-dependent maximum supported number of texture image units.

The type of the sampler identifies the target on the texture image unit. The texture object bound to that texture image unit’s target is then used for the texture lookup. For example, a variable of type sampler2D selects target TEXTURE_2D on its texture image unit. Binding of texture objects to targets is done as usual with BindTexture. Selecting the texture image unit to bind to is done as usual with ActiveTexture.

The location of a sampler needs to be queried with GetUniformLocation, just like any uniform variable. Sampler values need to be set by calling Uniform1i{v}. Loading samplers with any of the other Uniform* entry points is not allowed and will result in an INVALID_OPERATION error.

It is not allowed to have variables of different sampler types pointing to the same texture image unit within a program object. This situation can only be detected at the next rendering command issued, and an INVALID_OPERATION error will then be generated.

Active samplers are samplers actually being used in a program object. The LinkProgram command determines if a sampler is active or not. The LinkProgram command will attempt to determine if the active samplers in the shader(s) contained in the program object exceed the maximum allowable limits. If it determines that the count of active samplers exceeds the allowable limits, then the link fails (these limits can be different for different types of shaders). Each active sampler variable counts against the limit, even if multiple samplers refer to the same texture image unit.
2.11.7 Varying Variables

A vertex shader may define one or more varying variables (see the OpenGL Shading Language Specification). Varying variables are outputs of a vertex shader. The OpenGL Shading Language Specification also defines a set of built-in varying and special variables that vertex shaders can write to (see sections 7.1 and 7.6 of the OpenGL Shading Language Specification). These varying variables are either used as the mechanism to communicate values to the next active stage in the vertex processing pipeline: either the tessellation control shader, the tessellation evaluation shader, the geometry shader, or the fixed-function vertex processing stages leading to rasterization.

If the varying variables are passed directly to the vertex processing stages leading to rasterization, the values of all varying and special variables are expected to be interpolated across the primitive being rendered, unless flatshaded. Otherwise the values of all varying and special variables are collected by the primitive assembly stage and passed on to the subsequent pipeline stage once enough data for one primitive has been collected.

The number of components (individual scalar numeric values) of varying and special variables that can be written by the vertex shader, whether or not a tessellation control, tessellation evaluation, or geometry shader is active, is given by the value of the implementation-dependent constant MAX_VERTEX_OUTPUT_COMPONENTS. Outputs declared as vectors, matrices, and arrays will all consume multiple components. For the purposes of counting input and output components consumed by a shader, variables declared as vectors, matrices, and arrays will all consume multiple components. Each component of variables declared as double-precision floating-point scalars, vectors, or matrices may be counted as consuming two components.

When a program is linked, all components of any varying and special variable written by a vertex shader will count against this limit. A program whose vertex shader writes more than the value of MAX_VERTEX_OUTPUT_COMPONENTS components worth of varying variables may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.

Additionally, when linking a program containing only a vertex and fragment shader, there is a limit on the total number of components used as vertex shader outputs or fragment shader inputs. This limit is given by the value of the implementation-dependent constant MAX_VARYING_COMPONENTS. Each varying or special variable component used as either a vertex shader output or fragment shader input count against this limit, except for the components of gl_Position. A program containing only a vertex and fragment shader that accesses more than this limit’s worth of components of varying and special variables may fail to link,
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unless device-dependent optimizations are able to make the program fit within available hardware resources.

Each program object can specify a set of output variables from one shader to be recorded in transform feedback mode (see section 2.17). The variables that can be recorded are those emitted by the first active shader, in order, from the following list:

- geometry shader
- tessellation evaluation shader
- tessellation control shader
- vertex shader

The values to record are specified with the command

```c
void TransformFeedbackVaryings( uint program,
   sizei count, const char **varyings, enum bufferMode );
```

*program* specifies the program object. *count* specifies the number of varying variables used for transform feedback. *varyings* is an array of *count* zero-terminated strings specifying the names of the varying variables to use for transform feedback. Varying variables are written out in the order they appear in the array *varyings*. *bufferMode* is either `INTERLEAVED_ATTRIBS` or `SEPARATE_ATTRIBS`, and identifies the mode used to capture the varying variables when transform feedback is active. The error `INVALID_VALUE` is generated if *bufferMode* is `SEPARATE_ATTRIBS` and *count* is greater than the value of the implementation-dependent limit `MAX_TRANSFORM_FEEDBACK_SEPARATE_ATTRIBS`.

If a string in *varyings* is `gl_NextBuffer`, it does not identify a varying variable, but instead serves as a buffer separator value to direct subsequent varyings at the next transform feedback binding point. If a string in *varyings* is `gl_SkipComponents1`, `gl_SkipComponents2`, `gl_SkipComponents3`, or `gl_SkipComponents4`, it also does not identify a specific varying variable. Instead, such values are treated as requesting that the GL skip the next one to four components of varying data. Skipping components this way is equivalent to specifying a one- to four-component varying with undefined values, except that the corresponding memory in the buffer object is not modified. Such array entries are counted as being written to the buffer object for the purposes of determining whether the requested attributes exceed per-buffer component count limits. Each component skipped is considered to occupy a single float.
The error \texttt{INVALID\_OPERATION} is generated if any pointer in \texttt{varyings} identifies the special names \texttt{gl\_NextBuffer}, \texttt{gl\_SkipComponents1}, \texttt{gl\_SkipComponents2}, \texttt{gl\_SkipComponents3}, or \texttt{gl\_SkipComponents4} and \texttt{bufferMode} is not \texttt{INTERLEAVED\_ATTRIBS}, or if the number of \texttt{gl\_NextBuffer} pointers in \texttt{varyings} is greater than or equal to the limit \texttt{MAX\_TRANSFORM\_FEEDBACK\_BUFFERS}.

The state set by \texttt{TransformFeedbackVaryings} has no effect on the execution of the program until \texttt{program} is subsequently linked. When \texttt{LinkProgram} is called, the program is linked so that the values of the specified varying variables for the vertices of each primitive generated by the GL are written to a single buffer object (if the buffer mode is \texttt{INTERLEAVED\_ATTRIBS}) or multiple buffer objects (if the buffer mode is \texttt{SEPARATE\_ATTRIBS}). A program will fail to link if:

- the \texttt{count} specified by \texttt{TransformFeedbackVaryings} is non-zero, but the program object has no vertex, tessellation control, tessellation evaluation, or geometry shader;

- any variable name specified in the \texttt{varyings} array is not one of \texttt{gl\_NextBuffer}, \texttt{gl\_SkipComponents1}, \texttt{gl\_SkipComponents2}, \texttt{gl\_SkipComponents3}, or \texttt{gl\_SkipComponents4}, and is not declared as an output in the shader stage whose outputs can be recorded.

- any two entries in the \texttt{varyings} array specify the same varying variable;

- the total number of components to capture in any varying variable in \texttt{varyings} is greater than the value of \texttt{MAX\_TRANSFORM\_FEEDBACK\_SEPARATE\_COMPONENTS} and the buffer mode is \texttt{SEPARATE\_ATTRIBS};

- the total number of components to capture is greater than the constant \texttt{MAX\_TRANSFORM\_FEEDBACK\_INTERLEAVED\_COMPONENTS} and the buffer mode is \texttt{INTERLEAVED\_ATTRIBS}; or

- the set of varyings to capture to any single binding point includes varyings from more than one vertex stream.

For the purposes of counting the total number of components to capture, each component of outputs declared as double-precision floating-point scalars, vectors, or matrices may be counted as consuming two components.

To determine the set of varying variables in a linked program object that will be captured in transform feedback mode, the command:
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void GetTransformFeedbackVarying( uint program,
    uint index, sizei bufSize, sizei *length, sizei *size,
    enum *type, char *name );

provides information about the varying variable selected by index. An index of 0 selects the first varying variable specified in the varyings array of TransformFeedbackVaryings, and an index of TRANSFORM_FEEDBACK_VARYINGS-1 selects the last such varying variable. The value of TRANSFORM_FEEDBACK_VARYINGS can be queried with GetProgramiv (see section 6.1.12). If index is greater than or equal to TRANSFORM_FEEDBACK_VARYINGS, the error INVALID_VALUE is generated. The parameter program is the name of a program object for which the command LinkProgram has been issued in the past. If program has not been linked, the error INVALID_OPERATION is generated. If a new set of varying variables is specified by TransformFeedbackVaryings after a program object has been linked, the information returned by GetTransformFeedbackVarying will not reflect those variables until the program is re-linked.

The name of the selected varying is returned as a null-terminated string in name. The actual number of characters written into name, excluding the null terminator, is returned in length. If length is NULL, no length is returned. The maximum number of characters that may be written into name, including the null terminator, is specified by bufSize. The length of the longest varying name in program is given by TRANSFORM_FEEDBACK_VARYING_MAX_LENGTH, which can be queried with GetProgramiv (see section 6.1.12).

For the selected varying variable, its type is returned into type. The size of the varying is returned into size. The value in size is in units of the type returned in type. The type returned can be any of the types whose “Xfb” column is checked in table 2.12. If an error occurred, the return parameters length, size, type and name will be unmodified. This command will return as much information about the varying variables as possible. If no information is available, length will be set to zero and name will be an empty string. This situation could arise if GetTransformFeedbackVarying is called after a failed link.

Special varying names (e.g., gl_NextBuffer, gl_SkipComponents1) passed to TransformFeedbackVaryings in the varyings array are counted as varyings to be recorded for the purposes of determining the value of TRANSFORM_FEEDBACK_VARYINGS and for determining the variable selected by index in GetTransformFeedbackVarying. If index identifies gl_NextBuffer, the values zero and NONE will be written to size and type, respectively. If index is of the form gl_SkipComponentsn, the value NONE will be written to type and the number of components n will be written to size.
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2.11.8 Shader Execution

If a successfully linked program object that contains a vertex, tessellation control, tessellation evaluation, or geometry shader is made current by calling UseProgram, the executable versions of those shaders are used to process incoming vertex values.

Instead, the following sequence of operations is performed:

- Vertices are processed by the vertex shader (see section 2.11) and assembled into primitives as described in sections 2.5 through 2.8.

- If the current program contains a tessellation control shader, each individual patch primitive is processed by the tessellation control shader (section 2.12.1). Otherwise, primitives are passed through unmodified. If active, the tessellation control shader consumes its input patch and produces a new patch primitive, which is passed to subsequent pipeline stages.

- If the current program contains a tessellation evaluation shader, each individual patch primitive is processed by the tessellation primitive generator (section 2.12.2) and tessellation evaluation shader (see section 2.12.3). Otherwise, primitives are passed through unmodified. When a tessellation evaluation shader is active, the tessellation primitive generator produces a new collection of point, line, or triangle primitives to be passed to subsequent pipeline stages. The vertices of these primitives are processed by the tessellation evaluation shader. The patch primitive passed to the tessellation primitive generator is consumed by this process.

- If the current program contains a geometry shader, each individual primitive is processed by the geometry shader (section 2.13). Otherwise, primitives are passed through unmodified. If active, the geometry shader consumes its input patch. However, each geometry shader invocation may emit new vertices, which are arranged into primitives and passed to subsequent pipeline stages.

The following fixed-function operations are the applied to vertices of the resulting primitives:

- Transform feedback (section 2.17).
- Flatshading (section 2.19).
- Clipping, including client-defined half-spaces (section 2.20).
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- Perspective division on clip coordinates (section 2.14).
- Viewport mapping, including depth range scaling (section 2.14.1).
- Front face determination (section 3.6.1).
- Generic attribute clipping (section 2.20.1).
- Rasterization (chapter 3).

There are several special considerations for vertex shader execution described in the following sections.

Shader Only Texturing

This section describes texture functionality that is accessible through vertex, tessellation control, tessellation evaluation, geometry, or fragment shaders. Also refer to section 3.8 and to section 8.7 of the OpenGL Shading Language Specification.

Texel Fetches

The OpenGL Shading Language texel fetch functions provide the ability to extract a single texel from a specified texture image. The integer coordinates passed to the texel fetch functions are used directly as the texel coordinates \((i, j, k)\) into the texture image. This in turn means the texture image is point-sampled (no filtering is performed), but the remaining steps of texture access (described below) are still applied.

The level of detail accessed is computed by adding the specified level-of-detail parameter \(lod\) to the base level of the texture, \(level_{base}\).

The texel fetch functions can not perform depth comparisons or access cube maps. Unlike filtered texel accesses, texel fetches do not support LOD clamping or any texture wrap mode, and require a mipmapped minification filter to access any level of detail other than the base level.

The results of the texel fetch are undefined if any of the following conditions hold:

- the computed level of detail is less than the texture’s base level \((level_{base})\) or greater than the maximum level \((level_{max})\)
- the computed level of detail is not the texture’s base level and the texture’s minification filter is \text{NEAREST} or \text{LINEAR}
• the layer specified for array textures is negative or greater than the number of layers in the array texture,

• the texel coordinates \((i, j, k)\) refer to a texel outside the defined extents of the specified level of detail, where any of

\[
\begin{align*}
    i &< 0 & i &\geq w_s \\
    j &< 0 & j &\geq h_s \\
    k &< 0 & k &\geq d_s
\end{align*}
\]

and the size parameters \(w_s, h_s, d_s\) refer to the width, height, and depth of the image, as in equation 3.16

• the texture being accessed is not complete, as defined in section 3.8.14.

Multisample Texel Fetches

Multisample buffers do not have mipmaps, and there is no level of detail parameter for multisample texel fetches. Instead, an integer parameter selects the sample number to be fetched from the buffer. The number identifying the sample is the same as the value used to query the sample location using \texttt{GetMultisamplefv}.

Multisample textures support only \texttt{NEAREST} filtering. Additionally, this fetch may only be performed on a multisample texture sampler. No other sample or fetch commands may be performed on a multisample texture sampler.

Texture Size Query

The OpenGL Shading Language texture size functions provide the ability to query the size of a texture image. The LOD value \(\texttt{lod}\) passed in as an argument to the texture size functions is added to the \(\texttt{level}_{\text{base}}\) of the texture to determine a texture image level. The dimensions of that image level, excluding a possible border, are then returned. If the computed texture image level is outside the range \([\texttt{level}_{\text{base}}, \texttt{level}_{\text{max}}]\), the results are undefined. When querying the size of an array texture, both the dimensions and the layer index are returned.

Texture Access

Shaders have the ability to do a lookup into a texture map. The maximum number of texture image units available to shaders are the values of the implementation-dependent constants.
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• MAX_VERTEX_TEXTURE_IMAGE_UNITS (for vertex shaders),

• MAX_TESS_CONTROL_TEXTURE_IMAGE_UNITS (for tessellation control shaders),

• MAX_TESS_EVALUATION_TEXTURE_IMAGE_UNITS (for tessellation evaluation shaders),

• MAX_GEOMETRY_TEXTURE_IMAGE_UNITS (for geometry shaders), and

• MAX_TEXTURE_IMAGE_UNITS (for fragment shaders).

All active shaders combined cannot use more than the value of MAX_COMBINED_TEXTURE_IMAGE_UNITS texture image units. If more than one pipeline stage accesses the same texture image unit, each such access counts separately against the MAX_COMBINED_TEXTURE_IMAGE_UNITS limit.

When a texture lookup is performed in a shader, the filtered texture value \( \tau \) is computed in the manner described in sections 3.8.11 and 3.8.12, and converted to a texture base color \( C_b \) as shown in table 3.20, followed by application of the texture swizzle as described in section 3.9.2 to compute the texture source color \( C_s \) and \( A_s \).

The resulting four-component vector \((R_s, G_s, B_s, A_s)\) is returned to the shader. Texture lookup functions (see section 8.7 of the OpenGL Shading Language Specification) may return floating-point, signed, or unsigned integer values depending on the function and the internal format of the texture.

In shaders other than fragment shaders, it is not possible to perform automatic level-of-detail calculations using partial derivatives of the texture coordinates with respect to window coordinates as described in section 3.8.11. Hence, there is no automatic selection of an image array level. Minification or magnification of a texture map is controlled by a level-of-detail value optionally passed as an argument in the texture lookup functions. If the texture lookup function supplies an explicit level-of-detail value \( l \), then the pre-bias level-of-detail value \( \lambda_{base}(x, y) = l \) (replacing equation 3.17). If the texture lookup function does not supply an explicit level-of-detail value, then \( \lambda_{base}(x, y) = 0 \). The scale factor \( \rho(x, y) \) and its approximation function \( f(x, y) \) (see equation 3.21) are ignored.

Texture lookups involving textures with depth component data can either return the depth data directly or return the results of a comparison with a reference depth value specified in the coordinates passed to the texture lookup function, as described in section 3.8.16. The comparison operation is requested in the shader by using any of the shadow sampler types (sampler1DShadow, sampler2DShadow,
or sampler2DRectShadow), and in the texture using the TEXTURE_COMPARE_MODE parameter. These requests must be consistent; the results of a texture lookup are undefined if any of the following conditions are true:

- The sampler used in a texture lookup function is not one of the shadow sampler types, the texture object’s internal format is DEPTH_COMPONENT or DEPTH_STENCIL, and the TEXTURE_COMPARE_MODE is not NONE.
- The sampler used in a texture lookup function is one of the shadow sampler types, the texture object’s internal format is DEPTH_COMPONENT or DEPTH_STENCIL, and the TEXTURE_COMPARE_MODE is NONE.
- The sampler used in a texture lookup function is one of the shadow sampler types, and the texture object’s internal format is not DEPTH_COMPONENT or DEPTH_STENCIL.

The stencil index texture internal component is ignored if the base internal format is DEPTH_STENCIL.

Using a sampler in a shader will return \((R, G, B, A) = (0, 0, 0, 1)\) if the sampler’s associated texture is not complete, as defined in section 3.8.14.

Shader Inputs

Besides having access to vertex attributes and uniform variables, vertex shaders can access the read-only built-in variables \(\text{gl\_VertexID}\) and \(\text{gl\_InstanceID}\).

\(\text{gl\_VertexID}\) holds the integer index \(i\) implicitly passed by \text{DrawArrays} or one of the other drawing commands defined in section 2.8.3.

\(\text{gl\_InstanceID}\) holds the integer index of the current primitive in an instanced draw call (see section 2.8.3).

Section 7.1 of the OpenGL Shading Language Specification also describes these variables.

Shader Outputs

A vertex shader can write to user-defined varying variables. These values are expected to be interpolated across the primitive it outputs, unless they are specified to be flat shaded. Refer to sections 4.3.6, 7.1, and 7.6 of the OpenGL Shading Language Specification for more detail.

The built-in special variable \(\text{gl\_Position}\) is intended to hold the homogeneous vertex position. Writing \(\text{gl\_Position}\) is optional.
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The built-in special variable \texttt{gl\_ClipDistance} holds the clip distance(s) used in the clipping stage, as described in section 2.20. If clipping is enabled, \texttt{gl\_ClipDistance} should be written.

The built-in special variable \texttt{gl\_PointSize}, if written, holds the size of the point to be rasterized, measured in pixels.

Validation

It is not always possible to determine at link time if a program object actually will execute. Therefore validation is done when the first rendering command is issued, to determine if the currently active program object can be executed. If it cannot be executed then no fragments will be rendered, and the error \texttt{INVALID\_OPERATION} will be generated.

This error is generated by any command that transfers vertices to the GL if:

- any two active samplers in the current program object are of different types, but refer to the same texture image unit,
- the number of active samplers in the program exceeds the maximum number of texture image units allowed.

Undefined behavior results if the program object in use has no fragment shader unless transform feedback is enabled, in which case only a vertex shader is required.

The \texttt{INVALID\_OPERATION} error reported by these rendering commands may not provide enough information to find out why the currently active program object would not execute. No information at all is available about a program object that would still execute, but is inefficient or suboptimal given the current GL state. As a development aid, use the command

\begin{verbatim}
void ValidateProgram( uint program );
\end{verbatim}

to validate the program object \texttt{program} against the current GL state. Each program object has a boolean status, \texttt{VALIDATE\_STATUS}, that is modified as a result of validation. This status can be queried with \texttt{GetProgramiv} (see section 6.1.12). If validation succeeded this status will be set to \texttt{TRUE}, otherwise it will be set to \texttt{FALSE}. If validation succeeded the program object is guaranteed to execute, given the current GL state. If validation failed, the program object is guaranteed to not execute, given the current GL state.

\texttt{ValidateProgram} will check for all the conditions that could lead to an \texttt{INVALID\_OPERATION} error when rendering commands are issued, and may check
for other conditions as well. For example, it could give a hint on how to optimize
some piece of shader code. The information log of program is overwritten with
information on the results of the validation, which could be an empty string. The
results written to the information log are typically only useful during application
development; an application should not expect different GL implementations to
produce identical information.

A shader should not fail to compile, and a program object should not fail to
link due to lack of instruction space or lack of temporary variables. Implementa-
tions should ensure that all valid shaders and program objects may be successfully
compiled, linked and executed.

Undefined Behavior

When using array or matrix variables in a shader, it is possible to access a vari-
able with an index computed at run time that is outside the declared extent of the
variable. Such out-of-bounds accesses have undefined behavior, and system er-
rors (possibly including program termination) may occur. The level of protection
provided against such errors in the shader is implementation-dependent.

2.11.9 Required State

The GL maintains state to indicate which shader and program object names are in
use. Initially, no shader or program objects exist, and no names are in use.

The state required per shader object consists of:

- An unsigned integer specifying the shader object name.
- An integer holding the value of SHADER_TYPE.
- A boolean holding the delete status, initially FALSE.
- A boolean holding the status of the last compile, initially FALSE.
- An array of type char containing the information log, initially empty.
- An integer holding the length of the information log.
- An array of type char containing the concatenated shader string, initially
  empty.
- An integer holding the length of the concatenated shader string.

The state required per program object consists of:
• An unsigned integer indicating the program object name.

• A boolean holding the delete status, initially FALSE.

• A boolean holding the status of the last link attempt, initially FALSE.

• A boolean holding the status of the last validation attempt, initially FALSE.

• An integer holding the number of attached shader objects.

• A list of unsigned integers to keep track of the names of the shader objects attached.

• An array of type char containing the information log, initially empty.

• An integer holding the length of the information log.

• An integer holding the number of active uniforms.

• For each active uniform, three integers, holding its location, size, and type, and an array of type char holding its name.

• An array holding the values of each active uniform.

• An integer holding the number of active attributes.

• For each active attribute, three integers holding its location, size, and type, and an array of type char holding its name.

Additional state required to support vertex shaders consists of:

• A bit indicating whether or not vertex program two-sided color mode is enabled, initially disabled.

• A bit indicating whether or not program point size mode (section 3.4.1) is enabled, initially disabled.

Additionally, one unsigned integer is required to hold the name of the current program object, if any.
2.12 Tessellation

Tessellation is a process that reads a patch primitive and generates new primitives used by subsequent pipeline stages. The generated primitives are formed by subdividing a single triangle or quad primitive according to fixed or shader-computed levels of detail and transforming each of the vertices produced during this subdivision.

Tessellation functionality is controlled by two types of tessellation shaders: tessellation control shaders and tessellation evaluation shaders. Tessellation is considered active if and only if there is an active program object, and that program object contains a tessellation control or evaluation shader.

The tessellation control shader is used to read an input patch provided by the application, and emit an output patch. The tessellation control shader is run once for each vertex in the output patch and computes the attributes of that vertex. Additionally, the tessellation control shader may compute additional per-patch attributes of the output patch. The most important per-patch outputs are the tessellation levels, which are used to control the number of subdivisions performed by the tessellation primitive generator. The tessellation control shader may also write additional per-patch attributes for use by the tessellation evaluation shader. If no tessellation control shader is active, the patch provided is passed through to the tessellation primitive generator stage unmodified.

If a tessellation evaluation shader is active, the tessellation primitive generator subdivides a triangle or quad primitive into a collection of points, lines, or triangles according to the tessellation levels of the patch and the set of layout declarations specified in the tessellation evaluation shader text. The tessellation levels used to control subdivision are normally written by the tessellation control shader. If no tessellation control shader is active, default tessellation levels are instead used.

When a tessellation evaluation shader is active, it is run on each vertex generated by the tessellation primitive generator to compute the final position and other attributes of the vertex. The tessellation evaluation shader can read the relative location of the vertex in the subdivided output primitive, given by an \((u, v)\) or \((u, v, w)\) coordinate, as well as the position and attributes of any or all of the vertices in the input patch.

Tessellation operates only on patch primitives. If tessellation is active, any command that transfers vertices to the GL will generate an `INVALID_OPERATION` error if the primitive mode is not `PATCHES`.

Patch primitives are not supported by pipeline stages below the tessellation evaluation shader. If there is no active program object or the active program object does not contain a tessellation evaluation shader, the error `INVALID_OPERATION` is generated by any command that transfers vertices to the GL if the primitive...
mode is PATCHES.

A program object that includes a tessellation shader of any kind must also include a vertex shader, and will fail to link if no vertex shader is provided.

### 2.12.1 Tessellation Control Shaders

The tessellation control shader consumes an input patch provided by the application and emits a new output patch. The input patch is an array of vertices with attributes corresponding to input variables written by the vertex shader. The output patch consists of an array of vertices with attributes corresponding to per-vertex output variables written by the tessellation control shader and a set of per-patch attributes corresponding to per-patch output variables written by the tessellation control shader. Tessellation control output variables are per-vertex by default, but may be declared as per-patch using the `patch` qualifier.

The number of vertices in the output patch is fixed when the program is linked, and is specified in tessellation control shader source code using the output layout qualifier `vertices`, as described in the OpenGL Shading Language Specification. A program will fail to link if the output patch vertex count is not specified by any tessellation control shader object attached to the program, if it is specified differently by multiple tessellation control shader objects, if it is less than or equal to zero, or if it is greater than the implementation-dependent maximum patch size. The output patch vertex count may be queried by calling `GetProgramiv` with the symbolic constant `TESS_CONTROL_OUTPUT_VERTICES`.

Tessellation control shaders are created as described in section 2.11.1, using a type of `TESS_CONTROL_SHADER`. When a new input patch is received, the tessellation control shader is run once for each vertex in the output patch. The tessellation control shader invocations collectively specify the per-vertex and per-patch attributes of the output patch. The per-vertex attributes are obtained from the per-vertex output variables written by each invocation. Each tessellation control shader invocation may only write to per-vertex output variables corresponding to its own output patch vertex. The output patch vertex number corresponding to a given tessellation control point shader invocation is given by the built-in variable `glInvocationID`. Per-patch attributes are taken from the per-patch output variables, which may be written by any tessellation control shader invocation. While tessellation control shader invocations may read any per-vertex and per-patch output variable and write any per-patch output variable, reading or writing output variables also written by other invocations has ordering hazards discussed below.
2.12. TESSELLATION

Tessellation Control Shader Variables

Tessellation control shaders can access uniforms belonging to the current program object. The amount of storage available for uniform variables in the default uniform block accessed by a tessellation control shader is specified by the value of the implementation-dependent constant `MAX_TESS_CONTROL_UNIFORM_COMPONENTS`. The total amount of combined storage available for uniform variables in all uniform blocks accessed by a tessellation control shader (including the default uniform block) is specified by the value of the implementation-dependent constant `MAX_COMBINED_TESS_CONTROL_UNIFORM_COMPONENTS`. These values represent the numbers of individual floating-point, integer, or boolean values that can be held in uniform variable storage for a tessellation evaluation shader. A link error is generated if an attempt is made to utilize more than the space available for tessellation control shader uniform variables. Uniforms are manipulated as described in section 2.11.4. Tessellation control shaders also have access to samplers to perform texturing operations, as described in section 2.11.6.

Tessellation control shaders can access the transformed attributes of all vertices for their input primitive using input variables. A vertex shader writing to output variables generates the values of these input varying variables, including values for built-in as well as user-defined varying variables. Values for any varying variables that are not written by a vertex shader are undefined.

Additionally, tessellation control shaders can write to one or more output variables, including per-vertex attributes for the vertices of the output patch and per-patch attributes of the patch. Tessellation control shaders can also write to a set of built-in per-vertex and per-patch outputs defined in the OpenGL Shading Language. The per-vertex and per-patch attributes of the output patch are used by the tessellation primitive generator (section 2.12.2) and may be read by tessellation evaluation shader (section 2.12.3).

Tessellation Control Shader Execution Environment

If a successfully linked program object that contains a tessellation control shader is made current by calling `UseProgram`, the executable version of the tessellation control shader is used to process patches resulting from the primitive assembly stage. When tessellation control shader execution completes, the input patch is consumed. A new patch is assembled from the per-vertex and per-patch output variables written by the shader and is passed to subsequent pipeline stages.

There are several special considerations for tessellation control shader execution described in the following sections.
2.12. TESSELLATION

Texture Access

The Shader-Only Texturing subsection of section 2.11.8 describes texture lookup functionality accessible to a vertex shader. The texel fetch and texture size query functionality described there also applies to tessellation control shaders.

Tessellation Control Shader Inputs

Section 7.1 of the OpenGL Shading Language Specification describes the built-in variable array `gl_in` available as input to a tessellation control shader. `gl_in` receives values from equivalent built-in output variables written by the vertex shader (section 2.11.8). Each array element of `gl_in` is a structure holding values for a specific vertex of the input patch. The length of `gl_in` is equal to the implementation-dependent maximum patch size (`gl_MaxPatchVertices`). Behavior is undefined if `gl_in` is indexed with a vertex index greater than or equal to the current patch size. The members of each element of the `gl_in` array are `gl_Position`, `gl_PointSize`, `gl_ClipDistance`, and `gl_ClipVertex`.

Tessellation control shaders have available several other special input variables not replicated per-vertex and not contained in `gl_in`, including:

- The variable `gl_PatchVerticesIn` holds the number of vertices in the input patch being processed by the tessellation control shader.

- The variable `gl_PrimitiveID` is filled with the number of primitives processed by the drawing command which generated the input vertices. The first primitive generated by a drawing command is numbered zero, and the primitive ID counter is incremented after every individual point, line, or triangle primitive is processed. Restarting a primitive topology using the primitive restart index has no effect on the primitive ID counter.

- The variable `gl_InvocationID` holds an invocation number for the current tessellation control shader invocation. Tessellation control shaders are invoked once per output patch vertex, and invocations are numbered beginning with zero.

Similarly to the built-in varying variables, each user-defined input varying variable has a value for each vertex and thus needs to be declared as arrays or inside input blocks declared as arrays. Declaring an array size is optional. If no size is specified, it will be taken from the implementation-dependent maximum patch size (`gl_MaxPatchVertices`). If a size is specified, it must match the maximum patch size; otherwise, a link error will occur. Since the array size may be larger...
than the number of vertices found in the input patch, behavior is undefined if a per-vertex input variable is accessed using an index greater than or equal to the number of vertices in the input patch. The OpenGL Shading Language doesn’t support multi-dimensional arrays; therefore, user-defined tessellation control shader inputs corresponding to vertex shader outputs declared as arrays must be declared as array members of an input block that is itself declared as an array.

Similarly to the limit on vertex shader output components (see section 2.11.7), there is a limit on the number of components of built-in and user-defined input varying variables that can be read by the tessellation control shader, given by the value of the implementation-dependent constant MAX_TESS_CONTROL_INPUT_COMPONENTS.

When a program is linked, all components of any varying and special variable read by a tessellation control shader will count against this limit. A program whose tessellation control shader exceeds this limit may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.

Component counting rules for different variable types and variable declarations are the same as for MAX_VERTEX_OUTPUT_COMPONENTS. (see section 2.11.7).

**Tessellation Control Shader Outputs**

Section 7.1 of the OpenGL Shading Language Specification describes the built-in variable array `gl_out` available as an output for a tessellation control shader. `gl_out` passes values to equivalent built-in input variables read by subsequent shader stages or to subsequent fixed functionality vertex processing pipeline stages. Each array element of `gl_out` is a structure holding values for a specific vertex of the output patch. The length of `gl_out` is equal to the output patch size specified in the tessellation control shader output layout declaration (`gl_VerticesOut`). The members of each element of the `gl_out` array are `gl_Position`, `gl_PointSize`, and `gl_ClipDistance`, and behave identically to equivalently named vertex shader outputs (section 2.11.8).

Tessellation shaders additionally have two built-in per-patch output arrays, `gl_TessLevelOuter` and `gl_TessLevelInner`. These arrays are not replicated for each output patch vertex and are not members of `gl_out`. `gl_TessLevelOuter` is an array of four floating-point values specifying the approximate number of segments that the tessellation primitive generator should use when subdividing each outer edge of the primitive it subdivides. `gl_TessLevelInner` is an array of two floating-point values specifying the approximate number of segments used to produce a regularly-subdivided primitive interior. The values written to `gl_TessLevelOuter` and `gl_TessLevelInner` need not be integers, and
their interpretation depends on the type of primitive the tessellation primitive generator will subdivide and other tessellation parameters, as discussed in the following section.

A tessellation control shader may also declare user-defined per-vertex output variables. User-defined per-vertex output variables are declared with the qualifier `out` and have a value for each vertex in the output patch. Such variables must be declared as arrays or inside output blocks declared as arrays. Declaring an array size is optional. If no size is specified, it will be taken from output patch size (`gl_VerticesOut`) declared in the shader. If a size is specified, it must match the maximum patch size; otherwise, a link error will occur. The OpenGL Shading Language doesn’t support multi-dimensional arrays; therefore, user-defined per-vertex tessellation control shader outputs with multiple elements per vertex must be declared as array members of an output block that is itself declared as an array.

While per-vertex output variables are declared as arrays indexed by vertex number, each tessellation control shader invocation may write only to those outputs corresponding to its output patch vertex. Tessellation control shaders must use the special variable `gl_InvocationID` as the vertex number index when writing to per-vertex output variables.

Additionally, a tessellation control shader may declare per-patch output variables using the qualifier `patch out`. Unlike per-vertex outputs, per-patch outputs do not correspond to any specific vertex in the patch, and are not indexed by vertex number. Per-patch outputs declared as arrays have multiple values for the output patch; similarly declared per-vertex outputs would indicate a single value for each vertex in the output patch. User-defined per-patch outputs are not used by the tessellation primitive generator, but may be read by tessellation evaluation shaders.

There are several limits on the number of components of built-in and user-defined output variables that can be written by the tessellation control shader. The number of components of active per-vertex output variables may not exceed the value of `MAX_TESS_CONTROL_OUTPUT_COMPONENTS`. The number of components of active per-patch output variables may not exceed the value of `MAX_TESS_PATCH_COMPONENTS`. The built-in outputs `gl_TessLevelOuter` and `gl_TessLevelInner` are not counted against the per-patch limit. The total number of components of active per-vertex and per-patch outputs is derived by multiplying the per-vertex output component count by the output patch size and then adding the per-patch output component count. The total component count may not exceed `MAX_TESS_CONTROL_TOTAL_OUTPUT_COMPONENTS`.

When a program is linked, all components of any varying and special variables written by a tessellation control shader will count against this limit. A program exceeding any of these limits may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.
Counting rules for different variable types and variable declarations are the same as for `MAX_VERTEX_OUTPUT_COMPONENTS`. (see section 2.11.7).

**Tessellation Control Shader Execution Order**

For tessellation control shaders with a declared output patch size greater than one, the shader is invoked more than once for each input patch. The order of execution of one tessellation control shader invocation relative to the other invocations for the same input patch is largely undefined. The built-in function `barrier` provides some control over relative execution order. When a tessellation control shader calls the `barrier` function, its execution pauses until all other invocations have also called the same function. Output variable assignments performed by any invocation executed prior to calling `barrier` will be visible to any other invocation after the call to `barrier` returns. Shader output values read in one invocation but written by another may be undefined without proper use of `barrier`; full rules are found in the OpenGL Shading Language Specification.

The `barrier` function may only be called inside the main entry point of the tessellation control shader and may not be called in potentially divergent flow control. In particular, `barrier` may not be called inside a switch statement, in either sub-statement of an if statement, inside a do, for, or while loop, or at any point after a return statement in the function `main`.

### 2.12.2 Tessellation Primitive Generation

If a tessellation evaluation shader is present, the tessellation primitive generator consumes the input patch and produces a new set of basic primitives (points, lines, or triangles). These primitives are produced by subdividing a geometric primitive (rectangle or triangle) according to the per-patch tessellation levels written by the tessellation control shader, if present, or taken from default patch parameter values. This subdivision is performed in an implementation-dependent manner. If no tessellation evaluation shader is present, the tessellation primitive generator passes incoming primitives through without modification.

The type of subdivision performed by the tessellation primitive generator is specified by an input layout declaration in the tessellation evaluation shader using one of the identifiers `triangles`, `quads`, and `isolines`. For `triangles`, the primitive generator subdivides a triangle primitive into smaller triangles. For `quads`, the primitive generator subdivides a rectangle primitive into smaller triangles. For `isolines`, the primitive generator subdivides a rectangle primitive into a collection of line segments arranged in strips stretching horizontally across the rectangle. Each vertex produced by the primitive generator has an associated
(u, v, w) or (u, v) position in a normalized parameter space, with parameter values in the range [0, 1], as illustrated in figure 2.7. For triangles, the vertex position is a barycentric coordinate (u, v, w), where \( u + v + w = 1 \), and indicates the relative influence of the three vertices of the triangle on the position of the vertex. For quads and isolines, the position is a (u, v) coordinate indicating the relative horizontal and vertical position of the vertex relative to the subdivided rectangle. The subdivision process is explained in more detail in subsequent sections.

When no tessellation control shader is present, the tessellation levels are taken from default patch tessellation levels. These default levels are set by calling

```c
void PatchParameterfv( enum pname, const float *values );
```

If `pname` is `PATCH_DEFAULT_OUTER_LEVEL`, `values` specifies an array of four floating-point values corresponding to the four outer tessellation levels for each subsequent patch. If `pname` is `PATCH_DEFAULT_INNER_LEVEL`, `values` specifies an array of two floating-point values corresponding to the two inner tessellation levels.

A patch is discarded by the tessellation primitive generator if any relevant outer tessellation level is less than or equal to zero. Patches will also be discarded if any outer tessellation level corresponds to a floating-point NaN (not a number) in implementations supporting NaN. When patches are discarded, no new primitives will be generated and the tessellation evaluation program will not be run. For quads, all four outer levels are relevant. For triangles and isolines, only the first three or two outer levels, respectively, are relevant. Negative inner levels will not cause a patch to be discarded; they will be clamped as described below.

Each of the tessellation levels is used to determine the number and spacing of segments used to subdivide a corresponding edge. The method used to derive the number and spacing of segments is specified by an input layout declaration in the tessellation evaluation shader using one of the identifiers `equal_spacing`, `fractional_even_spacing`, or `fractional_odd_spacing`. If no spacing is specified in the tessellation evaluation shader, `equal_spacing` will be used.

If `equal_spacing` is used, the floating-point tessellation level is first clamped to the range \([1, \text{max}]\), where `max` is the implementation-dependent maximum tessellation level (the value of `MAX_TESS_GEN_LEVEL`). The result is rounded up to the nearest integer \( n \), and the corresponding edge is divided into \( n \) segments of equal length in \((u,v)\) space.

If `fractional_even_spacing` is used, the tessellation level is first clamped to the range \([2, \text{max}]\) and then rounded up to the nearest even integer \( n \). If `fractional_odd_spacing` is used, the tessellation level is clamped to the range
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Figure 2.7. Domain parameterization for tessellation generator primitive modes (triangles, quads, or isolines). The coordinates illustrate the value of gl_TessCoord at the corners of the domain. The labels on the edges indicate the inner (IL0 and IL1) and outer (OL0 through OL3) tessellation level values used to control the number of subdivisions along each edge of the domain.
[1, max – 1] and then rounded up to the nearest odd integer n. If n is one, the edge will not be subdivided. Otherwise, the corresponding edge will be divided into n – 2 segments of equal length, and two additional segments of equal length that are typically shorter than the other segments. The length of the two additional segments relative to the others will decrease monotonically with the value of n – f, where f is the clamped floating-point tessellation level. When n – f is zero, the additional segments will have equal length to the other segments. As n – f approaches 2.0, the relative length of the additional segments approaches zero. The two additional segments should be placed symmetrically on opposite sides of the subdivided edge. The relative location of these two segments is undefined, but must be identical for any pair of subdivided edges with identical values of f.

When the tessellation primitive generator produces triangles (in the triangles or quads modes), the orientation of all triangles can be specified by an input layout declaration in the tessellation evaluation shader using the identifiers cw and ccw. If the order is cw, the vertices of all generated triangles will have a clockwise ordering in (u, v) or (u, v, w) space, as illustrated in figure 2.7. If the order is ccw, the vertices will be specified in counter-clockwise order. If no layout is specified, ccw will be used.

For all primitive modes, the tessellation primitive generator is capable of generating points instead of lines or triangles. If an input layout declaration in the tessellation evaluation shader specifies the identifier point_mode, the primitive generator will generate one point for each unique vertex produced by tessellation. Otherwise, the primitive generator will produce a collection of line segments or triangles according to the primitive mode.

The points, lines, or triangles produced by the tessellation primitive generator are passed to subsequent pipeline stages in an implementation-dependent order.

**Triangle Tessellation**

If the tessellation primitive mode is triangles, an equilateral triangle is subdivided into a collection of triangles covering the area of the original triangle. First, the original triangle is subdivided into a collection of concentric equilateral triangles. The edges of each of these triangles are subdivided, and the area between each triangle pair is filled by triangles produced by joining the vertices on the subdivided edges. The number of concentric triangles and the number of subdivisions along each triangle except the outermost is derived from the first inner tessellation level. The edges of the outermost triangle are subdivided independently, using the first, second, and third outer tessellation levels to control the number of subdivisions of the u = 0 (left), v = 0 (bottom), and w = 0 (right) edges, respectively. The second inner tessellation level and the fourth outer tessellation level have no
If the first inner tessellation level and all three outer tessellation levels are ex-
actly one after clamping and rounding, only a single triangle with \((u, v, w)\) co-
ordinates of \((0, 0, 1), (1, 0, 0),\) and \((0, 1, 0)\) is generated. If the inner tessellation
level is one and any of the outer tessellation levels is greater than one, the inner
tessellation level is treated as though it were originally specified as \(1 + \epsilon\) and will
be rounded up to result in a two- or three-segment subdivision according to the
tessellation spacing.

If any tessellation level is greater than one, tessellation begins by producing a
set of concentric inner triangles and subdividing their edges. First, the three outer
edges are temporarily subdivided using the clamped and rounded first inner tes-
sellation level and the specified tessellation spacing, generating \(n\) segments. For
the outermost inner triangle, the inner triangle is degenerate – a single point at the
center of the triangle – if \(n\) is two. Otherwise, for each corner of the outer trian-
gle, an inner triangle corner is produced at the intersection of two lines extended
perpendicular to the corner’s two adjacent edges running through the vertex of the
subdivided outer edge nearest that corner. If \(n\) is three, the edges of the inner tri-
gle are not subdivided and is the final triangle in the set of concentric triangles.
Otherwise, each edge of the inner triangle is divided into \(n - 2\) segments, with the
\(n - 1\) vertices of this subdivision produced by intersecting the inner edge with
lines perpendicular to the edge running through the \(n - 1\) innermost vertices of the
subdivision of the outer edge. Once the outermost inner triangle is subdivided, the
previous subdivision process repeats itself, using the generated triangle as an outer
triangle. This subdivision process is illustrated in figure 2.8.

Once all the concentric triangles are produced and their edges are subdivided,
the area between each pair of adjacent inner triangles is filled completely with a
set of non-overlapping triangles. In this subdivision, two of the three vertices of
each triangle are taken from adjacent vertices on a subdivided edge of one triangle;
the third is one of the vertices on the corresponding edge of the other triangle.
If the innermost triangle is degenerate (i.e., a point), the triangle containing it is
subdivided into six triangles by connecting each of the six vertices on that triangle
with the center point. If the innermost triangle is not degenerate, that triangle is
added to the set of generated triangles as-is.

After the area corresponding to any inner triangles is filled, the primitive gen-
erator generates triangles to cover area between the outermost triangle and the out-
nermost inner triangle. To do this, the temporary subdivision of the outer triangle
dge above is discarded. Instead, the \(u = 0, v = 0,\) and \(w = 0\) edges are subdi-
vided according to the first, second, and third outer tessellation levels, respectively,
and the tessellation spacing. The original subdivision of the first inner triangle is
retained. The area between the outer and first inner triangles is completely filled by
Figure 2.8. Inner triangle tessellation with inner tessellation levels of (a) five and (b) four, respectively (not to scale) Solid black circles depict vertices along the bottom edges of the concentric triangles. The edges of inner triangles are subdivided by intersecting the edge with segments perpendicular to the edge passing through each inner vertex of the subdivided outer edge. Dotted lines depict edges connecting corresponding vertices on the inner and outer triangle edges.
2.12. Tessellation

non-overlapping triangles as described above. If the first (and only) inner triangle is degenerate, a set of triangles is produced by connecting each vertex on the outer triangle edges with the center point.

After all triangles are generated, each vertex in the subdivided triangle is assigned a barycentric \((u, v, w)\) coordinate based on its location relative to the three vertices of the outer triangle.

The algorithm used to subdivide the triangular domain in \((u, v, w)\) space into individual triangles is implementation-dependent. However, the set of triangles produced will completely cover the domain, and no portion of the domain will be covered by multiple triangles. The order in which the generated triangles passed to subsequent pipeline stages and the order of the vertices in those triangles are both implementation-dependent. However, when depicted in a manner similar to figure 2.8, the order of the vertices in the generated triangles will be either all clockwise or all counter-clockwise, according to the vertex order layout declaration.

Quad Tessellation

If the tessellation primitive mode is quads, a rectangle is subdivided into a collection of triangles covering the area of the original rectangle. First, the original rectangle is subdivided into a regular mesh of rectangles, where the number of rectangles along the \(u = 0\) and \(u = 1\) (vertical) and \(v = 0\) and \(v = 1\) (horizontal) edges are derived from the first and second inner tessellation levels, respectively. All rectangles, except those adjacent to one of the outer rectangle edges, are decomposed into triangle pairs. The outermost rectangle edges are subdivided independently, using the first, second, third, and fourth outer tessellation levels to control the number of subdivisions of the \(u = 0\) (left), \(v = 0\) (bottom), \(u = 1\) (right), and \(v = 1\) (top) edges, respectively. The area between the inner rectangles of the mesh and the outer rectangle edges are filled by triangles produced by joining the vertices on the subdivided outer edges to the vertices on the edge of the inner rectangle mesh.

If both clamped inner tessellation levels and all four clamped outer tessellation levels are exactly one, only a single triangle pair covering the outer rectangle is generated. Otherwise, if either clamped inner tessellation level is one, that tessellation level is treated as though it were originally specified as \(1 + \epsilon\), which would rounded up to result in a two- or three-segment subdivision according to the tessellation spacing.

If any tessellation level is greater than one, tessellation begins by subdividing the \(u = 0\) and \(u = 1\) edges of the outer rectangle into \(m\) segments using the clamped and rounded first inner tessellation level and the tessellation spacing. The \(v = 0\) and \(v = 1\) edges are subdivided into \(n\) segments using the second inner
tessellation level. Each vertex on the \( u = 0 \) and \( v = 0 \) edges are joined with the corresponding vertex on the \( u = 1 \) and \( v = 1 \) edges to produce a set of vertical and horizontal lines that divide the rectangle into a grid of smaller rectangles. The primitive generator emits a pair of non-overlapping triangles covering each such rectangle not adjacent to an edge of the outer rectangle. The boundary of the region covered by these triangles forms an inner rectangle, the edges of which are subdivided by the grid vertices that lie on the edge. If either \( m \) or \( n \) is two, the inner rectangle is degenerate, and one or both of the rectangle’s “edges” consist of a single point. This subdivision is illustrated in figure 2.9.

After the area corresponding to the inner rectangle is filled, the primitive generator must produce triangles to cover area between the inner and outer rectangles. To do this, the subdivision of the outer rectangle edge above is discarded. Instead, the \( u = 0, v = 0, u = 1, \) and \( v = 1 \) edges are subdivided according to the first, second, third, and fourth outer tessellation levels, respectively, and the tessellation spacing. The original subdivision of the inner rectangle is retained. The area between the outer and inner rectangles is completely filled by non-overlapping triangles. Two of the three vertices of each triangle are adjacent vertices on a subdivided edge of one rectangle; the third is one of the vertices on the corresponding edge of the other triangle. If either edge of the innermost rectangle is degenerate, the area near the corresponding outer edges is filled by connecting each vertex on the outer edge with the single vertex making up the inner “edge”.

The algorithm used to subdivide the rectangular domain in \((u, v)\) space into individual triangles is implementation-dependent. However, the set of triangles produced will completely cover the domain, and no portion of the domain will be covered by multiple triangles. The order in which the generated triangles passed to subsequent pipeline stages and the order of the vertices in those triangles are both implementation-dependent. However, when depicted in a manner similar to figure 2.9, the order of the vertices in the generated triangles will be either all clockwise or all counter-clockwise, according to the vertex order layout declaration.

Isoline Tessellation

If the tessellation primitive mode is *isolines*, a set of independent horizontal line segments is drawn. The segments are arranged into connected strips, where each strip has a constant \( v \) coordinate, and the \( u \) coordinates of the strip cover the full range \([0, 1]\). The number of segments in each strip is derived from the first outer tessellation level; the number of line strips drawn is derived from the second outer tessellation level. Both inner tessellation levels and the third and fourth outer tessellation levels have no effect in this mode.

As with quad tessellation above, isoline tessellation begins with a rectangle.
Figure 2.9. Inner quad tessellation with inner tessellation levels of (a) \((4, 2)\) and (b) \((7, 4)\), respectively. Gray regions on the bottom figure depict the 10 inner rectangles, each of which will be subdivided into two triangles. Solid black circles depict vertices on the boundary of the outer and inner rectangles, where the inner rectangle on the top figure is degenerate (a single line segment). Dotted lines depict the horizontal and vertical edges connecting corresponding vertices on the inner and outer rectangle edges.
The $u = 0$ and $u = 1$ edges of the rectangle are subdivided according to the second outer tessellation level. For the purposes of this subdivision, the tessellation spacing is ignored and treated as \texttt{EQUAL}. A line is drawn from each vertex on the $u = 0$ rectangle edge with the corresponding vertex on the $u = 1$ rectangle edge, except that no line is drawn between (0,1) and (1,1). If the number of segments on the subdivided $u = 0$ and $u = 1$ edges is $n$, this process will result in $n$ equally spaced lines with constant $v$ coordinates of $0, \frac{1}{n}, \frac{2}{n}, \ldots, \frac{n-1}{n}$.

Each of the $n$ lines is then subdivided according to the first outer tessellation level and the tessellation spacing, resulting in $m$ line segments. Each segment of each line is emitted by the tessellation primitive generator, as illustrated in figure 2.10.

The order in which the generated line segments are passed to subsequent pipeline stages and the order of the vertices in each generated line segment are both implementation-dependent.

### 2.12.3 Tessellation Evaluation Shaders

If active, the tessellation evaluation shader takes the $(u, v)$ or $(u, v, w)$ location of each vertex in the primitive subdivided by the tessellation primitive generator, and generates a vertex with a position and associated attributes. The tessellation evaluation shader can read any of the vertices of its input patch, which is the output patch produced by the tessellation control shader (if present) or provided by the application and transformed by the vertex shader (if no control shader is used). Tessellation evaluation shaders are created as described in section 2.11.1, using a type of \texttt{TESS_EVALUATION_SHADER}.

Each invocation of the tessellation evaluation shader writes the attributes of exactly one vertex. The number of vertices evaluated per patch depends on the tessellation level values computed by the tessellation control shaders (if present) or specified as patch parameters. Tessellation evaluation shader invocations run independently, and no invocation can access the variables belonging to another invocation. All invocations are capable of accessing all the vertices of their corresponding input patch.

If a tessellation control shader is present, the number of the vertices in the input patch is fixed and is equal to the tessellation control shader output patch size parameter in effect when the program was last linked. If no tessellation control shader is present, the input patch is provided by the application can have a variable number of vertices, as specified by \texttt{PatchParameteri}.
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Figure 2.10. Isoline tessellation with the first two outer tessellation levels of (a) $(3, 1)$ and (b) $(6, 4)$, respectively. Line segments connecting the vertices marked with solid black circles are emitted by the primitive generator. Vertices marked with empty circles correspond to $(u, v)$ coordinates of $(0, 1)$ and $(1, 1)$, where no line segments are generated.
2.12. TESSELLATION

**Tessellation Evaluation Shader Variables**

Tessellation evaluation shaders can access uniforms belonging to the current program object. The amount of storage available for uniform variables in the default uniform block accessed by a tessellation evaluation shader is specified by the value of the implementation-dependent constant `MAX_TESS_EVALUATION_UNIFORM_COMPONENTS`. The total amount of combined storage available for uniform variables in all uniform blocks accessed by a tessellation evaluation shader (including the default uniform block) is specified by the value of the implementation-dependent constant `MAX_COMBINED_TESS_EVALUATION_UNIFORM_COMPONENTS`. These values represent the numbers of individual floating-point, integer, or boolean values that can be held in uniform variable storage for a tessellation evaluation shader. A link error is generated if an attempt is made to utilize more than the space available for tessellation evaluation shader uniform variables. Uniforms are manipulated as described in section 2.11.4. Tessellation evaluation shaders also have access to samplers to perform texturing operations, as described in section 2.11.6.

Tessellation evaluation shaders can access the transformed attributes of all vertices for their input primitive using input variables. If active, a tessellation control shader writing to output variables generates the values of these input varying variables, including values for built-in as well as user-defined varying variables. If no tessellation control shader is active, input variables will be obtained from vertex shader outputs. Values for any varying variables that are not written by a vertex or tessellation control shader are undefined.

Additionally, tessellation evaluation shaders can write to one or more built-in or user-defined output variables that will be passed to subsequent programmable shader stages or fixed functionality vertex pipeline stages.

**Tessellation Evaluation Shader Execution Environment**

If a successfully linked program object that contains a tessellation evaluation shader is made current by calling `UseProgram`, the executable version of the tessellation evaluation shader is used to process vertices produced by the tessellation primitive generator. During this processing, the shader may access the input patch processed by the primitive generator. When tessellation evaluation shader execution completes, a new vertex is assembled from the output variables written by the shader and is passed to subsequent pipeline stages.

There are several special considerations for tessellation evaluation shader execution described in the following sections.
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Texture Access

The Shader-Only Texturing subsection of section 2.11.8 describes texture lookup functionality accessible to a vertex shader. The texel fetch and texture size query functionality described there also applies to tessellation evaluation shaders.

Tessellation Evaluation Shader Inputs

Section 7.1 of the OpenGL Shading Language Specification describes the built-in variable array gl_in available as input to a tessellation evaluation shader. gl_in receives values from equivalent built-in output variables written by a previous shader (section 2.11.8). If a tessellation control shader active, the values of gl_in will be taken from tessellation control shader outputs. Otherwise, they will be taken from vertex shader outputs. Each array element of gl_in is a structure holding values for a specific vertex of the input patch. The length of gl_in is equal to the implementation-dependent maximum patch size (gl_MaxPatchVertices). Behavior is undefined if gl_in is indexed with a vertex index greater than or equal to the current patch size. The members of each element of the gl_in array are gl_Position, gl_PointSize, and gl_ClipDistance.

Tessellation evaluation shaders have available several other special input variables not replicated per-vertex and not contained in gl_in, including:

- The variables gl_PatchVerticesIn and gl_PrimitiveID are filled with the number of the vertices in the input patch and a primitive number, respectively. They behave exactly as the identically named inputs for tessellation control shaders.

- The variable gl_TessCoord is a three-component floating-point vector consisting of the \((u, v, w)\) coordinate of the vertex being processed by the tessellation evaluation shader. The values of \(u\), \(v\), and \(w\) are in the range \([0, 1]\), and vary linearly across the primitive being subdivided. For tessellation primitive modes of quads or isolines, the \(w\) value is always zero. The \((u, v, w)\) coordinates are generated by the tessellation primitive generator in a manner dependent on the primitive mode, as described in section 2.12.2. gl_TessCoord is not an array; it specifies the location of the vertex being processed by the tessellation evaluation shader, not of any vertex in the input patch.

- The variables gl_TessLevelOuter and gl_TessLevelInner are arrays holding outer and inner tessellation levels of the patch, as used by the tessellation primitive generator. If a tessellation control shader is active, the tessellation levels will be taken from the corresponding outputs of...
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the tessellation control shader. Otherwise, the default levels provided as
patch parameters are used. Tessellation level values loaded in these vari-
ables will be prior to the clamping and rounding operations performed by
the primitive generator as described in section 2.12.2. For triangular tes-
sellation, \texttt{gl\_TessLevelOuter[3]} and \texttt{gl\_TessLevelInner[1]} will
be undefined. For isoline tessellation, \texttt{gl\_TessLevelOuter[2]}, \texttt{gl\_TessLevelOuter[3]}, and both values in \texttt{gl\_TessLevelInner} are un-
defined.

A tessellation evaluation shader may also declare user-defined per-vertex input
variables. User-defined per-vertex input variables are declared with the qualifier \texttt{in}
and have a value for each vertex in the input patch. User-defined per-vertex input
varying variables have a value for each vertex and thus need to be declared as arrays
or inside input blocks declared as arrays. Declaring an array size is optional. If no
size is specified, it will be taken from the implementation-dependent maximum
patch size (\texttt{gl\_MaxPatchVertices}). If a size is specified, it must match the
maximum patch size; otherwise, a link error will occur. Since the array size may be
larger than the number of vertices found in the input patch, behavior is undefined
if a per-vertex input variable is accessed using an index greater than or equal to
the number of vertices in the input patch. The OpenGL Shading Language doesn’t
support multi-dimensional arrays; therefore, user-defined tessellation evaluation
shader inputs corresponding to vertex shader outputs declared as arrays must be
declared as array members of an input block that is itself declared as an array.

Additionally, a tessellation evaluation shader may declare per-patch input vari-
ables using the qualifier \texttt{patch in}. Unlike per-vertex inputs, per-patch inputs do
not correspond to any specific vertex in the patch, and are not indexed by vertex
number. Per-patch inputs declared as arrays have multiple values for the input
patch; similarly declared per-vertex inputs would indicate a single value for each
vertex in the output patch. User-defined per-patch input variables are filled with
corresponding per-patch output values written by the tessellation control shader. If
no tessellation control shader is active, all such variables are undefined.

Similarly to the limit on vertex shader output components (see section 2.11.7),
there is a limit on the number of components of built-in and user-defined per-vertex
and per-patch input variables that can be read by the tessellation evaluation shader,
given by the values of the implementation-dependent constants \texttt{MAX\_TESS\_EVALUATION\_INPUT\_COMPONENTS} and \texttt{MAX\_TESS\_PATCH\_COMPONENTS}, re-
spectively. The built-in inputs \texttt{gl\_TessLevelOuter} and \texttt{gl\_TessLevelInner}
amre not counted against the per-patch limit.

When a program is linked, all components of any varying and special vari-
able read by a tessellation evaluation shader will count against this limit. A pro-
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A program whose tessellation evaluation shader exceeds this limit may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.

Component counting rules for different variable types and variable declarations are the same as for MAX_VERTEX_OUTPUT_COMPONENTS. (see section 2.11.7).

**Tessellation Evaluation Shader Outputs**

Tessellation evaluation shaders have a number of built-in output variables used to pass values to equivalent built-in input variables read by subsequent shader stages or to subsequent fixed functionality vertex processing pipeline stages. These variables are `gl_Position`, `gl_PointSize`, and `gl_ClipDistance`, and all behave identically to equivalently named vertex shader outputs (see section 2.11.8). A tessellation evaluation shader may also declare user-defined per-vertex output variables.

Similarly to the limit on vertex shader output components (see section 2.11.7), there is a limit on the number of components of built-in and user-defined output variables that can be written by the tessellation evaluation shader, given by the values of the implementation-dependent constant `MAX_TESS_EVALUATION_OUTPUT_COMPONENTS`.

When a program is linked, all components of any varying and special variable written by a tessellation evaluation shader will count against this limit. A program whose tessellation evaluation shader exceeds this limit may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.

Counting rules for different variable types and variable declarations are the same as for MAX_VERTEX_OUTPUT_COMPONENTS. (see section 2.11.7).

2.13 Geometry Shaders

After vertices are processed, they are arranged into primitives, as described in section 2.6.1. This section describes optional geometry shaders, an additional pipeline stage defining operations to further process those primitives. Geometry shaders are defined by source code in the OpenGL Shading Language, in the same manner as vertex shaders. They operate on a single primitive at a time and emit one or more output primitives, all of the same type, which are then processed like an equivalent OpenGL primitive specified by the application. The original primitive is discarded after geometry shader execution. The inputs available to a geometry shader are the transformed attributes of all the vertices that belong to the primitive. Additional...
adjacency primitives are available which also make the transformed attributes of neighboring vertices available to the shader. The results of the shader are a new set of transformed vertices, arranged into primitives by the shader.

The geometry shader pipeline stage is inserted after primitive assembly, prior to transform feedback (section 2.17).

Geometry shaders are created as described in section 2.11.1 using a type of GEOMETRY_SHADER. They are attached to and used in program objects as described in section 2.11.2. When the program object currently in use includes a geometry shader, its geometry shader is considered active, and is used to process primitives. If the program object has no geometry shader, this stage is bypassed.

A program object that includes a geometry shader must also include a vertex shader; otherwise a link error will occur.

2.13.1 Geometry Shader Input Primitives

A geometry shader can operate on one of five input primitive types. Depending on the input primitive type, one to six input vertices are available when the shader is executed. Each input primitive type supports a subset of the primitives provided by the GL. If a geometry shader is active, any command that transfers vertices to the GL will generate an INVALID_OPERATION error if the primitive mode parameter is incompatible with the input primitive type of the currently active program object, as discussed below.

A geometry shader that accesses more input vertices than are available for a given input primitive type can be successfully compiled, because the input primitive type is not part of the shader object. However, a program object containing a shader object that accesses more input vertices than are available for the input primitive type of the program object will not link.

The input primitive type is specified in the geometry shader source code using an input layout qualifier, as described in the OpenGL Shading Language Specification. A program will fail to link if the input primitive type is not specified by any geometry shader object attached to the program, or if it is specified differently by multiple geometry shader objects. The input primitive type may be queried by calling GetProgramiv with the symbolic constant GEOMETRY_INPUT_TYPE. The supported types and the corresponding OpenGL Shading Language input layout qualifier keywords are:

**Points (points)**

Geometry shaders that operate on points are valid only for the POINTS primitive type. There is only a single vertex available for each geometry shader invocation.
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Lines (lines)
Geometry shaders that operate on line segments are valid only for the LINES, LINE_STRIP, and LINE_LOOP primitive types. There are two vertices available for each geometry shader invocation. The first vertex refers to the vertex at the beginning of the line segment and the second vertex refers to the vertex at the end of the line segment. See also section 2.13.4.

Lines with Adjacency (lines_adjacency)
Geometry shaders that operate on line segments with adjacent vertices are valid only for the LINES_ADJACENCY and LINE_STRIP_ADJACENCY primitive types. There are four vertices available for each program invocation. The second vertex refers to attributes of the vertex at the beginning of the line segment and the third vertex refers to the vertex at the end of the line segment. The first and fourth vertices refer to the vertices adjacent to the beginning and end of the line segment, respectively.

Triangles (triangles)
Geometry shaders that operate on triangles are valid for the TRIANGLES, TRIANGLE_STRIP and TRIANGLE_FAN primitive types. There are three vertices available for each program invocation. The first, second and third vertices refer to attributes of the first, second and third vertex of the triangle, respectively.

Triangles with Adjacency (triangles_adjacency)
Geometry shaders that operate on triangles with adjacent vertices are valid for the TRIANGLES_ADJACENCY and TRIANGLE_STRIP_ADJACENCY primitive types. There are six vertices available for each program invocation. The first, third and fifth vertices refer to attributes of the first, second and third vertex of the triangle, respectively. The second, fourth and sixth vertices refer to attributes of the vertices adjacent to the edges from the first to the second vertex, from the second to the third vertex, and from the third to the first vertex, respectively.

2.13.2 Geometry Shader Output Primitives

A geometry shader can generate primitives of one of three types. The supported output primitive types are points (POINTS), line strips (LINE_STRIP), and triangle strips (TRIANGLE_STRIP). The vertices output by the geometry shader are assembled into points, lines, or triangles based on the output primitive type in the manner described in section 2.6.1. The resulting primitives are then further processed as described in section 2.13.4. If the number of vertices emitted by the geometry shader is not sufficient to produce a single primitive, nothing is drawn. The number
of vertices output by the geometry shader is limited to a maximum count specified in the shader.

The output primitive type and maximum output vertex count are specified in the geometry shader source code using an output layout qualifier, as described in section 4.3.8.1 of the OpenGL Shading Language Specification. A program will fail to link if either the output primitive type or maximum output vertex count are not specified by any geometry shader object attached to the program, or if they are specified differently by multiple geometry shader objects. The output primitive type and maximum output vertex count of a linked program may be queried by calling `GetProgramiv` with the symbolic constants `GEOMETRY_OUTPUT_TYPE` and `GEOMETRY_VERTICES_OUT`, respectively.

### 2.13.3 Geometry Shader Variables

Geometry shaders can access uniforms belonging to the current program object. The amount of storage available for geometry shader uniform variables is specified by the implementation dependent constant `MAX_GEOMETRY_UNIFORM_COMPONENTS`. This value represents the number of individual floating-point, integer, or boolean values that can be held in uniform variable storage for a geometry shader. A link error will be generated if an attempt is made to utilize more than the space available for geometry shader uniform variables. Uniforms are manipulated as described in section 2.11.4. Geometry shaders also have access to samplers to perform texturing operations, as described in sections 2.11.6 and 3.8.

Geometry shaders can access the transformed attributes of all vertices for their input primitive type using input varying variables. A vertex shader writing to output varying variables generates the values of these input varying variables, including values for built-in as well as user-defined varying variables. Values for any varying variables that are not written by a vertex shader are undefined. Additionally, a geometry shader has access to a built-in variable that holds the ID of the current primitive. This ID is generated by the primitive assembly stage that sits in between the vertex and geometry shader.

Additionally, geometry shaders can write to one or more varying variables for each vertex they output. These values are optionally flatshaded (using the OpenGL Shading Language varying qualifier `flat`) and clipped, then the clipped values interpolated across the primitive (if not flatshaded). The results of these interpolations are available to the fragment shader.
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2.13.4 Geometry Shader Execution Environment

If a successfully linked program object that contains a geometry shader is made current by calling `UseProgram`, the executable version of the geometry shader is used to process primitives resulting from the primitive assembly stage.

The following operations are applied to the primitives that are the result of executing a geometry shader:

- Perspective division on clip coordinates (section 2.14).
- Viewport mapping, including depth range scaling (section 2.14.1).
- Flatshading (section 2.19).
- Clipping, including client-defined half-spaces (section 2.20).
- Front face determination (section 3.6.1).
- Generic attribute clipping (section 2.20.1).

There are several special considerations for geometry shader execution described in the following sections.

Texture Access

The Shader Only Texturing subsection of section 2.11.8 describes texture lookup functionality accessible to a vertex shader. The texel fetch and texture size query functionality described there also applies to geometry shaders.

Instanced Geometry Shaders

For each input primitive received by the geometry shader pipeline stage, the geometry shader may be run once or multiple times. The number of times a geometry shader should be executed for each input primitive may be specified using a layout qualifier in a geometry shader of a linked program. If the invocation count is not specified in any layout qualifier, the invocation count will be one.

Each separate geometry shader invocation is assigned a unique invocation number. For a geometry shader with $N$ invocations, each input primitive spawns $N$ invocations, numbered 0 through $N-1$. The built-in uniform `gl_InvocationID` may be used by a geometry shader invocation to determine its invocation number.

When executing instanced geometry shaders, the output primitives generated from each input primitive are passed to subsequent pipeline stages using the shader...
invocation number to order the output. The first primitives received by the subse-
quent pipeline stages are those emitted by the shader invocation numbered zero,
followed by those from the shader invocation numbered one, and so forth. Additionally, all output primitives generated from a given input primitive are passed to
subsequent pipeline stages before any output primitives generated from subsequent
input primitives.

**Geometry Shader Vertex Streams**

Geometry shaders may emit primitives to multiple independent vertex streams.
Each vertex emitted by the geometry shader is directed at one of the vertex streams.
As vertices are received on each stream, they are arranged into primitives of the
type specified by the geometry shader output primitive type. The shading language
built-in functions `EndPrimitive` and `EndStreamPrimitive` may be used to
end the primitive being assembled on a given vertex stream and start a new empty
primitive of the same type. If an implementation supports $N$ vertex streams, the
individual streams are numbered 0 through $N - 1$. There is no requirement on the
order of the streams to which vertices are emitted, and the number of vertices emit-
ted to each stream may be completely independent, subject only to implementation-
dependent output limits.

The primitives emitted to all vertex streams are passed to the transform feed-
back stage to be captured and written to buffer objects in the manner specified
by the transform feedback state. The primitives emitted to all streams but stream
zero are discarded after transform feedback. Primitives emitted to stream zero are
passed to subsequent pipeline stages for clipping, rasterization, and subsequent
fragment processing.

Geometry shaders that emit vertices to multiple vertex streams are currently
limited to using only the `points` output primitive type. A program will fail to
link if it includes a geometry shader that calls the `EmitStreamVertex` built-in
function and has any other output primitive type parameter.

**Geometry Shader Inputs**

Section 7.1 of the OpenGL Shading Language Specification describes the built-in
variable array `gl_in[]` available as input to a geometry shader. `gl_in[]` receives
values from equivalent built-in output variables written by the vertex shader, and
each array element of `gl_in[]` is a structure holding values for a specific vertex of
the input primitive. The length of `gl_in[]` is determined by the geometry shader
input type (see section 2.13.1). The members of each element of the `gl_in[]`
array are:

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- Structure member `gl_ClipDistance[]` holds the per-vertex array of clip distances, as written by the vertex shader to its built-in output variable `gl_ClipDistance[]`.

- Structure member `gl_PointSize` holds the per-vertex point size written by the vertex shader to its built-in output varying variable `gl_PointSize`. If the vertex shader does not write `gl_PointSize`, the value of `gl_PointSize` is undefined, regardless of the value of the enable `PROGRAM_POINT_SIZE`.

- Structure member `gl_Position` holds the per-vertex position, as written by the vertex shader to its built-in output variable `gl_Position`. Note that writing to `gl_Position` from either the vertex or geometry shader is optional (also see section 7.1 of the OpenGL Shading Language Specification).

Geometry shaders also have available the built-in special variable `gl_PrimitiveIDIn`, which is not an array and has no vertex shader equivalent. It is filled with the number of primitives processed by the drawing command which generated the input vertices. The first primitive generated by a drawing command is numbered zero, and the primitive ID counter is incremented after every individual point, line, or triangle primitive is processed. For triangles drawn in point or line mode, the primitive ID counter is incremented only once, even though multiple points or lines may eventually be drawn. Restarting a primitive topology using the primitive restart index has no effect on the primitive ID counter.

Similarly to the built-in varying variables, each user-defined input varying variable has a value for each vertex and thus needs to be declared as arrays or inside input blocks declared as arrays. Declaring an array size is optional. If no size is specified, it will be inferred by the linker from the input primitive type. If a size is specified, it must match the number of vertices for the input primitive type; otherwise, a link error will occur. The OpenGL Shading Language doesn’t support multi-dimensional arrays; therefore, user-defined geometry shader inputs corresponding to vertex shader outputs declared as arrays must be declared as array members of an input block that is itself declared as an array. See sections 4.3.6 and 7.6 of the OpenGL Shading Language Specification for more information.

Similarly to the limit on vertex shader output components (see section 2.11.7), there is a limit on the number of components of built-in and user-defined input varying variables that can be read by the geometry shader, given by the value of the implementation-dependent constant `MAX_GEOMETRY_INPUT_COMPONENTS`.

When a program is linked, all components of any varying and special variable read by a geometry shader will count against this limit. A program whose geometry
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shader exceeds this limit may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.

Component counting rules for different variable types and variable declarations are the same as for MAX_VERTEX_OUTPUT_COMPONENTS. (see section 2.11.7).

Geometry Shader Outputs

A geometry shader is limited in the number of vertices it may emit per invocation. The maximum number of vertices a geometry shader can possibly emit is specified in the geometry shader source and may be queried after linking by calling GetProgramiv with the symbolic constant GEOMETRY_VERTICES_OUT. If a single invocation of a geometry shader emits more vertices than this value, the emitted vertices may have no effect.

There are two implementation-dependent limits on the value of GEOMETRY_VERTICES_OUT; it may not exceed the value of MAX_GEOMETRY_OUTPUT_VERTICES, and the product of the total number of vertices and the sum of all components of all active varying variables may not exceed the value of MAX_GEOMETRY_TOTAL_OUTPUT_COMPONENTS. LinkProgram will fail if it determines that the total component limit would be violated.

A geometry shader can write to built-in as well as user-defined varying variables. These values are expected to be interpolated across the primitive it outputs, unless they are specified to be flat shaded. To enable seamlessly inserting or removing a geometry shader from a program object, the rules, names and types of the output built-in varying variables and user-defined varying variables are the same as for the vertex shader. Refer to section 2.11.7, and sections 4.3.6, 7.1, and 7.6 of the OpenGL Shading Language Specification for more detail.

After a geometry shader emits a vertex, all built-in and user-defined output variables are undefined, as described in section 8.10 of the OpenGL Shading Language Specification.

The built-in special variable gl_Position is intended to hold the homogeneous vertex position. Writing gl_Position is optional.

The built-in special variable gl_ClipDistance holds the clip distance used in the clipping stage, as described in section 2.20.

The built-in special variable gl_PointSize, if written, holds the size of the point to be rasterized, measured in pixels.

The built-in special variable gl_PrimitiveID holds the primitive ID counter read by the fragment shader, replacing the value of gl_PrimitiveID generated by drawing commands when no geometry shader is active. The geometry shader must write to gl_PrimitiveID for the provoking vertex (see section 2.19) of a
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primitive being generated, or the primitive ID counter read by the fragment shader for that primitive is undefined.

The built-in special variable \texttt{gl\_Layer} is used in layered rendering, and discussed further in the next section.

Similarly to the limit on vertex shader output components (see section 2.11.7), there is a limit on the number of components of built-in and user-defined output varying variables that can be written by the geometry shader, given by the value of the implementation-dependent constant \texttt{MAX\_GEOMETRY\_OUTPUT\_COMPONENTS}.

When a program is linked, all components of any varying and special variable written by a geometry shader will count against this limit. A program whose geometry shader exceeds this limit may fail to link, unless device-dependent optimizations are able to make the program fit within available hardware resources.

Component counting rules for different variable types and variable declarations are the same as for \texttt{MAX\_VERTEX\_OUTPUT\_COMPONENTS}. (see section 2.11.7).

Layered Rendering

Geometry shaders can be used to render to one of several different layers of cube map textures, three-dimensional textures, or one-or two-dimensional texture arrays. This functionality allows an application to bind an entire complex texture to a framebuffer object, and render primitives to arbitrary layers computed at run time. For example, it can be used to project and render a scene onto all six faces of a cubemap texture in one pass. The layer to render to is specified by writing to the built-in output variable \texttt{gl\_Layer}. Layered rendering requires the use of framebuffer objects (see section 4.4.7).

Primitive Type Mismatches and Drawing Commands

A geometry shader will fail to execute if a mismatch exists between the type of primitive being drawn and the input primitive type of the shader. If it cannot be executed then no fragments will be rendered, and the error \texttt{INVALID\_OPERATION} will be generated.

This error is generated by any command that transfers vertices to the GL if a geometry shader is active and:

- the input primitive type of the current geometry shader is \texttt{POINTS} and \texttt{mode} is not \texttt{POINTS};
- the input primitive type of the current geometry shader is \texttt{LINES} and \texttt{mode} is not \texttt{LINES}, \texttt{LINE\_STRIP}, or \texttt{LINE\_LOOP};
2.14 Coordinate Transformations

Clip coordinates for a vertex result from vertex or, if active, geometry shader execution, which yields a vertex coordinate \( \text{gl\_Position} \). Perspective division on clip coordinates yields normalized device coordinates, followed by a viewport transformation to convert these coordinates into window coordinates.

If a vertex in clip coordinates is given by

\[
\begin{pmatrix}
  x_c \\
  y_c \\
  z_c \\
  w_c
\end{pmatrix}
\]

then the vertex’s normalized device coordinates are

\[
\begin{pmatrix}
  x_d \\
  y_d \\
  z_d
\end{pmatrix} = \frac{1}{w_c} \begin{pmatrix}
  x_c \\
  y_c \\
  z_c \\
  w_c
\end{pmatrix}.
\]

2.14.1 Controlling the Viewport

The viewport transformation is determined by the viewport’s width and height in pixels, \( p_x \) and \( p_y \), respectively, and its center \((o_x, o_y)\) (also in pixels). The vertex’s window coordinates, \( \begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix} \), are given by

\[
\begin{pmatrix}
  x_w \\
  y_w \\
  z_w
\end{pmatrix} = \begin{pmatrix}
  \frac{p_x}{2} x_d + o_x \\
  \frac{p_y}{2} y_d + o_y \\
  \frac{f-n}{2} z_d + \frac{n+f}{2}
\end{pmatrix}.
\]

The factor and offset applied to \( z_d \) encoded by \( n \) and \( f \) are set using

\[
\text{void DepthRange(clampd } n, \text{ clampd } f); \]

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$z_w$ is represented as either fixed- or floating-point depending on whether the framebuffer’s depth buffer uses a fixed- or floating-point representation. If the depth buffer uses fixed-point, we assume that it represents each value $k/(2^m - 1)$, where $k \in \{0, 1, \ldots, 2^m - 1\}$, as $k$ (e.g. 1.0 is represented in binary as a string of all ones). The parameters $n$ and $f$ are clamped to the range $[0, 1]$, as are all arguments of type clampd or clampf.

Viewport transformation parameters are specified using

```c
void Viewport(int x, int y, sizei w, sizei h);
```

where $x$ and $y$ give the $x$ and $y$ window coordinates of the viewport’s lower left corner and $w$ and $h$ give the viewport’s width and height, respectively. The viewport parameters shown in the above equations are found from these values as

$$
\begin{align*}
    o_x &= x + \frac{w}{2} \\
    o_y &= y + \frac{h}{2} \\
    p_x &= w \\
    p_y &= h.
\end{align*}
$$

Viewport width and height are clamped to implementation-dependent maximums when specified. The maximum width and height may be found by issuing an appropriate Get command (see chapter 6). The maximum viewport dimensions must be greater than or equal to the larger of the visible dimensions of the display being rendered to (if a display exists), and the largest renderbuffer image which can be successfully created and attached to a framebuffer object (see chapter 4). INVALID_VALUE is generated if either $w$ or $h$ is negative.

The state required to implement the viewport transformation is four integers and two clamped floating-point values. In the initial state, $w$ and $h$ are set to the width and height, respectively, of the window into which the GL is to do its rendering. If the default framebuffer is bound but no default framebuffer is associated with the GL context (see chapter 4), then $w$ and $h$ are initially set to zero. $o_x$, $o_y$, $n$, and $f$ are set to $\frac{w}{2}$, $\frac{h}{2}$, 0.0, and 1.0, respectively.

## 2.15 Asynchronous Queries

Asynchronous queries provide a mechanism to return information about the processing of a sequence of GL commands. There are four query types supported by the GL. Primitive queries with a target of PRIMITIVES_GENERATED (see section 2.18) return information on the number of primitives processed by the GL. Primitive queries with a target of TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN (see section 2.18) return information on the number of primitives written...
2.15. ASYNCHRONOUS QUERIES

to one more buffer objects. Occlusion queries (see section 4.1.6) count the number of fragments or samples that pass the depth test, or set a boolean to true when any fragments or samples pass the depth test. Timer queries (see section 5.1) record the amount of time needed to fully process these commands or the current time of the GL.

The results of asynchronous queries are not returned by the GL immediately after the completion of the last command in the set; subsequent commands can be processed while the query results are not complete. When available, the query results are stored in an associated query object. The commands described in section 6.1.7 provide mechanisms to determine when query results are available and return the actual results of the query. The name space for query objects is the unsigned integers, with zero reserved by the GL.

Each type of query supported by the GL has an active query object name. If the active query object name for a query type is non-zero, the GL is currently tracking the information corresponding to that query type and the query results will be written into the corresponding query object. If the active query object for a query type name is zero, no such information is being tracked.

A query object is created and made active by calling

```c
void BeginQuery( enum target, uint id );
```

target indicates the type of query to be performed; valid values of target are defined in subsequent sections. If id is an unused query object name, the name is marked as used and associated with a new query object of the type specified by target. Otherwise id must be the name of an existing query object of that type.

**BeginQuery** fails and an INVALID_OPERATION error is generated if id is not a name returned from a previous call to GenQueries, or if such a name has since been deleted with DeleteQueries.

**BeginQuery** sets the active query object name for the query type given by target to id. If **BeginQuery** is called with an id of zero, if the active query object name for target is non-zero (for the targets SAMPLES_PASSED and ANY_SAMPLES_PASSED, if the active query for either target is non-zero), if id is the name of an existing query object whose type does not match target, if id is the active query object name for any query type, or if id is the active query object for conditional rendering (see section 2.16), the error INVALID_OPERATION is generated.

Query targets also support multiple indexed queries. A query object may be created and made active on an indexed query target by calling:

```c
void BeginQueryIndexed( enum target, uint index, uint id );
```
target indicates the type of query to be performed as in BeginQuery. index is the index of the query and must be between 0 and a target-specific maximum. If index is outside of this range, the error INVALID_VALUE is generated. The number of indexed queries supported by specific targets is one, unless indicated otherwise in following sections. Calling BeginQuery is equivalent to calling BeginQueryIndexed with index set to zero.

The command

```c
void EndQuery( enum target );
```

marks the end of the sequence of commands to be tracked for the query type given by target. The active query object for target is updated to indicate that query results are not available, and the active query object name for target is reset to zero. When the commands issued prior to EndQuery have completed and a final query result is available, the query object active when EndQuery is called is updated by the GL. The query object is updated to indicate that the query results are available and to contain the query result. If the active query object name for target is zero when EndQuery is called, the error INVALID_OPERATION is generated.

The command

```c
void EndQueryIndexed( enum target, uint index );
```

may be used to mark the end of the query currently active at index index of target, and must be between zero and the target-specific maximum. If index is outside of this range, the error INVALID_VALUE is generated. Calling EndQuery is equivalent to calling EndQueryIndexed with index set to zero.

The command

```c
void GenQueries( sizei n, uint *ids );
```

returns n previously unused query object names in ids. These names are marked as used, but no object is associated with them until the first time they are used by BeginQuery.

Query objects are deleted by calling

```c
void DeleteQueries( sizei n, const uint *ids );
```

ids contains n names of query objects to be deleted. After a query object is deleted, its name is again unused. Unused names in ids are silently ignored. If an active query object is deleted its name immediately becomes unused, but the underlying object is not deleted until it is no longer active (see section D.1).
Query objects contain two pieces of state: a single bit indicating whether a query result is available, and an integer containing the query result value. The number of bits used to represent the query result is implementation-dependent. In the initial state of a query object, the result is available and its value is zero.

The necessary state for each query type is an unsigned integer holding the active query object name (zero if no query object is active), and any state necessary to keep the current results of an asynchronous query in progress. Only a single type of occlusion query can be active at one time, so the required state for occlusion queries is shared.

### 2.16 Conditional Rendering

Conditional rendering can be used to discard rendering commands based on the result of an occlusion query. Conditional rendering is started and stopped using the commands

```c
void BeginConditionalRender( uint id, enum mode);
void EndConditionalRender( void);
```

`id` specifies the name of an occlusion query object whose results are used to determine if the rendering commands are discarded. If the result (`SAMPLES_PASSED`) of the query is zero, or if the result (`ANY_SAMPLES_PASSED`) is false, all rendering commands between `BeginConditionalRender` and the corresponding `EndConditionalRender` are discarded. In this case, all vertex array commands (see section 2.8), as well as `Clear` and `ClearBuffer*` (see section 4.2.3), have no effect. The effect of commands setting current vertex state, such as `VertexAttrib`, are undefined. If the result (`SAMPLES_PASSED`) of the query is non-zero, or if the result (`ANY_SAMPLES_PASSED`) is true, such commands are not discarded.

`mode` specifies how `BeginConditionalRender` interprets the results of the occlusion query given by `id`. If `mode` is `QUERY_WAIT`, the GL waits for the results of the query to be available and then uses the results to determine if subsequent rendering commands are discarded. If `mode` is `QUERY_NO_WAIT`, the GL may choose to unconditionally execute the subsequent rendering commands without waiting for the query to complete.

If `mode` is `QUERY_BY_REGION_WAIT`, the GL will also wait for occlusion query results and discard rendering commands if the result of the occlusion query is zero. If the query result is non-zero, subsequent rendering commands are executed, but the GL may discard the results of the commands for any region of the framebuffer that did not contribute to the sample count in the specified occlusion query.
Any such discarding is done in an implementation-dependent manner, but the rendering command results may not be discarded for any samples that contributed to the occlusion query sample count. If \texttt{mode} is \texttt{QUERY\_BY\_REGION\_NO\_WAIT}, the GL operates as in \texttt{QUERY\_BY\_REGION\_WAIT}, but may choose to unconditionally execute the subsequent rendering commands without waiting for the query to complete.

If \texttt{BeginConditionalRender} is called while conditional rendering is in progress, the error \texttt{INVALID\_OPERATION} is generated. If \texttt{id} is not the name of an existing query object, the error \texttt{INVALID\_VALUE} is generated. If \texttt{id} is the name of a query object with a target other than \texttt{SAMPLES\_PASSED} or \texttt{ANY\_SAMPLES\_PASSED}, or if \texttt{id} is the name of a query currently in progress, the error \texttt{INVALID\_OPERATION} is generated. If \texttt{EndConditionalRender} is called while conditional rendering is not in progress, the error \texttt{INVALID\_OPERATION} is generated.

\section{Transform Feedback}

In transform feedback mode, attributes of the vertices of transformed primitives processed by a vertex shader, or primitives generated by a geometry shader if one is active, are written out to one or more buffer objects. The vertices are fed back after vertex color clamping, but before flatshading and clipping. If a geometry shader is active, the vertices recorded are those emitted from the geometry shader. The transformed vertices may be optionally discarded after being stored into one or more buffer objects, or they can be passed on down to the clipping stage for further processing. The set of attributes captured is determined when a program is linked.

\subsection{Transform Feedback Objects}

The set of buffer objects used to capture vertex attributes and related state are stored in a transform feedback object. If a vertex or geometry shader is active, the set of attributes captured in transform feedback mode is determined using the state of the active program object; otherwise, it is taken from the state of the currently bound transform feedback object, as described below. The name space for transform feedback objects is the unsigned integers. The name zero designates the default transform feedback object.

The command

\begin{verbatim}
void GenTransformFeedbacks(sizei n, uint *ids);
\end{verbatim}
2.17. TRANSFORM FEEDBACK

returns \( n \) previously unused transform feedback object names in \( ids \). These names are marked as used, for the purposes of \texttt{GenTransformFeedbacks} only, but they acquire transform feedback state only when they are first bound.

Transform feedback objects are deleted by calling

\[
\texttt{void DeleteTransformFeedbacks(sizei } n, \texttt{ const uint } *\texttt{ids});
\]

\( ids \) contains \( n \) names of transform feedback objects to be deleted. After a transform feedback object is deleted it has no contents, and its name is again unused. Unused names in \( ids \) are silently ignored, as is the value zero. The default transform feedback object cannot be deleted. If an active transform feedback object is deleted its name immediately becomes unused, but the underlying object is not deleted until it is no longer active (see section D.1).

A transform feedback object is created by binding a name returned by \texttt{GenTransformFeedbacks} with the command

\[
\texttt{void BindTransformFeedback(enum target, uint id});
\]

\texttt{target} must be \texttt{TRANSFORM_FEEDBACK} and \texttt{id} is the transform feedback object name. The resulting transform feedback object is a new state vector, initialized to the default state values described in table 6.38. Additionally, the new object is bound to the GL state vector and is used for subsequent transform feedback operations.

\texttt{BindTransformFeedback} can also be used to bind an existing transform feedback object to the GL state for subsequent use. If the bind is successful, no change is made to the state of the newly bound transform feedback object and any previous binding to \texttt{target} is broken.

While a transform feedback buffer object is bound, GL operations on the target to which it is bound affect the bound transform feedback object, and queries of the target to which a transform feedback object is bound return state from the bound object. When buffer objects are bound for transform feedback, they are attached to the currently bound transform feedback object. Buffer objects are used for transform feedback only if they are attached to the currently bound transform feedback object.

In the initial state, a default transform feedback object is bound and treated as a transform feedback object with a name of zero. That object is bound any time \texttt{BindTransformFeedback} is called with \texttt{id} of zero.

The error \texttt{INVALID_OPERATION} is generated by \texttt{BindTransformFeedback} if the transform feedback operation is active on the currently bound transform feedback object, and that operation is not paused (as described below).
2.17. TRANSFORM FEEDBACK

*BindTransformFeedback* fails and an *INVALID_OPERATION* error is generated if *id* is not zero or a name returned from a previous call to *GenTransformFeedbacks*, or if such a name has since been deleted with *DeleteTransformFeedbacks*.

2.17.2 Transform Feedback Primitive Capture

Transform feedback for the currently bound transform feedback object is started and finished by calling

```c
void BeginTransformFeedback( enum primitiveMode );
```

and

```c
void EndTransformFeedback( void );
```

respectively. Transform feedback is said to be active after a call to *BeginTransformFeedback* and inactive after a call to *EndTransformFeedback*. *primitiveMode* is one of *_TRIANGLES*, *LINES*, or *POINTS*, and specifies the output type of primitives that will be recorded into the buffer objects bound for transform feedback (see below). *primitiveMode* restricts the primitive types that may be rendered while transform feedback is active, as shown in table 2.13.

Transform feedback commands must be paired; the error *INVALID_OPERATION* is generated by *BeginTransformFeedback* if transform feedback is active, and by *EndTransformFeedback* if transform feedback is inactive. Transform feedback is initially inactive.

Transform feedback operations for the currently bound transform feedback object may be paused and resumed by calling

```c
void PauseTransformFeedback( void );
```

and

```c
void ResumeTransformFeedback( void );
```

respectively. When transform feedback operations are paused, transform feedback is still considered active and changing most transform feedback state related to the object results in an error. However, a new transform feedback object may be bound while transform feedback is paused. The error *INVALID_OPERATION* is generated by *PauseTransformFeedback* if the currently bound transform feedback is...
2.17. TRANSFORM FEEDBACK

Table 2.13: Legal combinations of the transform feedback primitive mode, as passed to `BeginTransformFeedback`, and the current primitive mode.

<table>
<thead>
<tr>
<th>Transform Feedback primitiveMode</th>
<th>Allowed render primitive modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>POINTS</td>
<td>POINTS</td>
</tr>
<tr>
<td>LINES</td>
<td>LINES, LINE_LOOP, LINE_STRIP</td>
</tr>
<tr>
<td>TRIANGLES</td>
<td>TRIANGLES, TRIANGLE_STRIP, TRIANGLE_FAN</td>
</tr>
</tbody>
</table>

not active or is paused. The error **INVALID_OPERATION** is generated by `ResumeTransformFeedback` if the currently bound transform feedback is not active or is not paused.

When transform feedback is active and not paused, all geometric primitives generated must be compatible with the value of `primitiveMode` passed to `BeginTransformFeedback`. The error **INVALID_OPERATION** is generated by `DrawArrays` and the other drawing commands defined in section 2.8.3 if `mode` is not one of the allowed modes in table 2.13. If a tessellation evaluation or geometry shader is active, the type of primitive emitted by that shader is used instead of of the `mode` parameter passed to drawing commands for the purposes of this error check. If tessellation evaluation and geometry shaders are both active, the output primitive type of the geometry shader will be used for the purposes of this error. Any primitive type may be used while transform feedback is paused.

Transform feedback mode captures the values of varying variables written by the vertex shader (or, if active, geometry shader).

Regions of buffer objects are bound as the targets of transform feedback by calling one of the commands `BindBufferRange` or `BindBufferBase` (see section 2.9.1) with `target` set to `TRANSFORM_FEEDBACK_BUFFER`. In addition to the general errors described in section 2.9.1, `BindBufferRange` will generate an **INVALID_VALUE** error if `index` is greater than or equal to the value of `MAX_TRANSFORM_FEEDBACK_BUFFERS`, or if either `offset` or `size` is not a multiple of 4.

When an individual point, line, or triangle primitive reaches the transform feedback stage while transform feedback is active and not paused, the values of the specified varying variables of the vertex are appended to the buffer objects bound to the transform feedback binding points. The attributes of the first vertex received after `BeginTransformFeedback` are written at the starting offsets of the bound buffer objects set by `BindBufferRange`, and subsequent vertex attributes are appended to the buffer object. When capturing line and triangle primitives, all at-
tributes of the first vertex are written first, followed by attributes of the subsequent vertices. When writing varying variables that are arrays, individual array elements are written in order. For multi-component varying variables, elements of varying arrays, or transformed vertex attributes, the individual components are written in order. The value for any attribute specified to be streamed to a buffer object but not actually written by a vertex or geometry shader is undefined. The results of appending a varying variable to a transform feedback buffer are undefined if any component of that variable would be written at an offset not aligned to the size of the component.

When transform feedback is paused, no vertices are recorded. When transform feedback is resumed, subsequent vertices are appended to the buffer objects bound immediately following the last vertex written while transform feedback was paused.

Individual lines or triangles of a strip or fan primitive will be extracted and recorded separately. Incomplete primitives are not recorded.

Transform feedback can operate in either INTERLEAVED_ATTRIBS or SEPARATE_ATTRIBS mode.

In INTERLEAVED_ATTRIBS mode, the values of one or more varying variables written by a vertex or geometry shader are written, interleaved, into the buffer objects bound to one or more transform feedback binding points. The list of varyings provided for capture in interleaved mode may include special separator values, which can be used to direct subsequent varyings to the next binding point. Each non-separator varying is written to the binding point numbered \( n \), where \( n \) is the number of separator values preceding it in the list. If more than one varying variable is written to a buffer object, they will be recorded in the order specified by \texttt{TransformFeedbackVaryings} (see section 2.11.7).

In SEPARATE_ATTRIBS mode, the first varying variable or transformed vertex attribute specified by \texttt{TransformFeedbackVaryings} is written to the first transform feedback binding point; subsequent varying variables are written to the subsequent transform feedback binding points. The total number of variables that may be captured in separate mode is given by \texttt{MAX_TRANSFORM_FEEDBACK_SEPARATE_ATTRIBS}.

When using a geometry shader or program that writes vertices to multiple vertex streams, each vertex emitted may trigger a new primitive in the vertex stream to which it was emitted. If transform feedback is active, the varyings of the primitive are written to a transform feedback binding point if and only if the varyings directed at that binding point belong to the vertex stream in question. All varyings assigned to a given binding point are required to come from a single vertex stream.

If recording the vertices of a primitive to the buffer objects being used for transform feedback purposes would result in either exceeding the limits of any buffer...
object’s size, or in exceeding the end position \( \text{offset} + \text{size} - 1 \), as set by \texttt{BindBufferRange}, then no vertices of that primitive are recorded in any buffer object, and the counter corresponding to the asynchronous query target \texttt{TRANSFORM\_FEEDBACK\_PRIMITIVES\_WRITTEN} (see section 2.18) is not incremented.

Transform feedback binding points zero through \textit{count} minus one must have buffer objects bound when \texttt{BeginTransformFeedback} is called, where \textit{count} is the parameter passed to \texttt{TransformFeedbackVaryings} in separate mode, or one more than the number of \texttt{gl\_NextBuffer} elements in the \textit{varyings} parameter to \texttt{TransformFeedbackVaryings} in interleaved mode. The error \texttt{INVALID\_OPERATION} is generated by \texttt{BeginTransformFeedback} if any of these binding points does not have a buffer object bound. In interleaved mode, only the first buffer object binding point is ever written to. The error \texttt{INVALID\_OPERATION} is also generated by \texttt{BeginTransformFeedback} if no binding points would be used, either because no program object is active or because the active program object has specified no varying variables to record.

When \texttt{BeginTransformFeedback} is called with an active program object containing a vertex or geometry shader, the set of varying variables captured during transform feedback is taken from the active program object and may not be changed while transform feedback is active. That program object must be active until the \texttt{EndTransformFeedback} is called, except while the transform feedback object is paused. The error \texttt{INVALID\_OPERATION} is generated:

- by \texttt{TransformFeedbackVaryings} if the current transform feedback object is active, even if paused;
- by \texttt{UseProgram} if the current transform feedback object is active and not paused;
- by \texttt{LinkProgram} if \textit{program} is the name of a program being used by one or more transform feedback objects, even if the objects are not currently bound or are paused;
- by \texttt{ResumeTransformFeedback} if the program object being used by the current transform feedback object is not active; and
- by \texttt{BindBufferRange}, \texttt{BindBufferOffset}, or \texttt{BindBufferBase} if \textit{target} is \texttt{TRANSFORM\_FEEDBACK\_BUFFER} and transform feedback is currently active.

Buffers should not be bound or in use for both transform feedback and other purposes in the GL. Specifically, if a buffer object is simultaneously bound to a transform feedback buffer binding point and elsewhere in the GL, any writes to OpenGL 4.0 (Core Profile) - March 11, 2010
or reads from the buffer generate undefined values. Examples of such bindings include `ReadPixels` to a pixel buffer object binding point and client access to a buffer mapped with `MapBuffer`.

However, if a buffer object is written and read sequentially by transform feedback and other mechanisms, it is the responsibility of the GL to ensure that data are accessed consistently, even if the implementation performs the operations in a pipelined manner. For example, `MapBuffer` may need to block pending the completion of a previous transform feedback operation.

### 2.17.3 Transform Feedback Draw Operations

When transform feedback is active, the values of varyings or transformed vertex attributes are captured into the buffer objects attached to the current transform feedback object. After transform feedback is complete, subsequent rendering operations may use the contents of these buffer objects (see section 2.9). The number of vertices captured from each vertex stream during transform feedback is stored in the corresponding transform feedback object and may be used in conjunction with the command

```c
void DrawTransformFeedback( enum mode, uint id );
void DrawTransformFeedbackStream( enum mode, uint id, uint stream );
```

to replay the captured vertices.

`DrawTransformFeedbackStream` is equivalent to calling `DrawArrays` with `mode` as specified, `first` set to zero, and `count` set to the number of vertices captured from the vertex stream numbered `stream` the last time transform feedback was active on the transform feedback object named by `id`. The error `INVALID_VALUE` is generated if `stream` is greater than or equal to the value of `MAX_VERTEX_STREAMS`. `DrawTransformFeedback` is equivalent to calling `DrawTransformFeedbackStream` with a `stream` of zero.

The error `INVALID_VALUE` is generated if `id` is not the name of a transform feedback object. The error `INVALID_OPERATION` is generated if `EndTransformFeedback` has never been called while the object named by `id` was bound. No error is generated if the transform feedback object named by `id` is active; the vertex count used for the rendering operation is set by the previous `EndTransformFeedback` command.

Note that the vertex count is from the number of vertices recorded to the selected vertex stream during the transform feedback operation. If no varyings belonging to the selected vertex stream are recorded, the corresponding vertex count will be zero even if complete primitives were emitted to the selected stream.
2.18 Primitive Queries

Primitive queries use query objects to track the number of primitives in each vertex stream that are generated by the GL and the number of primitives in each vertex stream that are written to buffer objects in transform feedback mode.

When `BeginQueryIndexed` is called with a `target` of `PRIMITIVES_GENERATED`, the primitives generated count maintained by the GL for the vertex stream `index` is set to zero. There is a separate query and counter for each vertex stream. The number of vertex streams is given by the value of the implementation-dependent constant `MAX_VERTEX_STREAMS`. If `index` is not an integer in the range zero to the value of `MAX_VERTEX_STREAMS` minus one, the error `INVALID_VALUE` is generated. When a generated primitive query for a vertex stream is active, the primitives-generated count is incremented every time a primitive emitted to that stream reaches the transform feedback stage (see section 2.17), whether or not transform feedback is active. This counter counts the number of primitives emitted by a geometry shader, if active, possibly further tessellated into separate primitives during the transform feedback stage, if active.

When `BeginQueryIndexed` is called with a `target` of `TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN`, the transform feedback primitives written count maintained by the GL for vertex stream `index` is set to zero. There is a separate query and counter for each vertex stream. If `index` is not an integer in the range zero to the value of `MAX_VERTEX_STREAMS` minus one, the error `INVALID_VALUE` is generated. When a transform feedback primitives written query for a vertex stream is active, the counter for that vertex stream is incremented every time the vertices of a primitive written to that stream are recorded into one or more buffer objects. If transform feedback is not active or if a primitive to be recorded does not fit in a buffer object, the counter is not incremented.

These two types of queries can be used together to determine if all primitives in a given vertex stream have been written to the bound feedback buffers; if both queries are run simultaneously and the query results are equal, all primitives have been written to the buffer(s). If the number of primitives written is less than the number of primitives generated, one or more buffers overflowed.

2.19 Flatshading

`Flatshading` a vertex shader varying output means to assign all vertices of the primitive the same value for that output.

The varying output values assigned are those of the `provoking vertex` of the primitive. The provoking vertex is controlled with the command
2.19. FLATSHADING

Table 2.14: Provoking vertex selection. The varying values used for flatshading the \(i\)th primitive generated by drawing commands with the indicated primitive type are derived from the corresponding values of the vertex whose index is shown in the table. Vertices are numbered 1 through \(n\), where \(n\) is the number of vertices drawn.

<table>
<thead>
<tr>
<th>Primitive type of polygon (i)</th>
<th>First vertex convention</th>
<th>Last vertex convention</th>
</tr>
</thead>
<tbody>
<tr>
<td>point</td>
<td>(i)</td>
<td>(i)</td>
</tr>
<tr>
<td>independent line</td>
<td>(2i - 1)</td>
<td>(2i)</td>
</tr>
<tr>
<td>line loop</td>
<td>(i)</td>
<td>(i + 1), if (i &lt; n)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1, if (i = n)</td>
</tr>
<tr>
<td>line strip</td>
<td>(i)</td>
<td>(i + 1)</td>
</tr>
<tr>
<td>independent triangle</td>
<td>(3i - 2)</td>
<td>(3i)</td>
</tr>
<tr>
<td>triangle strip</td>
<td>(i)</td>
<td>(i + 2)</td>
</tr>
<tr>
<td>triangle fan</td>
<td>(i + 1)</td>
<td>(i + 2)</td>
</tr>
<tr>
<td>line adjacency</td>
<td>(4i - 2)</td>
<td>(4i - 1)</td>
</tr>
<tr>
<td>line strip adjacency</td>
<td>(i + 1)</td>
<td>(i + 2)</td>
</tr>
<tr>
<td>triangle adjacency</td>
<td>(6i - 5)</td>
<td>(6i - 1)</td>
</tr>
<tr>
<td>triangle strip adjacency</td>
<td>(2i - 1)</td>
<td>(2i + 3)</td>
</tr>
</tbody>
</table>

void ProvokingVertex( enum provokeMode );

*provokeMode* must be either `FIRST_VERTEX_CONVENTION` or `LAST_VERTEX_CONVENTION`, and controls selection of the vertex whose values are assigned to flatshaded colors and varying outputs, as shown in table 2.14.

If a vertex or geometry shader is active, user-defined varying outputs may be flatshaded by using the `flat` qualifier when declaring the output, as described in section 4.3.6 of the OpenGL Shading Language Specification.

The state required for flatshading is one bit for the provoking vertex mode, and one implementation-dependent bit for the provoking vertex behavior of quad primitives. The initial value of the provoking vertex mode is `LAST_VERTEX_CONVENTION`.

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2.20 Primitive Clipping

Primitives are clipped to the *clip volume*. In clip coordinates, the *view volume* is defined by

\[-w_c \leq x_c \leq w_c\]
\[-w_c \leq y_c \leq w_c\]
\[-w_c \leq z_c \leq w_c.\]

This view volume may be further restricted by as many as \(n\) client-defined half-spaces. \((n\) is an implementation-dependent maximum that must be at least 8.) The clip volume is the intersection of all such half-spaces with the view volume (if no client-defined half-spaces are enabled, the clip volume is the view volume).

A vertex shader may write a single clip distance for each supported half-space to elements of the \texttt{gl_ClipDistance[]} array. Half-space \(n\) is then given by the set of points satisfying the inequality

\[c_n(P) \geq 0,\]

where \(c_n(P)\) is the value of clip distance \(n\) at point \(P\). For point primitives, \(c_n(P)\) is simply the clip distance for the vertex in question. For line and triangle primitives, per-vertex clip distances are interpolated using a weighted mean, with weights derived according to the algorithms described in sections 3.5 and 3.6.

Client-defined half-spaces are enabled with the generic \texttt{Enable} command and disabled with the \texttt{Disable} command. The value of the argument to either command is \texttt{CLIP_DISTANCE} \(i\), where \(i\) is an integer between 0 and \(n - 1\); specifying a value of \(i\) enables or disables the plane equation with index \(i\). The constants obey \texttt{CLIP_DISTANCE} \(i\) = \texttt{CLIP_DISTANCE0} + \(i\).

Depth clamping is enabled with the generic \texttt{Enable} command and disabled with the \texttt{Disable} command. The value of the argument to either command is \texttt{DEPTH_CLAMP}. If depth clamping is enabled, the

\[-w_c \leq z_c \leq w_c\]

plane equation is ignored by view volume clipping (effectively, there is no near or far plane clipping).

If the primitive under consideration is a point, then clipping passes it unchanged if it lies within the clip volume; otherwise, it is discarded.

If the primitive is a line segment, then clipping does nothing to it if it lies entirely within the clip volume, and discards it if it lies entirely outside the volume.

If part of the line segment lies in the volume and part lies outside, then the line segment is clipped and new vertex coordinates are computed for one or both
vertices. A clipped line segment endpoint lies on both the original line segment and the boundary of the clip volume.

This clipping produces a value, \(0 \leq t \leq 1\), for each clipped vertex. If the coordinates of a clipped vertex are \(P\) and the original vertices’ coordinates are \(P_1\) and \(P_2\), then \(t\) is given by

\[
P = tP_1 + (1-t)P_2.
\]

The value of \(t\) is used to clip vertex shader varying variables as described in section 2.20.1.

If the primitive is a polygon, then it is passed if every one of its edges lies entirely inside the clip volume and either clipped or discarded otherwise. Polygon clipping may cause polygon edges to be clipped, but because polygon connectivity must be maintained, these clipped edges are connected by new edges that lie along the clip volume’s boundary. Thus, clipping may require the introduction of new vertices into a polygon.

If it happens that a polygon intersects an edge of the clip volume’s boundary, then the clipped polygon must include a point on this boundary edge.

Primitives rendered with user-defined half-spaces must satisfy a complementarity criterion. Suppose a series of primitives is drawn where each vertex \(i\) has a single specified clip distance \(d_i\) (or a number of similarly specified clip distances, if multiple half-spaces are enabled). Next, suppose that the same series of primitives are drawn again with each such clip distance replaced by \(-d_i\) (and the GL is otherwise in the same state). In this case, primitives must not be missing any pixels, nor may any pixels be drawn twice in regions where those primitives are cut by the clip planes.

The state required for clipping is at least 8 bits indicating which of the client-defined half-spaces are enabled. In the initial state, all half-spaces are disabled.

### 2.20.1 Clipping Shader Varying Outputs

Next, vertex shader varying variables are clipped. The varying values associated with a vertex that lies within the clip volume are unaffected by clipping. If a primitive is clipped, however, the varying values assigned to vertices produced by clipping are clipped.

Let the varying values assigned to the two vertices \(P_1\) and \(P_2\) of an unclipped edge be \(c_1\) and \(c_2\). The value of \(t\) (section 2.20) for a clipped point \(P\) is used to obtain the varying value associated with \(P\) as

\[
2^\text{Since this computation is performed in clip space before division by } w_c, \text{ clipped varying values are perspective-correct.}
\]
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\[ \mathbf{c} = t\mathbf{c}_1 + (1 - t)\mathbf{c}_2. \]

(Multiplying a varying value by a scalar means multiplying each of \(x, y, z,\) and \(w\) by the scalar.)

Polygon clipping may create a clipped vertex along an edge of the clip volume’s boundary. This situation is handled by noting that polygon clipping proceeds by clipping against one half-space at a time. Varying value clipping is done in the same way, so that clipped points always occur at the intersection of polygon edges (possibly already clipped) with the clip volume’s boundary.

For vertex shader varying variables specified to be interpolated without perspective correction (using the `noperspective` qualifier), the value of \(t\) used to obtain the varying value associated with \(\mathbf{P}\) will be adjusted to produce results that vary linearly in screen space.

Varying outputs of integer or unsigned integer type must always be declared with the `flat` qualifier. Since such varyings are constant over the primitive being rasterized (see sections 3.5.1 and 3.6.1), no interpolation is performed.
Chapter 3

Rasterization

Rasterization is the process by which a primitive is converted to a two-dimensional image. Each point of this image contains such information as color and depth. Thus, rasterizing a primitive consists of two parts. The first is to determine which squares of an integer grid in window coordinates are occupied by the primitive. The second is assigning a depth value and one or more color values to each such square. The results of this process are passed on to the next stage of the GL (per-fragment operations), which uses the information to update the appropriate locations in the framebuffer. Figure 3.1 diagrams the rasterization process. The color values assigned to a fragment are determined by a fragment shader as defined in section 3.9. The final depth value is initially determined by the rasterization operations and may be modified or replaced by a fragment shader. The results from rasterizing a point, line, or polygon are routed through a fragment shader.

A grid square along with its \( z \) (depth) and varying shader output parameters is called a fragment; the parameters are collectively dubbed the fragment’s associated data. A fragment is located by its lower left corner, which lies on integer grid coordinates. Rasterization operations also refer to a fragment’s center, which is offset by \( (1/2, 1/2) \) from its lower left corner (and so lies on half-integer coordinates).

Grid squares need not actually be square in the GL. Rasterization rules are not affected by the actual aspect ratio of the grid squares. Display of non-square grids, however, will cause rasterized points and line segments to appear fatter in one direction than the other. We assume that fragments are square, since it simplifies antialiasing and texturing.

Several factors affect rasterization. Primitives may be discarded before rasterization. Points may be given differing diameters and line segments differing widths. A point, line segment, or polygon may be antialiased.
3.1 Discarding Primitives Before Rasterization

Primitives sent to vertex stream zero (see section 2.17) are processed further; primitives emitted to any other stream are discarded. When geometry shaders are disabled, all vertices are considered to be emitted to stream zero.

Primitives can be optionally discarded before rasterization by calling Enable and Disable with RASTERIZER_DISCARD. When enabled, primitives are discarded immediately before the rasterization stage, but after the optional transform feedback stage (see section 2.17). When disabled, primitives are passed through to the rasterization stage to be processed normally. When enabled, RASTERIZER_DISCARD also causes the Clear and ClearBuffer* commands to be ignored.

3.2 Invariance

Consider a primitive $p'$ obtained by translating a primitive $p$ through an offset $(x, y)$ in window coordinates, where $x$ and $y$ are integers. As long as neither $p'$ nor $p$ is clipped, it must be the case that each fragment $f'$ produced from $p'$ is identical to a corresponding fragment $f$ from $p$ except that the center of $f'$ is offset by $(x, y)$ from the center of $f$. 

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3.3 Antialiasing

The R, G, and B values of the rasterized fragment are left unaffected, but the A value is multiplied by a floating-point value in the range \([0, 1]\) that describes a fragment’s screen pixel coverage. The per-fragment stage of the GL can be set up to use the A value to blend the incoming fragment with the corresponding pixel already present in the framebuffer.

The details of how antialiased fragment coverage values are computed are difficult to specify in general. The reason is that high-quality antialiasing may take into account perceptual issues as well as characteristics of the monitor on which the contents of the framebuffer are displayed. Such details cannot be addressed within the scope of this document. Further, the coverage value computed for a fragment of some primitive may depend on the primitive’s relationship to a number of grid squares neighboring the one corresponding to the fragment, and not just on the fragment’s grid square. Another consideration is that accurate calculation of coverage values may be computationally expensive; consequently we allow a given GL implementation to approximate true coverage values by using a fast but not entirely accurate coverage computation.

In light of these considerations, we chose to specify the behavior of exact antialiasing in the prototypical case that each displayed pixel is a perfect square of uniform intensity. The square is called a fragment square and has lower left corner \((x, y)\) and upper right corner \((x + 1, y + 1)\). We recognize that this simple box filter may not produce the most favorable antialiasing results, but it provides a simple, well-defined model.

A GL implementation may use other methods to perform antialiasing, subject to the following conditions:

1. If \(f_1\) and \(f_2\) are two fragments, and the portion of \(f_1\) covered by some primitive is a subset of the corresponding portion of \(f_2\) covered by the primitive, then the coverage computed for \(f_1\) must be less than or equal to that computed for \(f_2\).

2. The coverage computation for a fragment \(f\) must be local: it may depend only on \(f\)’s relationship to the boundary of the primitive being rasterized. It may not depend on \(f\)’s \(x\) and \(y\) coordinates.

Another property that is desirable, but not required, is:

3. The sum of the coverage values for all fragments produced by rasterizing a particular primitive must be constant, independent of any rigid motions in window coordinates, as long as none of those fragments lies along window edges.
In some implementations, varying degrees of antialiasing quality may be obtained by providing GL hints (section 5.4), allowing a user to make an image quality versus speed tradeoff.

### 3.3.1 Multisampling

Multisampling is a mechanism to antialias all GL primitives: points, lines, and polygons. The technique is to sample all primitives multiple times at each pixel. The color sample values are resolved to a single, displayable color each time a pixel is updated, so the antialiasing appears to be automatic at the application level. Because each sample includes color, depth, and stencil information, the color (including texture operation), depth, and stencil functions perform equivalently to the single-sample mode.

An additional buffer, called the multisample buffer, is added to the framebuffer. Pixel sample values, including color, depth, and stencil values, are stored in this buffer. Samples contain separate color values for each fragment color. When the framebuffer includes a multisample buffer, it does not include depth or stencil buffers, even if the multisample buffer does not store depth or stencil values. Color buffers do coexist with the multisample buffer, however.

Multisample antialiasing is most valuable for rendering polygons, because it requires no sorting for hidden surface elimination, and it correctly handles adjacent polygons, object silhouettes, and even intersecting polygons. If only lines are being rendered, the “smooth” antialiasing mechanism provided by the base GL may result in a higher quality image. This mechanism is designed to allow multisample and smooth antialiasing techniques to be alternated during the rendering of a single scene.

If the value of SAMPLE_BUFFERS is one, the rasterization of all primitives is changed, and is referred to as multisample rasterization. Otherwise, primitive rasterization is referred to as single-sample rasterization. The value of SAMPLE_BUFFERS is queried by calling `GetIntegerv` with `pname` set to `SAMPLE_BUFFERS`.

During multisample rendering the contents of a pixel fragment are changed in two ways. First, each fragment includes a coverage value with SAMPLES bits. The value of SAMPLES is an implementation-dependent constant, and is queried by calling `GetIntegerv` with `pname` set to `SAMPLES`.

The location of a given sample is queried with the command

```c
void GetMultisamplefv(enum pname, uint index, float *val);
```

`pname` must be `SAMPLE_POSITION`, and `index` corresponds to the sample for which the location should be returned. The sample location is returned as two
3.3. ANTIALIASING

floating point values in val[0] and val[1], each between 0 and 1, corresponding to the x and y locations respectively in GL pixel space of that sample. (0.5, 0.5) thus corresponds to the pixel center. The error INVALID_VALUE is generated if index is greater than or equal to the value of SAMPLES. If the multisample mode does not have fixed sample locations, the returned values may only reflect the locations of samples within some pixels.

Second, each fragment includes SAMPLES depth values and sets of associated data, instead of the single depth value and set of associated data that is maintained in single-sample rendering mode. An implementation may choose to assign the same associated data to more than one sample. The location for evaluating such associated data can be anywhere within the pixel including the fragment center or any of the sample locations. The different associated data values need not all be evaluated at the same location. Each pixel fragment thus consists of integer x and y grid coordinates, SAMPLES depth values and sets of associated data, and a coverage value with a maximum of SAMPLES bits.

Multisample rasterization is enabled or disabled by calling Enable or Disable with the symbolic constant MULTISAMPLE.

If MULTISAMPLE is disabled, multisample rasterization of all primitives is equivalent to single-sample (fragment-center) rasterization, except that the fragment coverage value is set to full coverage. The color and depth values and the sets of texture coordinates may all be set to the values that would have been assigned by single-sample rasterization, or they may be assigned as described below for multisample rasterization.

If MULTISAMPLE is enabled, multisample rasterization of all primitives differs substantially from single-sample rasterization. It is understood that each pixel in the framebuffer has SAMPLES locations associated with it. These locations are exact positions, rather than regions or areas, and each is referred to as a sample point. The sample points associated with a pixel may be located inside or outside of the unit square that is considered to bound the pixel. Furthermore, the relative locations of sample points may be identical for each pixel in the framebuffer, or they may differ.

If MULTISAMPLE is enabled and the current program object includes a fragment shader with one or more input variables qualified with sample in, the data associated with those variables will be assigned independently. The values for each sample must be evaluated at the location of the sample. The data associated with any other variables not qualified with sample in need not be evaluated independently for each sample.

If the sample locations differ per pixel, they should be aligned to window, not screen, boundaries. Otherwise rendering results will be window-position specific. The invariance requirement described in section 3.2 is relaxed for all multisample

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Sample Shading

Sample shading can be used to specify a minimum number of unique samples to process for each fragment. Sample shading is controlled by calling `Enable` or `Disable` with the symbolic constant `SAMPLE_SHADING`.

If `MULTISAMPLE` or `SAMPLE_SHADING` is disabled, sample shading has no effect. Otherwise, an implementation must provide a minimum of

$$\max([mss \times samples], 1)$$

unique color values for each fragment, where `mss` is the value of `MIN_SAMPLE_SHADING_VALUE` and `samples` is the number of samples (the value of `SAMPLES`). These are associated with the samples in an implementation-dependent manner. The value of `MIN_SAMPLE_SHADING_VALUE` is specified by calling

```c
void MinSampleShading(clampf value);
```

with `value` set to the desired minimum sample shading fraction. `value` is clamped to [0, 1] when specified. The sample shading fraction may be queried by calling `GetFloatv` with the symbolic constant `MIN_SAMPLE_SHADING_VALUE`.

When the sample shading fraction is 1.0, a separate set of colors and other associated data are evaluated for each sample, and each set of values is evaluated at the sample location.

3.4 Points

A point is drawn by generating a set of fragments in the shape of a square or circle centered around the vertex of the point. Each vertex has an associated point size that controls the size of that square or circle.

If point size mode is enabled, then the derived point size is taken from the (potentially clipped) shader built-in `gl_PointSize` written by the geometry shader, or written by the vertex shader if no geometry shader is active, and clamped to the implementation-dependent point size range. If the value written to `gl_PointSize` is less than or equal to zero, results are undefined. If point size mode is disabled, then the derived point size is specified with the command

```c
void PointSize(float size);
```
3.4. POINTS

size specifies the requested size of a point. The default value is 1.0. A value less than or equal to zero results in the error INVALID VALUE. Program point size mode is enabled and disabled by calling Enable or Disable with the symbolic value PROGRAM_POINT_SIZE.

If multisampling is enabled, an implementation may optionally fade the point alpha (see section 3.11) instead of allowing the point width to go below a given threshold. In this case, the width of the rasterized point is

\[
width = \begin{cases} 
\text{derived} \cdot \text{size} & \text{derived} \cdot \text{size} \geq \text{threshold} \\
\text{threshold} & \text{otherwise}
\end{cases}
\] (3.1)

and the fade factor is computed as follows:

\[
fade = \begin{cases} 
1 & \text{derived} \cdot \text{size} \geq \text{threshold} \\
\left(\frac{\text{derived} \cdot \text{size}}{\text{threshold}}\right)^2 & \text{otherwise}
\end{cases}
\] (3.2)

The point fade threshold is specified with

\begin{verbatim}
void PointParameter(if)(enum pname, T param );
void PointParameter(if)v(enum pname, const T params );
\end{verbatim}

If pname is POINT_FADE_THRESHOLD_SIZE, then param specifies, or params points to the point fade threshold. Values of POINT_FADE_THRESHOLD_SIZE less than zero result in the error INVALID_VALUE.

The point sprite texture coordinate origin is set with the PointParameter* commands where pname is POINT_SPRITE_COORD_ORIGIN and param is LOWER_LEFT or UPPER_LEFT. The default value is UPPER_LEFT.

3.4.1 Basic Point Rasterization

Point rasterization produces a fragment for each framebuffer pixel whose center lies inside a square centered at the point’s \((x_w, y_w)\), with side length equal to the current point size.

All fragments produced in rasterizing a point sprite are assigned the same associated data, which are those of the vertex corresponding to the point. However, the fragment shader built-in gl_PointCoord contains point sprite texture coordinates. The \(s\) point sprite texture coordinate varies from 0 to 1 across the point horizontally left-to-right. If POINT_SPRITE_COORD_ORIGIN is LOWER_LEFT, the \(t\) coordinate varies from 0 to 1 vertically bottom-to-top. Otherwise if the point sprite texture coordinate origin is UPPER_LEFT, the \(t\) coordinate varies from 0 to 1 vertically top-to-bottom. The \(r\) and \(q\) coordinates are replaced with the constants 0 and 1, respectively.
3.4. POINTS

The following formula is used to evaluate the \( s \) and \( t \) point sprite texture coordinates:

\[
s = \frac{1}{2} + \frac{\left( x_f + \frac{1}{2} - x_w \right)}{size}
\]  
(3.3)

\[
t = \begin{cases} 
\frac{1}{2} + \frac{(y_f + \frac{1}{2} - y_w)}{size}, & \text{POINT_SPRITE_COORD_ORIGIN} = \text{LOWER_LEFT} \\
\frac{1}{2} - \frac{(y_f + \frac{1}{2} - y_w)}{size}, & \text{POINT_SPRITE_COORD_ORIGIN} = \text{UPPER_LEFT} 
\end{cases}
\]  
(3.4)

where \( size \) is the point’s size, \( x_f \) and \( y_f \) are the (integral) window coordinates of the fragment, and \( x_w \) and \( y_w \) are the exact, unrounded window coordinates of the vertex for the point.

Not all point widths need be supported, but the width 1.0 must be provided. The range of supported widths and the width of evenly-spaced gradations within that range are implementation-dependent. The range and gradations may be obtained using the query mechanism described in chapter 6. If, for instance, the width range is from 0.1 to 2.0 and the gradation width is 0.1, then the widths 0.1, 0.2, \ldots, 1.9, 2.0 are supported. Additional point widths may also be supported. There is no requirement that these widths must be equally spaced. If an unsupported width is requested, the nearest supported width is used instead.

3.4.2 Point Rasterization State

The state required to control point rasterization consists of the floating-point point width, a bit indicating whether or not vertex program point size mode is enabled, a bit for the point sprite texture coordinate origin, and a floating-point value specifying the point fade threshold size.

3.4.3 Point Multisample Rasterization

If \texttt{MULTISAMPLE} is enabled, and the value of \texttt{SAMPLE_BUFFERS} is one, then points are rasterized using the following algorithm. Point rasterization produces a fragment for each framebuffer pixel with one or more sample points that intersect a region centered at the point’s \((x_w, y_w)\). This region is a square with side equal to the current point width. Coverage bits that correspond to sample points that intersect the region are 1, other coverage bits are 0. All data associated with each sample for the fragment are the data associated with the point being rasterized.

The set of point sizes supported is equivalent to those for point sprites without multisample.
3.5 Line Segments

A line segment results from a line strip, a line loop, or a series of separate line segments. Line segment rasterization is controlled by several variables. Line width, which may be set by calling

```c
void LineWidth( float width );
```

with an appropriate positive floating-point width, controls the width of rasterized line segments. The default width is 1.0. Values less than or equal to 0.0 generate the error `INVALID_VALUE`. Antialiasing is controlled with `Enable` and `Disable` using the symbolic constant `LINE_SMOOTH`.

3.5.1 Basic Line Segment Rasterization

Line segment rasterization begins by characterizing the segment as either \(x\)-major or \(y\)-major. \(x\)-major line segments have slope in the closed interval \([-1, 1]\); all other line segments are \(y\)-major (slope is determined by the segment’s endpoints). We shall specify rasterization only for \(x\)-major segments except in cases where the modifications for \(y\)-major segments are not self-evident.

Ideally, the GL uses a “diamond-exit” rule to determine those fragments that are produced by rasterizing a line segment. For each fragment \(f\) with center at window coordinates \((x_f, y_f)\), define a diamond-shaped region that is the intersection of four half planes:

\[
R_f = \{ (x, y) \mid |x - x_f| + |y - y_f| < 1/2 \}.
\]

Essentially, a line segment starting at \(p_a\) and ending at \(p_b\) produces those fragments \(f\) for which the segment intersects \(R_f\), except if \(p_b\) is contained in \(R_f\). See figure 3.2.

To avoid difficulties when an endpoint lies on a boundary of \(R_f\) we (in principle) perturb the supplied endpoints by a tiny amount. Let \(p_a\) and \(p_b\) have window coordinates \((x_a, y_a)\) and \((x_b, y_b)\), respectively. Obtain the perturbed endpoints \(p'_a\) given by \((x_a, y_a) - (\epsilon, \epsilon^2)\) and \(p'_b\) given by \((x_b, y_b) - (\epsilon, \epsilon^2)\). Rasterizing the line segment starting at \(p_a\) and ending at \(p_b\) produces those fragments \(f\) for which the segment starting at \(p'_a\) and ending on \(p'_b\) intersects \(R_f\), except if \(p'_b\) is contained in \(R_f\). \(\epsilon\) is chosen to be so small that rasterizing the line segment produces the same fragments when \(\delta\) is substituted for \(\epsilon\) for any \(0 < \delta \leq \epsilon\).

When \(p_a\) and \(p_b\) lie on fragment centers, this characterization of fragments reduces to Bresenham’s algorithm with one modification: lines produced in this description are “half-open,” meaning that the final fragment (corresponding to \(p_b\))
is not drawn. This means that when rasterizing a series of connected line segments, shared endpoints will be produced only once rather than twice (as would occur with Bresenham’s algorithm).

Because the initial and final conditions of the diamond-exit rule may be difficult to implement, other line segment rasterization algorithms are allowed, subject to the following rules:

1. The coordinates of a fragment produced by the algorithm may not deviate by more than one unit in either $x$ or $y$ window coordinates from a corresponding fragment produced by the diamond-exit rule.

2. The total number of fragments produced by the algorithm may differ from that produced by the diamond-exit rule by no more than one.

3. For an $x$-major line, no two fragments may be produced that lie in the same window-coordinate column (for a $y$-major line, no two fragments may appear in the same row).

4. If two line segments share a common endpoint, and both segments are either $x$-major (both left-to-right or both right-to-left) or $y$-major (both bottom-to-top or both top-to-bottom), then rasterizing both segments may not produce
3.5. LINE SEGMENTS

duplicate fragments, nor may any fragments be omitted so as to interrupt continuity of the connected segments.

Next we must specify how the data associated with each rasterized fragment are obtained. Let the window coordinates of a produced fragment center be given by \( p_r = (x_d, y_d) \) and let \( p_a = (x_a, y_a) \) and \( p_b = (x_b, y_b) \). Set

\[
t = \frac{(p_r - p_a) \cdot (p_b - p_a)}{\|p_b - p_a\|^2}.
\]  

(Note that \( t = 0 \) at \( p_a \) and \( t = 1 \) at \( p_b \).) The value of an associated datum \( f \) for the fragment, whether it be a varying shader output or the clip \( w \) coordinate, is found as

\[
f = \frac{(1 - t)f_a/w_a + tf_b/w_b}{(1 - t)/w_a + t/w_b}
\]

(3.6)

where \( f_a \) and \( f_b \) are the data associated with the starting and ending endpoints of the segment, respectively; \( w_a \) and \( w_b \) are the clip \( w \) coordinates of the starting and ending endpoints of the segments, respectively. However, depth values for lines must be interpolated by

\[
z = (1 - t)z_a + tz_b
\]

(3.7)

where \( z_a \) and \( z_b \) are the depth values of the starting and ending endpoints of the segment, respectively.

The \texttt{noperspective} and \texttt{flat} keywords used to declare varying shader outputs affect how they are interpolated. When neither keyword is specified, interpolation is performed as described in equation 3.6. When the \texttt{noperspective} keyword is specified, interpolation is performed in the same fashion as for depth values, as described in equation 3.7. When the \texttt{flat} keyword is specified, no interpolation is performed, and varying outputs are taken from the corresponding varying value of the provoking vertex corresponding to that primitive (see section 2.19).

3.5.2 Other Line Segment Features

We have just described the rasterization of non-antialiased line segments of width one. We now describe the rasterization of line segments for general values of the line segment rasterization parameters.
3.5. LINE SEGMENTS

Figure 3.3. The region used in rasterizing and finding corresponding coverage values for an antialiased line segment (an x-major line segment is shown).

Antialiasing

Rasterized antialiased line segments produce fragments whose fragment squares intersect a rectangle centered on the line segment. Two of the edges are parallel to the specified line segment; each is at a distance of one-half the current width from that segment: one above the segment and one below it. The other two edges pass through the line endpoints and are perpendicular to the direction of the specified line segment. Coverage values are computed for each fragment by computing the area of the intersection of the rectangle with the fragment square (see figure 3.3; see also section 3.3). Equation 3.6 is used to compute associated data values just as with non-antialiased lines; equation 3.5 is used to find the value of $t$ for each fragment whose square is intersected by the line segment’s rectangle. Not all widths need be supported for line segment antialiasing, but width 1.0 antialiased segments must be provided. As with the point width, a GL implementation may be queried for the range and number of gradations of available antialiased line widths.

3.5.3 Line Rasterization State

The state required for line rasterization consists of the floating-point line width and a bit indicating whether line antialiasing is on or off. The initial value of the line width is 1.0. The initial state of line segment antialiasing is disabled.
3.6 Polygons

A polygon results from a triangle arising from a triangle strip, triangle fan, or series of separate triangles. Like points and line segments, polygon rasterization is controlled by several variables. Polygon antialiasing is controlled with Enable and Disable with the symbolic constant POLYGON_SMOOTH.

3.6.1 Basic Polygon Rasterization

The first step of polygon rasterization is to determine if the polygon is back-facing or front-facing. This determination is made based on the sign of the (clipped or unclipped) polygon’s area computed in window coordinates. One way to compute this area is

\[ a = \frac{1}{2} \sum_{i=0}^{n-1} x_w^i y_w^{i+1} - x_w^{i+1} y_w^i \]  

(3.8)

where \( x_w^i \) and \( y_w^i \) are the \( x \) and \( y \) window coordinates of the \( i \)th vertex of the \( n \)-vertex polygon (vertices are numbered starting at zero for purposes of this computation) and \( i \oplus 1 \) is \((i + 1) \mod n\). The interpretation of the sign of this value is controlled with

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void FrontFace( enum dir );

Setting dir to CCW (corresponding to counter-clockwise orientation of the projected polygon in window coordinates) uses a as computed above. Setting dir to CW (corresponding to clockwise orientation) indicates that the sign of a should be reversed prior to use. Front face determination requires one bit of state, and is initially set to CCW.

If the sign of a (including the possible reversal of this sign as determined by FrontFace) is positive, the polygon is front-facing; otherwise, it is back-facing. This determination is used in conjunction with the CullFace enable bit and mode value to decide whether or not a particular polygon is rasterized. The CullFace mode is set by calling

void CullFace( enum mode );

mode is a symbolic constant: one of FRONT, BACK or FRONT_AND_BACK. Culling is enabled or disabled with Enable or Disable using the symbolic constant CULL_FACE. Front-facing polygons are rasterized if either culling is disabled or the CullFace mode is BACK while back-facing polygons are rasterized only if either culling is disabled or the CullFace mode is FRONT. The initial setting of the CullFace mode is BACK. Initially, culling is disabled.

The rule for determining which fragments are produced by polygon rasterization is called point sampling. The two-dimensional projection obtained by taking the x and y window coordinates of the polygon’s vertices is formed. Fragment centers that lie inside of this polygon are produced by rasterization. Special treatment is given to a fragment whose center lies on a polygon edge. In such a case we require that if two polygons lie on either side of a common edge (with identical endpoints) on which a fragment center lies, then exactly one of the polygons results in the production of the fragment during rasterization.

As for the data associated with each fragment produced by rasterizing a polygon, we begin by specifying how these values are produced for fragments in a triangle. Define barycentric coordinates for a triangle. Barycentric coordinates are a set of three numbers, a, b, and c, each in the range [0, 1], with \( a + b + c = 1 \). These coordinates uniquely specify any point \( p \) within the triangle or on the triangle’s boundary as

\[
p = ap_a + bp_b + cp_c,
\]

where \( p_a, p_b, \) and \( p_c \) are the vertices of the triangle. \( a, b, \) and \( c \) can be found as

\[
a = \frac{A(pbp_c)}{A(pap_bpc)}, \quad b = \frac{A(ppap_c)}{A(pap_bpc)}, \quad c = \frac{A(ppap_b)}{A(pap_bpc)},
\]

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where $A(lmn)$ denotes the area in window coordinates of the triangle with vertices $l$, $m$, and $n$.

Denote an associated datum at $p_a$, $p_b$, or $p_c$ as $f_a$, $f_b$, or $f_c$, respectively. Then the value $f$ of a datum at a fragment produced by rasterizing a triangle is given by

$$f = \frac{a f_a / w_a + b f_b / w_b + c f_c / w_c}{a / w_a + b / w_b + c / w_c}$$

(3.9)

where $w_a$, $w_b$, and $w_c$ are the clip $w$ coordinates of $p_a$, $p_b$, and $p_c$, respectively. $a$, $b$, and $c$ are the barycentric coordinates of the fragment for which the data are produced. $a$, $b$, and $c$ must correspond precisely to the exact coordinates of the center of the fragment. Another way of saying this is that the data associated with a fragment must be sampled at the fragment’s center. However, depth values for polygons must be interpolated by

$$z = a z_a + b z_b + c z_c$$

(3.10)

where $z_a$, $z_b$, and $z_c$ are the depth values of $p_a$, $p_b$, and $p_c$, respectively.

The `noperspective` and `flat` keywords used to declare varying shader outputs affect how they are interpolated. When neither keyword is specified, interpolation is performed as described in equation 3.9. When the `noperspective` keyword is specified, interpolation is performed in the same fashion as for depth values, as described in equation 3.10. When the `flat` keyword is specified, no interpolation is performed, and varying outputs are taken from the corresponding varying value of the provoking vertex corresponding to that primitive (see section 2.19).

For a polygon with more than three edges, such as may be produced by clipping a triangle, we require only that a convex combination of the values of the datum at the polygon’s vertices can be used to obtain the value assigned to each fragment produced by the rasterization algorithm. That is, it must be the case that at every fragment

$$f = \sum_{i=1}^{n} a_i f_i$$

where $n$ is the number of vertices in the polygon, $f_i$ is the value of the $f$ at vertex $i$; for each $i$ $0 \leq a_i \leq 1$ and $\sum_{i=1}^{n} a_i = 1$. The values of the $a_i$ may differ from fragment to fragment, but at vertex $i$, $a_j = 0$, $j \neq i$ and $a_i = 1$.

One algorithm that achieves the required behavior is to triangulate a polygon (without adding any vertices) and then treat each triangle individually as already discussed. A scan-line rasterizer that linearly interpolates data along each edge and then linearly interpolates data across each horizontal span from edge to edge.
3.6. POLYGONS

also satisfies the restrictions (in this case, the numerator and denominator of equation 3.9 should be iterated independently and a division performed for each fragment).

3.6.2 Antialiasing

Polygon antialiasing rasterizes a polygon by producing a fragment wherever the interior of the polygon intersects that fragment’s square. A coverage value is computed at each such fragment, and this value is saved to be applied as described in section 3.10. An associated datum is assigned to a fragment by integrating the datum’s value over the region of the intersection of the fragment square with the polygon’s interior and dividing this integrated value by the area of the intersection. For a fragment square lying entirely within the polygon, the value of a datum at the fragment’s center may be used instead of integrating the value across the fragment.

3.6.3 Options Controlling Polygon Rasterization

The interpretation of polygons for rasterization is controlled using

```c
void PolygonMode( enum face, enum mode);
```

*face* must be *FRONT_AND_BACK*, indicating that the rasterizing method described by *mode* replaces the rasterizing method for both front- and back-facing polygons. *mode* is one of the symbolic constants *POINT*, *LINE*, or *FILL*. Calling *PolygonMode* with *POINT* causes the vertices of a polygon to be treated, for rasterization purposes, as if they had been drawn with *mode* *POINTS*. *LINE* causes edges to be rasterized as line segments. *FILL* is the default mode of polygon rasterization, corresponding to the description in sections 3.6.1, and 3.6.2. Note that these modes affect only the final rasterization of polygons: in particular, a polygon’s vertices are lit, and the polygon is clipped and possibly culled before these modes are applied.

Polygon antialiasing applies only to the *FILL* state of *PolygonMode*. For *POINT* or *LINE*, point antialiasing or line segment antialiasing, respectively, apply.

3.6.4 Depth Offset

The depth values of all fragments generated by the rasterization of a polygon may be offset by a single value that is computed for that polygon. The function that determines this value is specified by calling

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void PolygonOffset(float factor, float units);

factor scales the maximum depth slope of the polygon, and units scales an implementation-dependent constant that relates to the usable resolution of the depth buffer. The resulting values are summed to produce the polygon offset value. Both factor and units may be either positive or negative.

The maximum depth slope $m$ of a triangle is

$$m = \sqrt{\left(\frac{\partial z_w}{\partial x_w}\right)^2 + \left(\frac{\partial z_w}{\partial y_w}\right)^2}$$

(3.11)

where $(x_w, y_w, z_w)$ is a point on the triangle. $m$ may be approximated as

$$m = \max\left\{\left|\frac{\partial z_w}{\partial x_w}\right|, \left|\frac{\partial z_w}{\partial y_w}\right|\right\}.$$  

(3.12)

The minimum resolvable difference $r$ is an implementation-dependent parameter that depends on the depth buffer representation. It is the smallest difference in window coordinate $z$ values that is guaranteed to remain distinct throughout polygon rasterization and in the depth buffer. All pairs of fragments generated by the rasterization of two polygons with otherwise identical vertices, but $z_w$ values that differ by $r$, will have distinct depth values.

For fixed-point depth buffer representations, $r$ is constant throughout the range of the entire depth buffer. For floating-point depth buffers, there is no single minimum resolvable difference. In this case, the minimum resolvable difference for a given polygon is dependent on the maximum exponent, $e$, in the range of $z$ values spanned by the primitive. If $n$ is the number of bits in the floating-point mantissa, the minimum resolvable difference, $r$, for the given primitive is defined as

$$r = 2^{e-n}.$$  

The offset value $o$ for a polygon is

$$o = m \times \text{factor} + r \times \text{units}.$$  

(3.13)

$m$ is computed as described above. If the depth buffer uses a fixed-point representation, $m$ is a function of depth values in the range $[0, 1]$, and $o$ is applied to depth values in the same range.

Boolean state values POLYGON_OFFSET_POINT, POLYGON_OFFSET_LINE, and POLYGON_OFFSET_FILL determine whether $o$ is applied during the rasterization of polygons in POINT, LINE, and FILL modes. These boolean state values are enabled and disabled as argument values to the commands Enable and Disable.
If \texttt{POLYGON\_OFFSET\_POINT} is enabled, $o$ is added to the depth value of each fragment produced by the rasterization of a polygon in \texttt{POINT} mode. Likewise, if \texttt{POLYGON\_OFFSET\_LINE} or \texttt{POLYGON\_OFFSET\_FILL} is enabled, $o$ is added to the depth value of each fragment produced by the rasterization of a polygon in \texttt{LINE} or \texttt{FILL} modes, respectively.

For fixed-point depth buffers, fragment depth values are always limited to the range $[0, 1]$, either by clamping after offset addition is performed (preferred), or by clamping the vertex values used in the rasterization of the polygon. Fragment depth values are clamped even when the depth buffer uses a floating-point representation.

\subsection*{3.6.5 Polygon Multisample Rasterization}

If \texttt{MULTISAMPLE} is enabled and the value of \texttt{SAMPLE\_BUFFERS} is one, then polygons are rasterized using the following algorithm, regardless of whether polygon antialiasing (\texttt{POLYGON\_SMOOTH}) is enabled or disabled. Polygon rasterization produces a fragment for each framebuffer pixel with one or more sample points that satisfy the point sampling criteria described in section 3.6.1. If a polygon is culled, based on its orientation and the \texttt{CullFace} mode, then no fragments are produced during rasterization.

Coverage bits that correspond to sample points that satisfy the point sampling criteria are 1, other coverage bits are 0. Each associated datum is produced as described in section 3.6.1, but using the corresponding sample location instead of the fragment center. An implementation may choose to assign the same associated data values to more than one sample by barycentric evaluation using any location within the pixel including the fragment center or one of the sample locations.

When using a vertex shader, the \texttt{noperspective} and \texttt{flat} qualifiers affect how varying shader outputs are interpolated in the same fashion as described for for basic polygon rasterization in section 3.6.1.

The rasterization described above applies only to the \texttt{FILL} state of \texttt{Polygon\_Mode}. For \texttt{POINT} and \texttt{LINE}, the rasterizations described in sections 3.4.3 (Point Multisample Rasterization) and 3.5.4 (Line Multisample Rasterization) apply.

\subsection*{3.6.6 Polygon Rasterization State}

The state required for polygon rasterization consists of the current state of polygon antialiasing (enabled or disabled), the current values of the \texttt{Polygon\_Mode} setting, whether point, line, and fill mode polygon offsets are enabled or disabled, and the factor and bias values of the polygon offset equation. The initial setting of polygon antialiasing is disabled. The initial state for \texttt{Polygon\_Mode} is \texttt{FILL}. The
initial polygon offset factor and bias values are both 0; initially polygon offset is disabled for all modes.

3.7 Pixel Rectangles

Rectangles of color, depth, and certain other values may be specified to the GL using \texttt{TexImage*D} (see section 3.8.3). Some of the parameters and operations governing the operation of these commands are shared by \texttt{ReadPixels} (used to obtain pixel values from the framebuffer); the discussion of \texttt{ReadPixels}, however, is deferred until chapter 4 after the framebuffer has been discussed in detail. Nevertheless, we note in this section when parameters and state pertaining to these commands also pertain to \texttt{ReadPixels}.

A number of parameters control the encoding of pixels in buffer object or client memory (for reading and writing) and how pixels are processed before being placed in or after being read from the framebuffer (for reading, writing, and copying). These parameters are set with \texttt{PixelStore}.

3.7.1 Pixel Storage Modes and Pixel Buffer Objects

Pixel storage modes affect the operation of \texttt{TexImage*D}, \texttt{TexSubImage*D}, and \texttt{ReadPixels} when one of these commands is issued. Pixel storage modes are set with

\begin{verbatim}
void PixelStore\{if\}( enum pname, T param );
\end{verbatim}

\textit{pname} is a symbolic constant indicating a parameter to be set, and \textit{param} is the value to set it to. Table 3.1 summarizes the pixel storage parameters, their types, their initial values, and their allowable ranges. Setting a parameter to a value outside the given range results in the error \texttt{INVALID_VALUE}.

The version of \texttt{PixelStore} that takes a floating-point value may be used to set any type of parameter; if the parameter is boolean, then it is set to \texttt{FALSE} if the passed value is 0.0 and \texttt{TRUE} otherwise, while if the parameter is an integer, then the passed value is rounded to the nearest integer. The integer version of the command may also be used to set any type of parameter; if the parameter is boolean, then it is set to \texttt{FALSE} if the passed value is 0 and \texttt{TRUE} otherwise, while if the parameter is a floating-point value, then the passed value is converted to floating-point.

In addition to storing pixel data in client memory, pixel data may also be stored in buffer objects (described in section 2.9). The current pixel unpack and
### Table 3.1: PixelStore parameters pertaining to one or more of TexImage1D, TexImage2D, TexImage3D, TexSubImage1D, TexSubImage2D, and TexSubImage3D.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Type</th>
<th>Initial Value</th>
<th>Valid Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNPACK_SWAP_BYTES</td>
<td>boolean</td>
<td>FALSE</td>
<td>TRUE/FALSE</td>
</tr>
<tr>
<td>UNPACK_LSB_FIRST</td>
<td>boolean</td>
<td>FALSE</td>
<td>TRUE/FALSE</td>
</tr>
<tr>
<td>UNPACK_ROW_LENGTH</td>
<td>integer</td>
<td>0</td>
<td>0, ∞</td>
</tr>
<tr>
<td>UNPACK_SKIP_ROWS</td>
<td>integer</td>
<td>0</td>
<td>0, ∞</td>
</tr>
<tr>
<td>UNPACK_SKIP_PIXELS</td>
<td>integer</td>
<td>0</td>
<td>0, ∞</td>
</tr>
<tr>
<td>UNPACK_ALIGNMENT</td>
<td>integer</td>
<td>4</td>
<td>1, 2, 4, 8</td>
</tr>
<tr>
<td>UNPACK_IMAGE_HEIGHT</td>
<td>integer</td>
<td>0</td>
<td>0, ∞</td>
</tr>
<tr>
<td>UNPACK_SKIP_IMAGES</td>
<td>integer</td>
<td>0</td>
<td>0, ∞</td>
</tr>
</tbody>
</table>

3.7. Transfer of Pixel Rectangles

The process of transferring pixels encoded in buffer object or client memory is diagrammed in figure 3.4. We describe the stages of this process in the order in which they occur.

Commands accepting or returning pixel rectangles take the following arguments (as well as additional arguments specific to their function):

- **format** is a symbolic constant indicating what the values in memory represent.
- **width** and **height** are the width and height, respectively, of the pixel rectangle to be transferred.
- **data** refers to the data to be drawn. These data are represented with one of several GL data types, specified by **type**. The correspondence between the **type** token values and the GL data types they indicate is given in table 3.2.

Not all combinations of **format** and **type** are valid. If **format** is **DEPTH_STENCIL** and **type** is not **UNSIGNED_INT_24_8** or **FLOAT_32_UNSIGNED_INT_24_8_REV**, then the error **INVALID_ENUM** occurs. If **format** is one of the...
Figure 3.4. Transfer of pixel rectangles to the GL. Output is RGBA pixels. Depth and stencil pixel paths are not shown.
integer component formats as defined in table 3.3 and type is FLOAT, the error INVALID_ENUM occurs. Some additional constraints on the combinations of format and type values that are accepted are discussed below. Additional restrictions may be imposed by specific commands.

Unpacking

Data are taken from the currently bound pixel unpack buffer or client memory as a sequence of signed or unsigned bytes (GL data types byte and ubyte), signed or unsigned short integers (GL data types short and ushort), signed or unsigned integers (GL data types int and uint), or floating point values (GL data types half and float). These elements are grouped into sets of one, two, three, or four values, depending on the format, to form a group. Table 3.3 summarizes the format of groups obtained from memory; it also indicates those formats that yield indices and those that yield floating-point or integer components.

If a pixel unpack buffer is bound (as indicated by a non-zero value of PIXEL_UNPACK_BUFFER_BINDING), data is an offset into the pixel unpack buffer and the pixels are unpacked from the buffer relative to this offset; otherwise, data is a pointer to client memory and the pixels are unpacked from client memory relative to the pointer. If a pixel unpack buffer object is bound and unpacking the pixel data according to the process described below would access memory beyond the size of the pixel unpack buffer’s memory size, an INVALID_OPERATION error results. If a pixel unpack buffer object is bound and data is not evenly divisible by the number of basic machine units needed to store in memory the corresponding GL data type from table 3.2 for the type parameter (or not evenly divisible by 4 for type FLOAT_32_UNSIGNED_INT_24_8_REV, which does not have a corresponding GL data type), an INVALID_OPERATION error results.

By default the values of each GL data type are interpreted as they would be specified in the language of the client’s GL binding. If UNPACK_SWAP_BYTES is enabled, however, then the values are interpreted with the bit orderings modified as per table 3.4. The modified bit orderings are defined only if the GL data type ubyte has eight bits, and then for each specific GL data type only if that type is represented with 8, 16, or 32 bits.

The groups in memory are treated as being arranged in a rectangle. This rectangle consists of a series of rows, with the first element of the first group of the first row pointed to by data. If the value of UNPACK_ROW_LENGTH is not positive, then the number of groups in a row is width; otherwise the number of groups is UNPACK_ROW_LENGTH. If p indicates the location in memory of the first element
### 3.7. PIXEL RECTANGLES

<table>
<thead>
<tr>
<th>type Parameter Token Name</th>
<th>Corresponding GL Data Type</th>
<th>Special Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSIGNED_BYTE</td>
<td>ubyte</td>
<td>No</td>
</tr>
<tr>
<td>BYTE</td>
<td>byte</td>
<td>No</td>
</tr>
<tr>
<td>UNSIGNED_SHORT</td>
<td>ushort</td>
<td>No</td>
</tr>
<tr>
<td>SHORT</td>
<td>short</td>
<td>No</td>
</tr>
<tr>
<td>UNSIGNED_INT</td>
<td>uint</td>
<td>No</td>
</tr>
<tr>
<td>INT</td>
<td>int</td>
<td>No</td>
</tr>
<tr>
<td>HALF_FLOAT</td>
<td>half</td>
<td>No</td>
</tr>
<tr>
<td>FLOAT</td>
<td>float</td>
<td>No</td>
</tr>
<tr>
<td>UNSIGNED_BYTE_3_3_2</td>
<td>ubyte</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_BYTE_2_3_3_REV</td>
<td>ubyte</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_6_5</td>
<td>ushort</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_6_5_REV</td>
<td>ushort</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_4_4_4_4</td>
<td>ushort</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_4_4_4_4_REV</td>
<td>ushort</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_5_5_1</td>
<td>ushort</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_1_5_5_5_REV</td>
<td>ushort</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_8_8_8_8</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_8_8_8_8_REV</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_10_10_10_2</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_2_10_10_10_REV</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_24_8</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_10F_11F_11F_REV</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>UNSIGNED_INT_5_9_9_9_REV</td>
<td>uint</td>
<td>Yes</td>
</tr>
<tr>
<td>FLOAT_32_UNSIGNED_INT_24_8_REV</td>
<td>n/a</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3.2: Pixel data type parameter values and the corresponding GL data types. Refer to table 2.2 for definitions of GL data types. Special interpretations are described near the end of section 3.5.
### 3.7. PIXEL RECTANGLES

<table>
<thead>
<tr>
<th>Format Name</th>
<th>Element Meaning and Order</th>
<th>Target Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>STENCIL_INDEX</td>
<td>Stencil Index</td>
<td>Stencil</td>
</tr>
<tr>
<td>DEPTH_COMPONENT</td>
<td>Depth</td>
<td>Depth</td>
</tr>
<tr>
<td>DEPTH_STENCIL</td>
<td>Depth and Stencil Index</td>
<td>Depth and Stencil</td>
</tr>
<tr>
<td>RED</td>
<td>R</td>
<td>Color</td>
</tr>
<tr>
<td>GREEN</td>
<td>G</td>
<td>Color</td>
</tr>
<tr>
<td>BLUE</td>
<td>B</td>
<td>Color</td>
</tr>
<tr>
<td>RG</td>
<td>R, G</td>
<td>Color</td>
</tr>
<tr>
<td>RGB</td>
<td>R, G, B</td>
<td>Color</td>
</tr>
<tr>
<td>RGBA</td>
<td>R, G, B, A</td>
<td>Color</td>
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<td>BGR</td>
<td>B, G, R</td>
<td>Color</td>
</tr>
<tr>
<td>BGRA</td>
<td>B, G, R, A</td>
<td>Color</td>
</tr>
<tr>
<td>RED_INTEGER</td>
<td>iR</td>
<td>Color</td>
</tr>
<tr>
<td>GREEN_INTEGER</td>
<td>iG</td>
<td>Color</td>
</tr>
<tr>
<td>BLUE_INTEGER</td>
<td>iB</td>
<td>Color</td>
</tr>
<tr>
<td>RG_INTEGER</td>
<td>iR, iG</td>
<td>Color</td>
</tr>
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<td>RGB_INTEGER</td>
<td>iR, iG, iB</td>
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<td>RGBA_INTEGER</td>
<td>iR, iG, iB, iA</td>
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<td>BGR_INTEGER</td>
<td>iB, iG, iR</td>
<td>Color</td>
</tr>
<tr>
<td>BGRA_INTEGER</td>
<td>iB, iG, iR, iA</td>
<td>Color</td>
</tr>
</tbody>
</table>

Table 3.3: Pixel data formats. The second column gives a description of and the number and order of elements in a group. Unless specified as an index, formats yield components. Components are floating-point unless prefixed with the letter ‘i’, which indicates they are integer.

<table>
<thead>
<tr>
<th>Element Size</th>
<th>Default Bit Ordering</th>
<th>Modified Bit Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 bit</td>
<td>[7..0]</td>
<td>[7..0]</td>
</tr>
<tr>
<td>16 bit</td>
<td>[15..0]</td>
<td>7..0[15..8]</td>
</tr>
<tr>
<td>32 bit</td>
<td>[31..0]</td>
<td>7..0[15..8][23..16][31..24]</td>
</tr>
</tbody>
</table>

Table 3.4: Bit ordering modification of elements when UNPACK_SWAP_BYTES is enabled. These reorderings are defined only when GL data type ubyte has 8 bits, and then only for GL data types with 8, 16, or 32 bits. Bit 0 is the least significant.
of the first row, then the first element of the \( N \)th row is indicated by

\[
p + Nk
\]  

where \( N \) is the row number (counting from zero) and \( k \) is defined as

\[
k = \begin{cases} 
  \frac{nl}{s} & s \geq a, \\
  \left\lceil \frac{snl}{a} \right\rceil & s < a
\end{cases}
\]  

where \( n \) is the number of elements in a group, \( l \) is the number of groups in the row, \( a \) is the value of \text{UNPACK\_ALIGNMENT}, and \( s \) is the size, in units of \text{GL\_ubyte\_s}, of an element. If the number of bits per element is not 1, 2, 4, or 8 times the number of bits in a \text{GL\_ubyte}, then \( k = nl \) for all values of \( a \).

There is a mechanism for selecting a sub-rectangle of groups from a larger containing rectangle. This mechanism relies on three integer parameters: \text{UNPACK\_ROW\_LENGTH}, \text{UNPACK\_SKIP\_ROWS}, and \text{UNPACK\_SKIP\_PIXELS}. Before obtaining the first group from memory, the data pointer is advanced by \((\text{UNPACK\_SKIP\_PIXELS})n + (\text{UNPACK\_SKIP\_ROWS})k\) elements. Then \text{width} groups are obtained from contiguous elements in memory (without advancing the pointer), after which the pointer is advanced by \( k \) elements. \text{height} sets of \text{width} groups of values are obtained this way. See figure 3.5.

**Special Interpretations**
A type matching one of the types in table 3.5 is a special case in which all the components of each group are packed into a single unsigned byte, unsigned short, or unsigned int, depending on the type. If type is `FLOAT_32_UNSIGNED_INT_24_8_REV`, the components of each group are contained within two 32-bit words; the first word contains the float component, and the second word contains a packed 24-bit unused field, followed by an 8-bit component. The number of components per packed pixel is fixed by the type, and must match the number of components per group indicated by the `format` parameter, as listed in table 3.5. The error `INVALID_OPERATION` is generated by any command processing pixel rectangles if a mismatch occurs.

Bitfield locations of the first, second, third, and fourth components of each packed pixel type are illustrated in tables 3.6-3.9. Each bitfield is interpreted as an unsigned integer value. If the base GL type is supported with more than the minimum precision (e.g. a 9-bit byte) the packed components are right-justified in the pixel.

Components are normally packed with the first component in the most significant bits of the bitfield, and successive component occupying progressively less significant locations. Types whose token names end with `_REV` reverse the component packing order from least to most significant locations. In all cases, the most significant bit of each component is packed in the most significant bit location of its location in the bitfield.
### Table 3.5: Packed pixel formats.

<table>
<thead>
<tr>
<th>type Parameter Token Name</th>
<th>GL Data Type</th>
<th>Number of Components</th>
<th>Matching Pixel Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSIGNED_BYTE_3_3_2</td>
<td>ubyte</td>
<td>3</td>
<td>RGB, RGB_INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_BYTE_2_3_3_REV</td>
<td>ubyte</td>
<td>3</td>
<td>RGB, RGB_INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_6_5</td>
<td>ushort</td>
<td>3</td>
<td>RGB, RGB_INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_6_5_REV</td>
<td>ushort</td>
<td>3</td>
<td>RGB, RGB_INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_4_4_4</td>
<td>ushort</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_4_4_4_4_REV</td>
<td>ushort</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_5_5_1</td>
<td>ushort</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_1_5_5_5_REV</td>
<td>ushort</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_INT_8_8_8_8</td>
<td>uint</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_INT_8_8_8_8_REV</td>
<td>uint</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_INT_10_10_10_2</td>
<td>uint</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_INT_2_10_10_10_REV</td>
<td>uint</td>
<td>4</td>
<td>RGBA, BGRA, RGBA_-INTEGER, BGRA_-INTEGER</td>
</tr>
<tr>
<td>UNSIGNED_INT_24_8</td>
<td>uint</td>
<td>2</td>
<td>DEPTH_STENCIL</td>
</tr>
<tr>
<td>UNSIGNED_INT_10F_11F_11F_REV</td>
<td>uint</td>
<td>3</td>
<td>RGB</td>
</tr>
<tr>
<td>UNSIGNED_INT_5_9_9_9_REV</td>
<td>uint</td>
<td>4</td>
<td>RGB</td>
</tr>
<tr>
<td>FLOAT_32_UNSIGNED_INT_24_8_REV</td>
<td>n/a</td>
<td>2</td>
<td>DEPTH_STENCIL</td>
</tr>
</tbody>
</table>
### 3.7. PIXEL RECTANGLES

UNSIGNED\_BYTE\_3\_3\_2:

<table>
<thead>
<tr>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Component</td>
<td>2nd</td>
<td>3rd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

UNSIGNED\_BYTE\_2\_3\_3\_REV:

<table>
<thead>
<tr>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd</td>
<td>2nd</td>
<td>1st Component</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6: UNSIGNED\_BYTE formats. Bit numbers are indicated for each component.
3.7. PIXEL RECTANGLES

| UNSIGNED_SHORT_5_6_5:       | 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|                            | 1st Component | 2nd | 3rd |
|UNSIGNED_SHORT_5_6_5_REV:   | 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 | 3rd | 2nd | 1st Component |
|UNSIGNED_SHORT_4_4_4_4:     | 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 | 1st Component | 2nd | 3rd | 4th |
|UNSIGNED_SHORT_4_4_4_4_REV: | 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 | 4th | 3rd | 2nd | 1st Component |
|UNSIGNED_SHORT_5_5_5_1:     | 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 | 1st Component | 2nd | 3rd | 4th |
|UNSIGNED_SHORT_1_5_5_5_REV: | 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 | 4th | 3rd | 2nd | 1st Component |

Table 3.7: UNSIGNED_SHORT formats
### 3.7. PIXEL RECTANGLES

**UNSIGNED\_INT\_8\_8\_8\_8:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1st Component                   | 2nd                             | 3rd                             | 4th                             |

**UNSIGNED\_INT\_8\_8\_8\_8\_REV:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 4th                             | 3rd                             | 2nd                             | 1st Component                   |

**UNSIGNED\_INT\_10\_10\_10\_2:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1st Component                   | 2nd                             | 3rd                             | 4th                             |

**UNSIGNED\_INT\_2\_10\_10\_10\_REV:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 4th                             | 3rd                             | 2nd                             | 1st Component                   |

**UNSIGNED\_INT\_24\_8:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1st Component                   | 2nd                             |                                |                                |

**UNSIGNED\_INT\_10F\_11F\_11F\_REV:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 3rd                             | 2nd                             | 1st Component                   |                                |

**UNSIGNED\_INT\_5\_9\_9\_9\_REV:**

| 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 4th                             | 3rd                             | 2nd                             | 1st Component                   |

Table 3.8: UNSIGNED\_INT formats
### FLOAT\_32\_UNSIGNED\_INT$\_24\_8\_REV$:

|       | 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  | 4  | 3  | 2  | 1  | 0  |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1st Component | 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  | 4  | 3  | 2  | 1  | 0  |
| Unused | 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  | 4  | 3  | 2  | 1  | 0  |
| 2nd   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

Table 3.9: FLOAT\_UNSIGNED\_INT formats
3.7. PIXEL RECTANGLES

<table>
<thead>
<tr>
<th>Format</th>
<th>First Component</th>
<th>Second Component</th>
<th>Third Component</th>
<th>Fourth Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB</td>
<td>red</td>
<td>green</td>
<td>blue</td>
<td></td>
</tr>
<tr>
<td>RGBA</td>
<td>red</td>
<td>green</td>
<td>blue</td>
<td>alpha</td>
</tr>
<tr>
<td>BGRA</td>
<td>blue</td>
<td>green</td>
<td>red</td>
<td>alpha</td>
</tr>
<tr>
<td>DEPTH_STENCIL</td>
<td>depth</td>
<td>stencil</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.10: Packed pixel field assignments.

The assignment of component to fields in the packed pixel is as described in table 3.10.

Byte swapping, if enabled, is performed before the components are extracted from each pixel. The above discussions of row length and image extraction are valid for packed pixels, if “group” is substituted for “component” and the number of components per group is understood to be one.

A type of UNSIGNED_INT_10F_11F_11F_REV and format of RGB is a special case in which the data are a series of GL uint values. Each uint value specifies 3 packed components as shown in table 3.8. The 1st, 2nd, and 3rd components are called \( f_{\text{red}} \) (11 bits), \( f_{\text{green}} \) (11 bits), and \( f_{\text{blue}} \) (10 bits) respectively.

\( f_{\text{red}} \) and \( f_{\text{green}} \) are treated as unsigned 11-bit floating-point values and converted to floating-point red and green components respectively as described in section 2.1.3. \( f_{\text{blue}} \) is treated as an unsigned 10-bit floating-point value and converted to a floating-point blue component as described in section 2.1.4.

A type of UNSIGNED_INT_5_9_9_9_REV and format of RGB is a special case in which the data are a series of GL uint values. Each uint value specifies 4 packed components as shown in table 3.8. The 1st, 2nd, 3rd, and 4th components are called \( p_{\text{red}} \), \( p_{\text{green}} \), \( p_{\text{blue}} \), and \( p_{\exp} \) respectively and are treated as unsigned integers. These are then used to compute floating-point RGB components (ignoring the “Conversion to floating-point” section below in this case) as follows:

\[
\begin{align*}
\text{red} &= p_{\text{red}}2^{p_{\exp}-B-N} \\
\text{green} &= p_{\text{green}}2^{p_{\exp}-B-N} \\
\text{blue} &= p_{\text{blue}}2^{p_{\exp}-B-N}
\end{align*}
\]

where \( B = 15 \) (the exponent bias) and \( N = 9 \) (the number of mantissa bits).
Conversion to floating-point

This step applies only to groups of floating-point components. It is not performed on indices or integer components. For groups containing both components and indices, such as `DEPTH_STENCIL`, the indices are not converted.

Each element in a group is converted to a floating-point value. For unsigned integer elements, equation 2.1 is used. For signed integer elements, equation 2.2 is used unless the final destination of the transferred element is a texture or framebuffer component in one of the `SNORM` formats described in table 3.12, in which case equation 2.3 is used instead.

Final Expansion to RGBA

This step is performed only for non-depth component groups. Each group is converted to a group of 4 elements as follows: if a group does not contain an A element, then A is added and set to 1 for integer components or 1.0 for floating-point components. If any of R, G, or B is missing from the group, each missing element is added and assigned a value of 0 for integer components or 0.0 for floating-point components.

3.8 Texturing

Texturing maps a portion of one or more specified images onto a fragment or vertex. This mapping is accomplished in shaders by sampling the color of an image at the location indicated by specified \((s, t, r)\) texture coordinates. Texture lookups are typically used to modify a fragment’s RGBA color but may be used for any purpose in a shader.

The internal data type of a texture may be signed or unsigned normalized fixed-point, signed or unsigned integer, or floating-point, depending on the internal format of the texture. The correspondence between the internal format and the internal data type is given in tables 3.12-3.13. Fixed-point and floating-point textures return a floating-point value and integer textures return signed or unsigned integer values. The fragment shader is responsible for interpreting the result of a texture lookup as the correct data type, otherwise the result is undefined.

Each of the supported types of texture is a collection of images built from one-, two-, or three-dimensional arrays of image elements referred to as texels. One-, two-, and three-dimensional textures consist respectively of one-, two-, or three-dimensional texel arrays. One- and two-dimensional array textures are arrays of one- or two-dimensional images, consisting of one or more layers. Two-dimensional multisample and two-dimensional multisample array textures are spe-
3.8. TEXTURING

cial two-dimensional and two-dimensional array textures, respectively, containing multiple samples in each texel. Cube maps are special two-dimensional array textures with six layers that represent the faces of a cube. When accessing a cube map, the texture coordinates are projected onto one of the six faces of the cube. A cube map array is a collection of cube map layers stored as a two-dimensional array texture. When accessing a cube map array, the texture coordinate \( s, t, \) and \( r \) are applied similarly as cube maps while the last texture coordinate \( q \) is used as the index of one of the cube map slices. Rectangular textures are special two-dimensional textures consisting of only a single image and accessed using unnormalized coordinates. Buffer textures are special one-dimensional textures whose texel arrays are stored in separate buffer objects.

Implementations must support texturing using multiple images. The following subsections (up to and including section 3.8.11) specify the GL operation with a single texture. The process by which multiple texture images may be sampled and combined by the application-supplied vertex and fragment shaders is described in sections 2.11 and 3.9.

The coordinates used for texturing in a fragment shader are defined by the OpenGL Shading Language Specification.

The command

```c
void ActiveTexture( enum texture );
```

specifies the active texture unit selector, `ACTIVE_TEXTURE`. Each texture image unit consists of all the texture state defined in section 3.8.

The active texture unit selector selects the texture image unit accessed by commands involving texture image processing. Such commands include `TexParameter`, `TexImage`, `BindTexture`, and queries of all such state.

`ActiveTexture` generates the error `INVALID_ENUM` if an invalid `texture` is specified. `texture` is a symbolic constant of the form `TEXTURE_i`, indicating that texture unit \( i \) is to be modified. The constants obey `TEXTURE_i = TEXTURE0 + i` (\( i \) is in the range 0 to \( k - 1 \), where \( k \) is the value of `MAX_COMBINED_TEXTURE_IMAGE_UNITS`).

The state required for the active texture image unit selector is a single integer. The initial value is `TEXTURE0`.

### 3.8.1 Texture Objects

Textures in GL are represented by named objects. The name space for texture objects is the unsigned integers, with zero reserved by the GL to represent the default texture object. The default texture object is bound to
3.8. TEXTURING

Each of the TEXTURE_1D, TEXTURE_2D, TEXTURE_3D, TEXTURE_1D_ARRAY, TEXTURE_2D_ARRAY, TEXTURE_RECTANGLE, TEXTURE_BUFFER, TEXTURE_CUBE_MAP, TEXTURE_CUBE_MAP_ARRAY, TEXTURE_2D_MULTISAMPLE, and TEXTURE_2D_MULTISAMPLE_ARRAY targets during context initialization.

A new texture object is created by binding an unused name to one of these texture targets. The command

```c
void GenTextures( sizei n, uint *textures );
```

returns \( n \) previously unused texture names in `textures`. These names are marked as used, for the purposes of `GenTextures` only, but they acquire texture state and a dimensionality only when they are first bound, just as if they were unused. The binding is effected by calling

```c
void BindTexture( enum target, uint texture );
```

with `target` set to the desired texture target and `texture` set to the unused name. The resulting texture object is a new state vector, comprising all the state and with the same initial values listed in section 3.8.15 The new texture object bound to `target` is, and remains a texture of the dimensionality and type specified by `target` until it is deleted.

`BindTexture` may also be used to bind an existing texture object to any of these targets. The error `INVALID_OPERATION` is generated if an attempt is made to bind a texture object of different dimensionality than the specified `target`. If the bind is successful no change is made to the state of the bound texture object, and any previous binding to `target` is broken.

`BindTexture` fails and an `INVALID_OPERATION` error is generated if `texture` is not zero or a name returned from a previous call to `GenTextures`, or if such a name has since been deleted.

While a texture object is bound, GL operations on the target to which it is bound affect the bound object, and queries of the target to which it is bound return state from the bound object. If texture mapping of the dimensionality of the target to which a texture object is bound is enabled, the state of the bound texture object directs the texturing operation.

Texture objects are deleted by calling

```c
void DeleteTextures( sizei n, const uint *textures );
```

`textures` contains \( n \) names of texture objects to be deleted. After a texture object is deleted, it has no contents or dimensionality, and its name is again unused. If a texture that is currently bound to any of the target bindings of `BindTexture` is
deleted, it is as though `BindTexture` had been executed with the same target and texture zero. Additionally, special care must be taken when deleting a texture if any of the images of the texture are attached to a framebuffer object. See section 4.4.2 for details.

Unused names in `textures` are silently ignored, as is the name zero.

The texture object name space, including the initial one-, two-, and three- dimensional, one- and two-dimensional array, rectangular, buffer, cube map, cube map array, two-dimensional multisample, and two-dimensional multisample array texture objects, is shared among all texture units. A texture object may be bound to more than one texture unit simultaneously. After a texture object is bound, any GL operations on that target object affect any other texture units to which the same texture object is bound.

Texture binding is affected by the setting of the state `ACTIVE_TEXTURE`. If a texture object is deleted, it as if all texture units which are bound to that texture object are rebound to texture object zero.

### 3.8.2 Sampler Objects

The state necessary for texturing can be divided into two categories as described in section 3.8.15. A GL texture object includes both categories. The first category represents dimensionality and other image parameters, and the second category represents sampling state. Additionally, a sampler object may be created to encapsulate only the second category - the sampling state - of a texture object.

A new sampler object is created by binding an unused name to a texture unit. The command

```c
void GenSamplers(sizei count, uint *samplers);
```

returns `count` previously unused sampler object names in `samplers`. The name zero is reserved by the GL to represent no sampler being bound to a sampler unit. The names are marked as used, for the purposes of `GenSamplers` only, but they acquire state only when they are first used as a parameter to `BindSampler`, `SamplerParameter*`, `GetSamplerParameter*`, or `IsSampler`. When a sampler object is first used in one of these functions, the resulting sampler object is initialized with a new state vector, comprising all the state and with the same initial values listed in table 6.18.

When a sampler object is bound to a texture unit, its state supersedes that of the texture object bound to that texture unit. If the sampler name zero is bound to a texture unit, the currently bound texture’s sampler state becomes active. A single sampler object may be bound to multiple texture units simultaneously.

A sampler binding is effected by calling

```
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```
void BindSampler(uint unit, uint sampler);

with unit set to the texture unit to which to bind the sampler and sampler set to the
name of a sampler object returned from a previous call to GenSamplers.

If the bind is successful no change is made to the state of the bound sampler
object, and any previous binding to unit is broken.

BindSampler fails and an INVALID_OPERATION error is generated if sampler
is not zero or a name returned from a previous call to GenSamplers, or if such a
name has since been deleted with DeleteSamplers. An INVALID_VALUE error is
generated if unit is greater than or equal to the value of MAX_TEXTURE_IMAGE_-UNITS.

If state is present in a sampler object bound to a texture unit that would have
been rejected by a call to TexParameter for the texture bound to that unit, the be-
behavior of the implementation is as if the texture were incomplete. For example, if
TEXTURE_WRAP_S, TEXTURE_WRAP_T, or TEXTURE_WRAP_R is set to REPEAT or
MIRRORED_REPEAT on the sampler object bound to a texture unit and the texture
bound to that unit is a rectangular texture, the texture will be considered incom-
plete.

The currently bound sampler may be queried by calling GetIntegerv with
pname set to SAMPLER_BINDING. When a sampler object is unbound from the
texture unit (by binding another sampler object, or the sampler object named zero,
to that texture unit) the modified state is again replaced with the sampler state as-
associated with the texture object bound to that texture unit.

The parameters represented by a sampler object are a subset of those described
in section 3.8.8. Each parameter of a sampler object is set by calling

void SamplerParameter{if}v(uint sampler, enum pname,
const T param);
void SamplerParameterI{u ui}v(uint sampler, enum pname,
const T *params);

sampler is the name of a sampler object previously reserved by a call to
GenSamplers. pname is the name of a parameter to modify and param is
the new value of that parameter. An INVALID_VALUE error is gener-
ated if sampler is not the name of a sampler object previously returned
from a call to GenSamplers. The values accepted in the pname parameter
are TEXTURE_WRAP_S, TEXTURE_WRAP_T, TEXTURE_WRAP_R, TEXTURE_MIN_-FILTER, TEXTURE_MAG_FILTER, TEXTURE_BORDER_COLOR, TEXTURE_MIN_-LOD, TEXTURE_MAX_LOD, TEXTURE_LOD_BIAS, TEXTURE_COMPARE_MODE, and
TEXTURE_COMPARE_FUNC. Texture state listed in table 6.17 but not listed here and

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in the sampler state in table 6.18 is not part of the sampler state, and remains in the texture object.

If the values for TEXTURE_BORDER_COLOR are specified with a call to SamplerParameterIiv or SamplerParameterIuiv, the values are unmodified and stored with an internal data type of integer. If specified with SamplerParameterIiv, they are converted to floating-point using equation 2.1. Otherwise, the values are unmodified and stored as floating-point.

An INVALID_ENUM error is generated if pname is not the name of a parameter accepted by SamplerParameter*. If the value of param is not an acceptable value for the parameter specified in pname, an error is generated as specified in the description of TexParameter*.

Modifying a parameter of a sampler object affects all texture units to which that sampler object is bound. Calling TexParameter has no effect on the sampler object bound to the active texture unit. It will modify the parameters of the texture object bound to that unit.

Sampler objects are deleted by calling

```c
void DeleteSamplers( sizei count, const uint *samplers );
```

samplers contains count names of sampler objects to be deleted. After a sampler object is deleted, its name is again unused. If a sampler object that is currently bound to a sampler unit is deleted, it is as though BindSampler is called with unit set to the unit the sampler is bound to and sampler zero. Unused names in samplers are silently ignored, as is the reserved name zero.

### 3.8.3 Texture Image Specification

The command

```c
void TexImage3D( enum target, int level, int internalformat, 
    sizei width, sizei height, sizei depth, int border, 
    enum format, enum type, const void *data );
```

is used to specify a three-dimensional texture image. target must be one of TEXTURE_3D for a three-dimensional texture, TEXTURE_2D_ARRAY for an two-dimensional array texture, or TEXTURE_CUBE_MAP_ARRAY for a cube map array texture. Additionally, target may be either PROXY_TEXTURE_3D for a three-dimensional proxy texture, PROXY_TEXTURE_2D_ARRAY for a two-dimensional proxy array texture, or PROXY_TEXTURE_CUBE_MAP_ARRAY for a cube map array texture, as discussed in section 3.8.15. format, type, and data specify the format of the image data, the type of those data, and a reference to the image data.
in the currently bound pixel unpack buffer or client memory, as described in section 3.7.2. The format STENCIL_INDEX is not allowed.

The groups in memory are treated as being arranged in a sequence of adjacent rectangles. Each rectangle is a two-dimensional image, whose size and organization are specified by the width and height parameters to TexImage3D. The values of UNPACK_ROW_LENGTH and UNPACK_ALIGNMENT control the row-to-row spacing in these images as described in section 3.7.2. If the value of the integer parameter UNPACK_IMAGE_HEIGHT is not positive, then the number of rows in each two-dimensional image is height; otherwise the number of rows is UNPACK_IMAGE_HEIGHT. Each two-dimensional image comprises an integral number of rows, and is exactly adjacent to its neighbor images.

The mechanism for selecting a sub-volume of a three-dimensional image relies on the integer parameter UNPACK_SKIP_IMAGES. If UNPACK_SKIP_IMAGES is positive, the pointer is advanced by UNPACK_SKIP_IMAGES times the number of elements in one two-dimensional image before obtaining the first group from memory. Then depth two-dimensional images are processed, each having a subimage extracted as described in section 3.7.2.

The selected groups are transferred to the GL as described in section 3.7.2 and then clamped to the representable range of the internal format. If the internalformat of the texture is signed or unsigned integer, components are clamped to \([-2^{n-1}, 2^{n-1} - 1]\) or \([0, 2^n - 1]\), respectively, where \(n\) is the number of bits per component. For color component groups, if the internalformat of the texture is signed or unsigned normalized fixed-point, components are clamped to \([-1, 1]\) or \([0, 1]\), respectively. For depth component groups, the depth value is clamped to \([0, 1]\). Otherwise, values are not modified. Stencil index values are masked by \(2^n - 1\), where \(n\) is the number of stencil bits in the internal format resolution (see below). If the base internal format is DEPTH_STENCIL and format is not DEPTH_STENCIL, then the values of the stencil index texture components are undefined.

Components are then selected from the resulting R, G, B, A, depth, or stencil values to obtain a texture with the base internal format specified by (or derived from) internalformat. Table 3.11 summarizes the mapping of R, G, B, A, depth, or stencil values to texture components, as a function of the base internal format of the texture image. internalformat may be specified as one of the internal format symbolic constants listed in table 3.11, as one of the sized internal format symbolic constants listed in tables 3.12- 3.13, as one of the generic compressed internal format symbolic constants listed in table 3.14, or as one of the specific compressed internal format symbolic constants (if listed in table 3.14). Specifying a value for internalformat that is not one of the above values generates the error INVALID_VALUE.
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<table>
<thead>
<tr>
<th>Base Internal Format</th>
<th>RGBA, Depth, and Stencil Values</th>
<th>Internal Components</th>
</tr>
</thead>
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<tr>
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</tr>
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<td>Depth,Stencil</td>
<td>( D,S )</td>
</tr>
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<td>( R )</td>
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<tr>
<td>RGBA</td>
<td>R,G,B,A</td>
<td>( R,G,B,A )</td>
</tr>
</tbody>
</table>

Table 3.11: Conversion from RGBA, depth, and stencil pixel components to internal texture components. Texture components \( R, G, B, \) and \( A \) are converted back to RGBA colors during filtering as shown in table 3.20.

Textures with a base internal format of DEPTH_COMPONENT or DEPTH_STENCIL are supported by texture image specification commands only if `target` is TEXTURE_1D, TEXTURE_2D, TEXTURE_1D_ARRAY, TEXTURE_2D_ARRAY, TEXTURE_RECTANGLE, TEXTURE_CUBE_MAP, TEXTURE_CUBE_MAP_ARRAY, PROXY_TEXTURE_1D, PROXY_TEXTURE_2D, PROXY_TEXTURE_1D_ARRAY, PROXY_TEXTURE_2D_ARRAY, PROXY_TEXTURE_RECTANGLE, PROXY_TEXTURE_CUBE_MAP, or PROXY_TEXTURE_CUBE_MAP_ARRAY. Using these formats in conjunction with any other `target` will result in an INVALID_OPERATION error.

Textures with a base internal format of DEPTH_COMPONENT or DEPTH_STENCIL require either depth component data or depth/stencil component data. Textures with other base internal formats require RGBA component data. The error INVALID_OPERATION is generated if one of the base internal format and `format` is DEPTH_COMPONENT or DEPTH_STENCIL, and the other is neither of these values.

Textures with integer internal formats (see table 3.12) require integer data. The error INVALID_OPERATION is generated if the internal format is integer and `format` is not one of the integer formats listed in table 3.3; if the internal format is not integer and `format` is an integer format; or if `format` is an integer format and `type` is FLOAT, HALF_FLOAT, UNSIGNED_INT_10F_11F_11F_REV, or UNSIGNED_INT_5_9_9_9_REV.

In addition to the specific compressed internal formats listed in table 3.14, the GL provides a mechanism to obtain token values for all such formats provided by extensions. The number of specific compressed internal formats supported by the renderer can be obtained by querying the value of `NUM_COMPRESSED_TEXTURE_FORMATS`. The set of specific compressed internal formats supported by the renderer can be obtained by querying the value of `COMPRESSED_TEXTURE_FORMATS`.

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The only values returned by this query are those corresponding to formats suitable for general-purpose usage. The renderer will not enumerate formats with restrictions that need to be specifically understood prior to use.

Generic compressed internal formats are never used directly as the internal formats of texture images. If `internalformat` is one of the six generic compressed internal formats, its value is replaced by the symbolic constant for a specific compressed internal format of the GL’s choosing with the same base internal format. If no specific compressed format is available, `internalformat` is instead replaced by the corresponding base internal format. If `internalformat` is given as or mapped to a specific compressed internal format, but the GL can not support images compressed in the chosen internal format for any reason (e.g., the compression format might not support 3D textures), `internalformat` is replaced by the corresponding base internal format and the texture image will not be compressed by the GL.

The `internal component resolution` is the number of bits allocated to each value in a texture image. If `internalformat` is specified as a base internal format, the GL stores the resulting texture with internal component resolutions of its own choosing. If a sized internal format is specified, the mapping of the R, G, B, A, depth, and stencil values to texture components is equivalent to the mapping of the corresponding base internal format’s components, as specified in table 3.11; the type (unsigned int, float, etc.) is assigned the same type specified by `internalformat`; and the memory allocation per texture component is assigned by the GL to match the allocations listed in tables 3.12- 3.13 as closely as possible. (The definition of closely is left up to the implementation. However, a non-zero number of bits must be allocated for each component whose desired allocation in tables 3.12- 3.13 is non-zero, and zero bits must be allocated for all other components).

**Required Texture Formats**

Implementations are required to support at least one allocation of internal component resolution for each type (unsigned int, float, etc.) for each base internal format.

In addition, implementations are required to support the following sized and compressed internal formats. Requesting one of these sized internal formats for any texture type will allocate at least the internal component sizes, and exactly the component types shown for that format in tables 3.12-3.13:

- Texture and renderbuffer color formats (see section 4.4.2).

  - RGBA32F, RGBA32I, RGBA32UI, RGBA16, RGBA16F, RGBA16I, RGBA16UI, RGBA8, RGBA8I, RGBA8UI, SRGB8_ALPHA8, RGB10_A2, and RGB10_A2UI.

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- R11F_G11F_B10F.
- RG32F, RG32I, RG32UI, RG16, RG16F, RG16I, RG16UI, RG8, RG8I, and RG8UI.
- R32F, R32I, R32UI, R16F, R16I, R16UI, R16, R8, R8I, and R8UI.

- Texture-only color formats:
  - RGBA16_SNORM and RGBA8_SNORM.
  - RGB32F, RGB32I, and RGB32UI.
  - RGB16_SNORM, RGB16F, RGB16I, and RGB16.
  - RGB8_SNORM, RGB8, RGB8I, RGB8UI, and SRGB8.
  - RGB9_E5.
  - RG16_SNORM, RG8_SNORM, COMPRESSED_RG_RGTC2 and COMPRESSED_SIGNED_RG_RGTC2.
  - R16_SNORM, R8_SNORM, COMPRESSED_RED_RGTC1 and COMPRESSED_SIGNED_RED_RGTC1.

- Depth formats: DEPTH_COMPONENT32F, DEPTH_COMPONENT24, and DEPTH_COMPONENT16.

- Combined depth-stencil formats: DEPTH32F_STENCIL8 and DEPTH24_STENCIL8.

**Encoding of Special Internal Formats**

If internalformat is R11F_G11F_B10F, the red, green, and blue bits are converted to unsigned 11-bit, unsigned 11-bit, and unsigned 10-bit floating-point values as described in sections 2.1.3 and 2.1.4.

If internalformat is RGB9_E5, the red, green, and blue bits are converted to a shared exponent format according to the following procedure:

Components red, green, and blue are first clamped (in the process, mapping NaN to zero) as follows:

\[
\begin{align*}
red_c &= \max(0, \min(\text{sharedexp}_{\max}, \text{red})) \\
green_c &= \max(0, \min(\text{sharedexp}_{\max}, \text{green})) \\
blue_c &= \max(0, \min(\text{sharedexp}_{\max}, \text{blue}))
\end{align*}
\]

where

\[
\text{sharedexp}_{\max} = \left(\frac{2^N - 1}{2^N}\right)2^{E_{\max} - B}.
\]
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N is the number of mantissa bits per component (9), B is the exponent bias (15), and $E_{max}$ is the maximum allowed biased exponent value (31).

The largest clamped component, $max_c$, is determined:

$$max_c = \max(red_c, green_c, blue_c)$$

A preliminary shared exponent $exp_p$ is computed:

$$exp_p = \max(-B - 1, \lfloor \log_2(max_c) \rfloor) + 1 + B$$

A refined shared exponent $exp_s$ is computed:

$$exp_s = \begin{cases} 
exp_p, & 0 \leq max_s < 2^N \\
exp_p + 1, & max_s = 2^N 
\end{cases}$$

Finally, three integer values in the range 0 to $2^N - 1$ are computed:

$$red_s = \lfloor \frac{red_c}{2^{exp_s-B-N}} + 0.5 \rfloor$$

$$green_s = \lfloor \frac{green_c}{2^{exp_s-B-N}} + 0.5 \rfloor$$

$$blue_s = \lfloor \frac{blue_c}{2^{exp_s-B-N}} + 0.5 \rfloor$$

The resulting $red_s$, $green_s$, $blue_s$, and $exp_s$ are stored in the red, green, blue, and shared bits respectively of the texture image.

An implementation accepting pixel data of type `UNSIGNED_INT_5_9_9_9_REV` with format `RGB` is allowed to store the components “as is”.

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<tr>
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<th>Base Internal Format</th>
<th>$R$ bits</th>
<th>$G$ bits</th>
<th>$B$ bits</th>
<th>$A$ bits</th>
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Sized internal color formats continued on next page
### 3.8. TEXTURING

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Sized internal color formats continued on next page
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Table 3.12: Correspondence of sized internal color formats to base internal formats, internal data type, and desired component resolutions for each sized internal format. The component resolution prefix indicates the internal data type: *f* is floating point, *i* is signed integer, *ui* is unsigned integer, *s* is signed normalized fixed-point, and no prefix is unsigned normalized fixed-point.

<table>
<thead>
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<th>Sized Internal Format</th>
<th>Base Internal Format</th>
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<th>$G$ bits</th>
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<td>RGB16I</td>
<td>RGB</td>
<td>i16</td>
<td>i16</td>
<td>i16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGB16UI</td>
<td>RGB</td>
<td>ui16</td>
<td>ui16</td>
<td>ui16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGB32I</td>
<td>RGB</td>
<td>i32</td>
<td>i32</td>
<td>i32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGB32UI</td>
<td>RGB</td>
<td>ui32</td>
<td>ui32</td>
<td>ui32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGBA8I</td>
<td>RGBA</td>
<td>i8</td>
<td>i8</td>
<td>i8</td>
<td>i8</td>
<td></td>
</tr>
<tr>
<td>RGBA8UI</td>
<td>RGBA</td>
<td>ui8</td>
<td>ui8</td>
<td>ui8</td>
<td>ui8</td>
<td></td>
</tr>
<tr>
<td>RGBA16I</td>
<td>RGBA</td>
<td>i16</td>
<td>i16</td>
<td>i16</td>
<td>i16</td>
<td></td>
</tr>
<tr>
<td>RGBA16UI</td>
<td>RGBA</td>
<td>ui16</td>
<td>ui16</td>
<td>ui16</td>
<td>ui16</td>
<td></td>
</tr>
<tr>
<td>RGBA32I</td>
<td>RGBA</td>
<td>i32</td>
<td>i32</td>
<td>i32</td>
<td>i32</td>
<td></td>
</tr>
<tr>
<td>RGBA32UI</td>
<td>RGBA</td>
<td>ui32</td>
<td>ui32</td>
<td>ui32</td>
<td>ui32</td>
<td></td>
</tr>
</tbody>
</table>

If a compressed internal format is specified, the mapping of the R, G, B, and A values to texture components is equivalent to the mapping of the corresponding values.
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### Table 3.13: Correspondence of sized internal depth and stencil formats to base internal formats, internal data type, and desired component resolutions for each sized internal format. The component resolution prefix indicates the internal data type: \( f \) is floating point, \( i \) is signed integer, \( ui \) is unsigned integer, and no prefix is fixed-point.

<table>
<thead>
<tr>
<th>Sized Internal Format</th>
<th>Base Internal Format</th>
<th>( D ) bits</th>
<th>( S ) bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEPTH_COMPONENT16</td>
<td>DEPTH_COMPONENT</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>DEPTH_COMPONENT24</td>
<td>DEPTH_COMPONENT</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>DEPTH_COMPONENT32</td>
<td>DEPTH_COMPONENT</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>DEPTH_COMPONENT32F</td>
<td>DEPTH_COMPONENT</td>
<td>( f32 )</td>
<td></td>
</tr>
<tr>
<td>DEPTH24_STENCIL8</td>
<td>DEPTH_STENCIL</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>DEPTH32F_STENCIL8</td>
<td>DEPTH_STENCIL</td>
<td>( f32 )</td>
<td>8</td>
</tr>
</tbody>
</table>

### Table 3.14: Generic and specific compressed internal formats. The specific *RGTC* formats are described in appendix C.1.

<table>
<thead>
<tr>
<th>Compressed Internal Format</th>
<th>Base Internal Format</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPRESSED_RED</td>
<td>RED</td>
<td>Generic</td>
</tr>
<tr>
<td>COMPRESSED_RG</td>
<td>RG</td>
<td>Generic</td>
</tr>
<tr>
<td>COMPRESSED_RGB</td>
<td>RGB</td>
<td>Generic</td>
</tr>
<tr>
<td>COMPRESSED_RGBA</td>
<td>RGBA</td>
<td>Generic</td>
</tr>
<tr>
<td>COMPRESSED_SRGB</td>
<td>RGB</td>
<td>Generic</td>
</tr>
<tr>
<td>COMPRESSED_SRGB_ALPHA</td>
<td>RGBA</td>
<td>Generic</td>
</tr>
<tr>
<td>COMPRESSED_RED_RGTC1</td>
<td>RED</td>
<td>Specific</td>
</tr>
<tr>
<td>COMPRESSED_SIGNED_RED_RGTC1</td>
<td>RED</td>
<td>Specific</td>
</tr>
<tr>
<td>COMPRESSED_RG_RGTC2</td>
<td>RG</td>
<td>Specific</td>
</tr>
<tr>
<td>COMPRESSED_SIGNED_RG_RGTC2</td>
<td>RG</td>
<td>Specific</td>
</tr>
</tbody>
</table>

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base internal format’s components, as specified in table 3.11. The specified image is compressed using a (possibly lossy) compression algorithm chosen by the GL.

A GL implementation may vary its allocation of internal component resolution or compressed internal format based on any TexImage3D, TexImage2D (see below), or TexImage1D (see below) parameter (except target), but the allocation and chosen compressed image format must not be a function of any other state and cannot be changed once they are established. In addition, the choice of a compressed image format may not be affected by the data parameter. Allocations must be invariant; the same allocation and compressed image format must be chosen each time a texture image is specified with the same parameter values. These allocation rules also apply to proxy textures, which are described in section 3.8.15.

The image itself (referred to by data) is a sequence of groups of values. The first group is the lower left back corner of the texture image. Subsequent groups fill out rows of width width from left to right; height rows are stacked from bottom to top forming a single two-dimensional image slice; and depth slices are stacked from back to front. When the final R, G, B, and A components have been computed for a group, they are assigned to components of a texel as described by table 3.11. Counting from zero, each resulting Nth texel is assigned internal integer coordinates (i, j, k), where

\[
i = (N \mod \text{width}) - w_b
\]
\[
j = \left( \frac{N}{\text{width}} \right) \mod \text{height} - h_b
\]
\[
k = \left( \frac{N}{\text{width} \times \text{height}} \right) \mod \text{depth} - d_b
\]

and \(w_b\), \(h_b\), and \(d_b\) are the specified border width, height, and depth. \(w_b\) and \(h_b\) are the specified border value; \(d_b\) is the specified border value if target is TEXTURE_3D, or zero if target is TEXTURE_2D_ARRAY or TEXTURE_CUBE_MAP_ARRAY. Thus the last two-dimensional image slice of the three-dimensional image is indexed with the highest value of k.

When target is TEXTURE_CUBE_MAP_ARRAY, specifying a cube map array texture, k refers to a layer-face. The layer is given by

\[
\text{layer} = \left\lfloor \frac{k}{6} \right\rfloor,
\]

and the face is given by

\[
\text{face} = k \mod 6.
\]
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The face number corresponds to the cube map faces as shown in table 4.12. If the internal data type of the image array is signed or unsigned normalized fixed-point, each color component is converted using equation 2.6 or 2.4, respectively. If the internal type is floating-point or integer, components are clamped to the representable range of the corresponding internal component, but are not converted.

The level argument to TexImage3D is an integer level-of-detail number. Levels of detail are discussed below, under Mipmapping. The main texture image has a level of detail number of 0. If a level-of-detail less than zero is specified, the error INVALID_VALUE is generated.

The border argument to TexImage3D is a border width. The significance of borders is described below. The border width affects the dimensions of the texture image: let

\[ w_s = w_t + 2w_b \]
\[ h_s = h_t + 2h_b \]
\[ d_s = d_t + 2d_b \]

(3.16)

where \( w_s, h_s, \) and \( d_s \) are the specified image width, height, and depth, and \( w_t, h_t, \) and \( d_t \) are the dimensions of the texture image internal to the border. If \( w_t, h_t, \) or \( d_t \) are less than zero, then the error INVALID_VALUE is generated.

The maximum border width \( b_t \) is 0. If \( border \) is less than zero, or greater than \( b_t \), then the error INVALID_VALUE is generated.

The maximum allowable width, height, or depth of a texel array for a three-dimensional texture is an implementation-dependent function of the level-of-detail and internal format of the resulting image array. It must be at least \( 2^{k_{lod}} + 2b_t \) for image arrays of level-of-detail 0 through \( k \), where \( k \) is the log base 2 of \( \text{MAX}_3D\_TEXTURE\_SIZE \), \( lod \) is the level-of-detail of the image array, and \( b_t \) is the maximum border width. It may be zero for image arrays of any level-of-detail greater than \( k \). The error INVALID_VALUE is generated if the specified image is too large to be stored under any conditions.

When \( target \) is TEXTURE_CUBE_MAP_ARRAY or PROXY_TEXTURE_CUBE_MAP_ARRAY width and height must be equal, otherwise the error INVALID_VALUE is generated. Also, depth must be a multiple of six indicating \( 6N \) layer-faces in the cube map array, otherwise the error INVALID_VALUE is generated.

If a pixel unpack buffer object is bound and storing texture data would access memory beyond the end of the pixel unpack buffer, an INVALID_OPERATION error results.

In a similar fashion, the maximum allowable width of a texel array for a one- or two-dimensional, one- or two-dimensional array, two-dimensional multisample, or
two-dimensional multisample array texture, and the maximum allowable height of a two-dimensional, two-dimensional array, two-dimensional multisample, or two-dimensional multisample array texture, must be at least \(2^{k-\text{lod}} + 2b_t\) for image arrays of level 0 through \(k\), where \(k\) is the log base 2 of \(\text{MAX\_TEXTURE\_SIZE}\).

The maximum allowable width and height of a cube map or cube map array texture must be the same, and must be at least \(2^{k-\text{lod}} + 2b_t\) for image arrays level 0 through \(k\), where \(k\) is the log base 2 of the value of \(\text{MAX\_CUBE\_MAP\_TEXTURE\_SIZE}\). The maximum number of layers for one- and two-dimensional array textures (height or depth, respectively), and the maximum number of layer-faces for cube map array textures (depth), must be at least the value of \(\text{MAX\_ARRAY\_TEXTURE\_LAYERS}\) for all levels.

The maximum allowable width and height of a rectangular texture image must each be at least the value of the implementation-dependent constant \(\text{MAX\_RECTANGLE\_TEXTURE\_SIZE}\).

An implementation may allow an image array of level 0 to be created only if that single image array can be supported. Additional constraints on the creation of image arrays of level 1 or greater are described in more detail in section 3.8.14.

The command

```c
void TexImage2D( enum target, int level, int internalformat,
sizei width, sizei height, int border, enum format, 
enum type, const void *data );
```

is used to specify a two-dimensional texture image. \(\text{target}\) must be one of \(\text{TEXTURE\_2D}\) for a two-dimensional texture, \(\text{TEXTURE\_1D\_ARRAY}\) for a one-dimensional array texture, \(\text{TEXTURE\_RECTANGLE}\) for a rectangle texture, or one of \(\text{TEXTURE\_CUBE\_MAP\_POSITIVE\_X}, \text{TEXTURE\_CUBE\_MAP\_NEGATIVE\_-X}, \text{TEXTURE\_CUBE\_MAP\_POSITIVE\_Y}, \text{TEXTURE\_CUBE\_MAP\_NEGATIVE\_-Y}, \text{TEXTURE\_CUBE\_MAP\_POSITIVE\_Z}, \text{TEXTURE\_CUBE\_MAP\_NEGATIVE\_-Z}\) for a cube map texture. Additionally, \(\text{target}\) may be either \(\text{PROXY\_TEXTURE\_2D}\) for a two-dimensional proxy texture, \(\text{PROXY\_TEXTURE\_1D\_ARRAY}\) for a one-dimensional proxy array texture, \(\text{PROXY\_TEXTURE\_RECTANGLE}\) for a rectangle proxy texture, or \(\text{PROXY\_TEXTURE\_CUBE\_MAP}\) for a cube map proxy texture in the special case discussed in section 3.8.15. The other parameters match the corresponding parameters of \text{TexImage3D}.

For the purposes of decoding the texture image, \text{TexImage2D} is equivalent to calling \text{TexImage3D} with corresponding arguments and \(\text{depth}\) of 1, except that \text{UNPACK\_SKIP\_IMAGES} is ignored.

A two-dimensional or rectangle texture consists of a single two-dimensional texture image. A cube map texture is a set of six two-dimensional texture images. The six cube map texture targets form a single cube map texture though
each target names a distinct face of the cube map. The `TEXTURE_CUBE_MAP_+` targets listed above update their appropriate cube map face 2D texture image. Note that the six cube map two-dimensional image tokens such as `TEXTURE_CUBE_MAP_POSITIVE_X` are used when specifying, updating, or querying one of a cube map’s six two-dimensional images, but when binding to a cube map texture object (that is when the cube map is accessed as a whole as opposed to a particular two-dimensional image), the `TEXTURE_CUBE_MAP` target is specified.

When the `target` parameter to `TexImage2D` is one of the six cube map two-dimensional image targets, the error `INVALID_VALUE` is generated if the `width` and `height` parameters are not equal.

When `target` is `TEXTURE_RECTANGLE`, an `INVALID_VALUE` error is generated if `level` is non-zero.

An `INVALID_VALUE` error is generated if `border` is non-zero.

Finally, the command

```c
void TexImage1D( enum target, int level,
    int internalformat, sizei width, int border,
    enum format, enum type, const void *data );
```

is used to specify a one-dimensional texture image. `target` must be either `TEXTURE_1D`, or `PROXY_TEXTURE_1D` in the special case discussed in section 3.8.15.

For the purposes of decoding the texture image, `TexImage1D` is equivalent to calling `TexImage2D` with corresponding arguments and `height` of 1.

The image indicated to the GL by the image pointer is decoded and copied into the GL’s internal memory.

We shall refer to the decoded image as the texel array. A three-dimensional texel array has width, height, and depth \( w_s, h_s, d_s \) as defined in equation 3.16. A two-dimensional or rectangular texel array has depth \( d_s = 1 \), with height \( h_s \) and width \( w_s \) as above. A one-dimensional texel array has depth \( d_s = 1 \), height \( h_s = 1 \), and width \( w_s \) as above.

An element \((i, j, k)\) of the texel array is called a texel (for a two-dimensional texture or one-dimensional array texture, \( k \) is irrelevant; for a one-dimensional texture, \( j \) and \( k \) are both irrelevant). The texture value used in texturing a fragment is determined by sampling the texture in a shader, but may not correspond to any actual texel. See figure 3.6. If target is `TEXTURE_CUBE_MAP_ARRAY`, the texture value is determined by \((s, t, r, q)\) coordinates where \( s, t, \) and \( r \) are defined to be the same as for `TEXTURE_CUBE_MAP` and \( q \) is defined as the index of a specific cube map in the cube map array.

If the `data` argument of `TexImage1D`, `TexImage2D`, or `TexImage3D` is a null pointer (a zero-valued pointer in the C implementation), and the pixel unpack...
Figure 3.6. A texture image and the coordinates used to access it. This is a two-dimensional texture with \( n = 3 \) and \( m = 2 \). A one-dimensional texture would consist of a single horizontal strip. \( \alpha \) and \( \beta \), values used in blending adjacent texels to obtain a texture value, are also shown.
buffer object is zero, a one-, two-, or three-dimensional texel array is created with
the specified target, level, internalformat, border, width, height, and depth, but
with unspecified image contents. In this case no pixel values are accessed in client
memory, and no pixel processing is performed. Errors are generated, however, ex-
actly as though the data pointer were valid. Otherwise if the pixel unpack buffer
object is non-zero, the data argument is treatedly normally to refer to the beginning
of the pixel unpack buffer object’s data.

3.8.4 Alternate Texture Image Specification Commands

Two-dimensional and one-dimensional texture images may also be specified using
image data taken directly from the framebuffer, and rectangular subregions of
existing texture images may be respecified.

The command

```c
void CopyTexImage2D( enum target, int level,
                     enum internalformat, int x, int y, sizei width,
                     sizei height, int border );
```
defines a two-dimensional texel array in exactly the manner of TexImage2D, ex-
cept that the image data are taken from the framebuffer rather than from client
memory. Currently, target must be one of TEXTURE_2D, TEXTURE_1D_ARRAY,
TEXTURE_RECTANGLE, TEXTURE_CUBE_MAP_POSITIVE_X, TEXTURE_CUBE_-_MAP_NEGATIVE_X,
TEXTURE_CUBE_MAP_POSITIVE_Y, TEXTURE_CUBE_MAP_NEGATIVE_Y, TEXTURE_CUBE_MAP_POSITIVE_Z, or
TEXTURE_CUBE_MAP_NEGATIVE_Z. x, y, width, and height correspond precisely
to the corresponding arguments to ReadPixels (refer to section 4.3.1); they specify
the image’s width and height, and the lower left (x, y) coordinates of the frame-
buffer region to be copied. The image is taken from the framebuffer exactly as
if these arguments were passed to ReadPixels with argument type set to COLOR,
DEPTH, or DEPTH_STENCIL, depending on internalformat, stopping after con-
version of depth values. RGBA data is taken from the current color buffer, while
depth component and stencil index data are taken from the depth and sten-
cil buffers, respectively. The error INVALID_OPERATION is generated if depth
component data is required and no depth buffer is present; if stencil index data is
required and no stencil buffer is present; if integer RGBA data is required and the
format of the current color buffer is not integer; or if floating- or fixed-point RGBA
data is required and the format of the current color buffer is integer.

Subsequent processing is identical to that described for TexImage2D, begin-
ning with clamping of the R, G, B, A, or depth values, and masking of the stencil.
index values from the resulting pixel groups. Parameters *level*, *internalformat*, and *border* are specified using the same values, with the same meanings, as the equivalent arguments of *TexImage2D*. An invalid value specified for *internalformat* generates the error *INVALID_ENUM*. The constraints on *width*, *height*, and *border* are exactly those for the equivalent arguments of *TexImage2D*.

When the *target* parameter to *CopyTexImage2D* is one of the six cube map two-dimensional image targets, the error *INVALID_VALUE* is generated if the *width* and *height* parameters are not equal.

An *INVALID_FRAMEBUFFER_OPERATION* error will be generated if the object bound to *READ_FRAMEBUFFER_BINDING* (see section 4.4) is not framebuffer complete (as defined in section 4.4.4). An *INVALID_OPERATION* error will be generated if the object bound to *READ_FRAMEBUFFER_BINDING* is framebuffer complete and the value of *SAMPLE_BUFFERS* is greater than zero.

The command

```c
void CopyTexImage1D(enum target, int level,
                   enum internalformat, int x, int y, sizei width,
                   int border);
```

defines a one-dimensional texel array in exactly the manner of *TexImage1D*, except that the image data are taken from the framebuffer, rather than from client memory. Currently, *target* must be *TEXTURE_1D*. For the purposes of decoding the texture image, *CopyTexImage1D* is equivalent to calling *CopyTexImage2D* with corresponding arguments and *height* of 1, except that the *height* of the image is always 1, regardless of the value of *border*. *level*, *internalformat*, and *border* are specified using the same values, with the same meanings, as the equivalent arguments of *TexImage1D*. The constraints on *width* and *border* are exactly those of the equivalent arguments of *TexImage1D*.

Six additional commands,

```c
void TexSubImage3D( enum target, int level, int xoffset, int yoffset, int zoffset, sizei width, sizei height,
                    sizei depth, enum format, enum type, const void *data );
void TexSubImage2D( enum target, int level, int xoffset, int yoffset, sizei width, sizei height,
                    enum type, const void *data );
void TexSubImage1D( enum target, int level, int xoffset, sizei width, enum format, enum type, const void *data );
```

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void CopyTexSubImage3D(
  enum target, int level,
  int xoffset, int yoffset, int zoffset, int x, int y,
  sizei width, sizei height);
void CopyTexSubImage2D(
  enum target, int level,
  int xoffset, int yoffset, int x, int y, sizei width,
  sizei height);
void CopyTexSubImage1D( enum target, int level,
  int xoffset, int x, int y, sizei width);

respecify only a rectangular subregion of an existing texel array. No change is made to the internalformat, width, height, depth, or border parameters of the specified texel array, nor is any change made to texel values outside the specified subregion.

The target arguments of TexSubImage1D and CopyTexSubImage1D must be TEXTURE_1D, the target arguments of TexSubImage2D and CopyTexSubImage2D must be one of TEXTURE_2D, TEXTURE_1D_ARRAY, TEXTURE_RECTANGLE, TEXTURE_CUBE_MAP_POSITIVE_X, TEXTURE_CUBE_MAP_NEGATIVE_X, TEXTURE_CUBE_MAP_POSITIVE_Y, TEXTURE_CUBE_MAP_NEGATIVE_Y, TEXTURE_CUBE_MAP_POSITIVE_Z, or TEXTURE_CUBE_MAP_NEGATIVE_Z, and the target arguments of TexSubImage3D and CopyTexSubImage3D must be TEXTURE_3D, TEXTURE_2D_ARRAY, or TEXTURE_CUBE_MAP_ARRAY.

The level parameter of each command specifies the level of the texel array that is modified. If level is less than zero or greater than the base 2 logarithm of the maximum texture width, height, or depth, the error INVALID_VALUE is generated. If target is TEXTURE_RECTANGLE and level is not zero, the error INVALID_VALUE is generated. TexSubImage3D arguments width, height, depth, format, type, and data match the corresponding arguments to TexImage3D, meaning that they are specified using the same values, and have the same meanings. Likewise, TexSubImage2D arguments width, height, format, type, and data match the corresponding arguments to TexImage2D, and TexSubImage1D arguments width, format, type, and data match the corresponding arguments to TexImage1D.

CopyTexSubImage3D and CopyTexSubImage2D arguments x, y, width, and height match the corresponding arguments to CopyTexImage2D\(^1\). CopyTexSubImage1D arguments x, y, and width match the corresponding arguments to CopyTexImage1D. Each of the TexSubImage commands interprets and processes pixel groups in exactly the manner of its TexImage counterpart, except that the assignment of R, G, B, A, depth, and stencil index pixel group values to the texture

---

\(^1\) Because the framebuffer is inherently two-dimensional, there is no CopyTexImage3D command.
components is controlled by the \textit{internalformat} of the texel array, not by an argument to the command. The same constraints and errors apply to the \texttt{TexSubImage} commands’ argument \texttt{format} and the \textit{internalformat} of the texel array being re-specified as apply to the \texttt{format} and \textit{internalformat} arguments of its \texttt{TexImage} counterparts.

Arguments \texttt{xoffset}, \texttt{yoffset}, and \texttt{zoffset} of \texttt{TexSubImage3D} and \texttt{CopyTexImage3D} specify the lower left texel coordinates of a \textit{width}-wide by \textit{height}-high by \textit{depth}-deep rectangular subregion of the texel array. For cube map array textures, \texttt{zoffset} is the first layer-face to update, and \textit{depth} is the number of layer-faces to update. The \textit{depth} argument associated with \texttt{CopyTexImage3D} is always 1, because framebuffer memory is two-dimensional - only a portion of a single \((s,t)\) slice of a three-dimensional texture is replaced by \texttt{CopyTexImage3D}.

Negative values of \texttt{xoffset}, \texttt{yoffset}, and \texttt{zoffset} correspond to the coordinates of border texels, addressed as in figure 3.6. Taking \(w_s, h_s, d_s, w_b, h_b,\) and \(d_b\) to be the specified width, height, depth, and border width, border height, and border depth of the texel array, and taking \(x, y, z, w, h,\) and \(d\) to be the \texttt{xoffset}, \texttt{yoffset}, \texttt{zoffset}, \texttt{width}, \texttt{height}, and \texttt{depth} argument values, any of the following relationships generates the error \texttt{INVALID_VALUE}:

\[
\begin{align*}
  x &< -w_b \\
  x + w &> w_s - w_b \\
  y &< -h_b \\
  y + h &> h_s - h_b \\
  z &< -d_b \\
  z + d &> d_s - d_b 
\end{align*}
\]

Counting from zero, the \(n\)th pixel group is assigned to the texel with internal integer coordinates \([i, j, k]\), where

\[
\begin{align*}
  i &= x + (n \mod w) \\
  j &= y + (\left\lfloor \frac{n}{w} \right\rfloor \mod h) \\
  k &= z + (\left\lfloor \frac{n}{\text{width} \times \text{height}} \right\rfloor \mod d)
\end{align*}
\]

Arguments \texttt{xoffset} and \texttt{yoffset} of \texttt{TexSubImage2D} and \texttt{CopyTexImage2D} specify the lower left texel coordinates of a \textit{width}-wide by \textit{height}-high rectangular subregion of the texel array. Negative values of \texttt{xoffset} and \texttt{yoffset} correspond to
the coordinates of border texels, addressed as in figure 3.6. Taking \( w_s, h_s, \) and \( b_s \)
to be the specified width, height, and border width of the texel array, and taking \( x, y, w, \) and \( h \)
to be the \( x\text{-offset}, y\text{-offset}, \text{width}, \) and \( \text{height} \) argument values, any of the
following relationships generates the error \text{INVALID\_VALUE}:

\[
\begin{align*}
  x &< -b_s \\
  x + w &> w_s - b_s \\
  y &< -b_s \\
  y + h &> h_s - b_s
\end{align*}
\]

Counting from zero, the \( n \)th pixel group is assigned to the texel with internal integer
coordinates \([i,j]\), where

\[
\begin{align*}
  i &= x + (n \mod w) \\
  j &= y + (\lfloor \frac{n}{w} \rfloor \mod h)
\end{align*}
\]

The \( x\text{-offset} \) argument of \texttt{TexSubImage1D} and \texttt{CopyTexSubImage1D} specifies the left texel coordinate of a \texttt{width}-wide subregion of the texel array. Negative
values of \( x\text{-offset} \) correspond to the coordinates of border texels. Taking \( w_s \) and \( b_s \)
to be the specified width and border width of the texel array, and \( x \) and \( w \) to be the
\( x\text{-offset} \) and \texttt{width} argument values, either of the following relationships generates
the error \text{INVALID\_VALUE}:

\[
\begin{align*}
  x &< -b_s \\
  x + w &> w_s - b_s
\end{align*}
\]

Counting from zero, the \( n \)th pixel group is assigned to the texel with internal integer
coordinates \([i]\), where

\[
  i = x + (n \mod w)
\]

Texture images with compressed internal formats may be stored in such a way
that it is not possible to modify an image with subimage commands without having
to decompress and recompress the texture image. Even if the image were modified
in this manner, it may not be possible to preserve the contents of some of the
texels outside the region being modified. To avoid these complications, the
GL does not support arbitrary modifications to texture images with compressed
internal formats. Calling \texttt{TexSubImage3D}, \texttt{CopyTexSubImage3D}, \texttt{TexSubImage2D}, \texttt{CopyTexSubImage2D}, \texttt{TexSubImage1D}, or \texttt{CopyTexSubImage1D} will
result in an \texttt{INVALID\_OPERATION} error if \(xoffset\), \(yoffset\), or \(zoffset\) is not equal to 
\(-b_s\) (border width). In addition, the contents of any texel outside the region mod-
ified by such a call are undefined. These restrictions may be relaxed for specific
compressed internal formats whose images are easily modified.

If the internal format of the texture image being modified is one of the spe-
cific \texttt{RGTC} formats described in table 3.14, the texture is stored using one of the
\texttt{RGTC} texture image encodings (see appendix C.1). Since \texttt{RGTC} images are easily
edited along \(4 \times 4\) texel boundaries, the limitations on subimage location and size
are relaxed for \texttt{TexSubImage2D}, \texttt{TexSubImage3D}, \texttt{CopyTexSubImage2D}, and
\texttt{CopyTexSubImage3D}. These commands will generate an \texttt{INVALID\_OPERATION}
error if one of the following conditions occurs:

- \texttt{width} is not a multiple of four, \texttt{width + xoffset} is not equal to the value of
  \texttt{TEXTURE\_WIDTH}, and either \(xoffset\) or \(yoffset\) is non-zero.

- \texttt{height} is not a multiple of four, \texttt{height + yoffset} is not equal to the value of
  \texttt{TEXTURE\_HEIGHT}, and either \(xoffset\) or \(yoffset\) is non-zero.

- \(xoffset\) or \(yoffset\) is not a multiple of four.

The contents of any \(4 \times 4\) block of texels of an \texttt{RGTC} compressed texture
image that does not intersect the area being modified are preserved during valid
\texttt{TexSubImage*} and \texttt{CopyTexSubImage*} calls.

Calling \texttt{CopyTexSubImage3D}, \texttt{CopyTexImage2D}, \texttt{CopyTexSubImage2D},
\texttt{CopyTexImage1D}, or \texttt{CopyTexSubImage1D} will result in an \texttt{INVALID\_FRAMEBUFFER\_OPERATION}
error if the object bound to \texttt{READ\_FRAMEBUFFER\_BINDING} is not framebuffer complete (see section 4.4.4).

Texture Copying Feedback Loops

Calling \texttt{CopyTexSubImage3D}, \texttt{CopyTexImage2D}, \texttt{CopyTexSubImage2D},
\texttt{CopyTexImage1D}, or \texttt{CopyTexSubImage1D} will result in undefined behavior if
the destination texture image level is also bound to to the selected read buffer (see
section 4.3.1) of the read framebuffer. This situation is discussed in more detail in
the description of feedback loops in section 4.4.3.

3.8.5 Compressed Texture Images

Texture images may also be specified or modified using image data already stored
in a known compressed image format, such as the \texttt{RGTC} formats defined in ap-
pendix C, or additional formats defined by GL extensions.

The commands
void CompressedTexImage1D(enum target, int level,
        enum internalformat,sizei width, int border,
        sizei imageSize, const void *data);
void CompressedTexImage2D(enum target, int level,
        enum internalformat,sizei width,sizei height,
        int border, sizei imageSize, const void *data);
void CompressedTexImage3D(enum target, int level,
        enum internalformat,sizei width,sizei height,
       sizei depth, int border, sizei imageSize, const
        void *data);

define one-, two-, and three-dimensional texture images, respectively, with incoming
data stored in a specific compressed image format. The target, level, internalformat, width, height, depth, and border parameters have the same meaning as in
TexImage1D, TexImage2D, and TexImage3D, except that compressed rectangular texture formats are not supported. data refers to compressed image data stored in the specific compressed image format corresponding to internalformat. If a pixel unpack buffer is bound (as indicated by a non-zero value of PIXEL_UNPACK_BUFFER_BINDING), data is an offset into the pixel unpack buffer and the compressed data is read from the buffer relative to this offset; otherwise, data is a pointer to client memory and the compressed data is read from client memory relative to the pointer.

If the target parameter to any of the CompressedTexImage\textsuperscript{n}D commands is TEXTURE_RECTANGLE or PROXY_TEXTURE_RECTANGLE, the error INVALID_ENUM is generated.

internalformat must be a supported specific compressed internal format. An INVALID_ENUM error will be generated if any other values, including any of the generic compressed internal formats, is specified.

For all other compressed internal formats, the compressed image will be decoded according to the specification defining the internalformat token. Compressed texture images are treated as an array of imageSize ubyte relative to data. If a pixel unpack buffer object is bound and data + imageSize is greater than the size of the pixel buffer, an INVALID_OPERATION error results. All pixel storage modes are ignored when decoding a compressed texture image. If the imageSize parameter is not consistent with the format, dimensions, and contents of the compressed image, an INVALID_VALUE error results. If the compressed image is not encoded according to the defined image format, the results of the call are undefined.

Specific compressed internal formats may impose format-specific restrictions on the use of the compressed image specification calls or parameters. For example,
3.8. TEXTURING

the compressed image format might be supported only for 2D textures, or might not allow non-zero border values. Any such restrictions will be documented in the extension specification defining the compressed internal format; violating these restrictions will result in an INVALID_OPERATION error.

Any restrictions imposed by specific compressed internal formats will be invariant, meaning that if the GL accepts and stores a texture image in compressed form, providing the same image to CompressedTexImage1D, CompressedTexImage2D, or CompressedTexImage3D will not result in an INVALID_OPERATION error if the following restrictions are satisfied:

- data points to a compressed texture image returned by GetCompressedTexImage (section 6.1.4).
- target, level, and internalformat match the target, level and format parameters provided to the GetCompressedTexImage call returning data.
- width, height, depth, internalformat, and imageSize match the values of TEXTURE_WIDTH, TEXTURE_HEIGHT, TEXTURE_DEPTH, TEXTURE_INTERNAL_FORMAT, and TEXTURE_COMPRESSED_IMAGE_SIZE for image level level in effect at the time of the GetCompressedTexImage call returning data.

This guarantee applies not just to images returned by GetCompressedTexImage, but also to any other properly encoded compressed texture image of the same size and format.

If internalformat is one of the specific RGTC formats described in table 3.14, the compressed image data is stored using one of the RGTC compressed texture image encodings (see appendix C.1) The RGTC texture compression algorithm supports only two-dimensional images without borders. If internalformat is an RGTC format, CompressedTexImage1D will generate an INVALID_ENUM error; CompressedTexImage2D will generate an INVALID_OPERATION error if border is non-zero or target is TEXTURE_RECTANGLE; and CompressedTexImage3D will generate an INVALID_OPERATION error if border is non-zero or target is not TEXTURE_2D_ARRAY.

If the data argument of CompressedTexImage1D, CompressedTexImage2D, or CompressedTexImage3D is a null pointer (a zero-valued pointer in the C implementation), and the pixel unpack buffer object is zero, a texel array with unspecified image contents is created, just as when a null pointer is passed to TexImage1D, TexImage2D, or TexImage3D.

The commands
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```c
void CompressedTexSubImage1D( enum target, int level,
    int xoffset, sizei width, enum format, sizei imageSize,
    const void *data );
void CompressedTexSubImage2D( enum target, int level,
    int xoffset, int yoffset, sizei width, sizei height,
    enum format, sizei imageSize, const void *data );
void CompressedTexSubImage3D( enum target, int level,
    int xoffset, int yoffset, int zoffset, sizei width,
    sizei height, sizei depth, enum format,
    sizei imageSize, const void *data );
```

respecify only a rectangular region of an existing texel array, with incoming data stored in a known compressed image format. The `target`, `level`, `xoffset`, `yoffset`, `zoffset`, `width`, `height`, and `depth` parameters have the same meaning as in `TexSubImage1D`, `TexSubImage2D`, and `TexSubImage3D`. `data` points to compressed image data stored in the compressed image format corresponding to `format`. Using any of the generic compressed internal formats as `format` will result in an `INVALID_ENUM` error.

If the `target` parameter to any of the `CompressedTexSubImage1D` commands is `TEXTURE_RECTANGLE` or `PROXY_TEXTURE_RECTANGLE`, the error `INVALID_ENUM` is generated.

The image pointed to by `data` and the `imageSize` parameter are interpreted as though they were provided to `CompressedTexImage1D`, `CompressedTexImage2D`, and `CompressedTexImage3D`. These commands do not provide for image format conversion, so an `INVALID_OPERATION` error results if `format` does not match the internal format of the texture image being modified. If the `imageSize` parameter is not consistent with the format, dimensions, and contents of the compressed image (too little or too much data), an `INVALID_VALUE` error results.

As with `CompressedTexImage` calls, compressed internal formats may have additional restrictions on the use of the compressed image specification calls or parameters. Any such restrictions will be documented in the specification defining the compressed internal format; violating these restrictions will result in an `INVALID_OPERATION` error.

Any restrictions imposed by specific compressed internal formats will be invariant, meaning that if the GL accepts and stores a texture image in compressed form, providing the same image to `CompressedTexSubImage1D`, `CompressedTexSubImage2D`, `CompressedTexSubImage3D` will not result in an `INVALID_OPERATION` error if the following restrictions are satisfied:

- `data` points to a compressed texture image returned by `GetCompressedTexImage` (section 6.1.4).
3.8. TEXTURING

- target, level, and format match the target, level and format parameters provided to the `GetCompressedTexImage` call returning data.

- width, height, depth, format, and imageSize match the values of `TEXTURE_WIDTH`, `TEXTURE_HEIGHT`, `TEXTURE_DEPTH`, `TEXTURE_INTERNAL_FORMAT`, and `TEXTURE_COMPRESSED_IMAGE_SIZE` for image level level in effect at the time of the `GetCompressedTexImage` call returning data.

- width, height, depth, and format match the values of `TEXTURE_WIDTH`, `TEXTURE_HEIGHT`, `TEXTURE_DEPTH`, and `TEXTURE_INTERNAL_FORMAT` currently in effect for image level level.

- xoffset, yoffset, and zoffset are all zero.

This guarantee applies not just to images returned by `GetCompressedTexImage`, but also to any other properly encoded compressed texture image of the same size.

Calling `CompressedTexSubImage3D`, `CompressedTexSubImage2D`, or `CompressedTexSubImage1D` will result in an `INVALID_OPERATION` error if xoffset, yoffset, or zoffset are not equal to zero, or if width, height, and depth do not match the values of `TEXTURE_WIDTH`, `TEXTURE_HEIGHT`, or `TEXTURE_DEPTH`, respectively. The contents of any texel outside the region modified by the call are undefined. These restrictions may be relaxed for specific compressed internal formats whose images are easily modified.

If internalformat is one of the specific RGTC formats described in table 3.14, the texture is stored using one of the RGTC compressed texture image encodings (see appendix C.1). If internalformat is an RGTC format, `CompressedTexSubImage1D` will generate an `INVALID_ENUM` error; `CompressedTexSubImage2D` will generate an `INVALID_OPERATION` error if border is non-zero; and `CompressedTexSubImage3D` will generate an `INVALID_OPERATION` error if border is non-zero or target is not `TEXTURE_2D_ARRAY`. Since RGTC images are easily edited along 4×4 texel boundaries, the limitations on subimage location and size are relaxed for `CompressedTexSubImage2D` and `CompressedTexSubImage3D`. These commands will result in an `INVALID_OPERATION` error if one of the following conditions occurs:

- width is not a multiple of four, and width + xoffset is not equal to the value of `TEXTURE_WIDTH`.

- height is not a multiple of four, and height + yoffset is not equal to the value of `TEXTURE_HEIGHT`. 

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- \( x_{offset} \) or \( y_{offset} \) is not a multiple of four.

The contents of any \( 4 \times 4 \) block of texels of an RGTC compressed texture image that does not intersect the area being modified are preserved during valid \( \text{TexSubImage}^* \) and \( \text{CopyTexSubImage}^* \) calls.

3.8.6 Multisample Textures

In addition to the texture types described in previous sections, two additional types of textures are supported. A multisample texture is similar to a two-dimensional or two-dimensional array texture, except it contains multiple samples per texel. Multisample textures do not have multiple image levels.

The commands

```c
void \textbf{TexImage2DMultisample}(\text{enum target, sizei samples, int internalformat, sizei width, sizei height, boolean fixedsamplelocations});
```

```c
void \textbf{TexImage3DMultisample}(\text{enum target, sizei samples, int internalformat, sizei width, sizei height,sizei depth, boolean fixedsamplelocations});
```

establish the data storage, format, dimensions, and number of samples of a multisample texture’s image. For \textbf{TexImage2DMultisample}, \textit{target} must be \texttt{TEXTURE_2D_MULTISAMPLE} or \texttt{PROXY_TEXTURE_2D_MULTISAMPLE} and for \textbf{TexImage3DMultisample} \textit{target} must be \texttt{TEXTURE_2D_MULTISAMPLE_ARRAY} or \texttt{PROXY_TEXTURE_2D_MULTISAMPLE_ARRAY}. \textit{width} and \textit{height} are the dimensions in texels of the texture.

\textit{internalformat} must be color-renderable, depth-renderable, or stencil-renderable (as defined in section 4.4.4). The error \texttt{INVALID_OPERATION} may be generated if any of the following are true:

- \textit{internalformat} is a depth/stencil-renderable format and \textit{samples} is greater than the value of \texttt{MAX_DEPTH_TEXTURE_SAMPLES}

- \textit{internalformat} is a color-renderable format and \textit{samples} is greater than the value of \texttt{MAX_COLOR_TEXTURE_SAMPLES}

- \textit{internalformat} is a signed or unsigned integer format and \textit{samples} is greater than the value of \texttt{MAX_INTEGER_SAMPLES}.
If `fixedsamplelocations` is `TRUE`, the image will use identical sample locations and the same number of samples for all texels in the image, and the sample locations will not depend on the `internalformat` or size of the image. If either `width` or `height` is greater than `MAX_TEXTURE_SIZE`, or if `samples` is greater than `MAX_SAMPLES`, then the error `INVALID_VALUE` is generated. If the GL is unable to create a texture level of the requested size, the error `OUT_OF_MEMORY` is generated.

When a multisample texture is accessed in a shader, the access takes one vector of integers describing which texel to fetch and an integer corresponding to the sample numbers described in section 3.3.1 describing which sample within the texel to fetch. No standard sampling instructions are allowed on the multisample texture targets.

### 3.8.7 Buffer Textures

In addition to one-, two-, and three-dimensional, one- and two-dimensional array, and cube map textures described in previous sections, one additional type of texture is supported. A buffer texture is similar to a one-dimensional texture. However, unlike other texture types, the texel array is not stored as part of the texture. Instead, a buffer object is attached to a buffer texture and the texel array is taken from that buffer object’s data store. When the contents of a buffer object’s data store are modified, those changes are reflected in the contents of any buffer texture to which the buffer object is attached. Buffer textures do not have multiple image levels; only a single data store is available.

The command

```c
void TexBuffer(enum target, enum internalformat, uint buffer);
```

attaches the storage for the buffer object named `buffer` to the active buffer texture, and specifies an internal format for the texel array found in the attached buffer object. If `buffer` is zero, any buffer object attached to the buffer texture is detached, and no new buffer object is attached. If `buffer` is non-zero, but is not the name of an existing buffer object, the error `INVALID_OPERATION` is generated. `target` must be `TEXTURE_BUFFER`. `internalformat` specifies the storage format, and must be one of the sized internal formats found in table 3.15.

When a buffer object is attached to a buffer texture, the buffer object’s data store is taken as the texture’s texel array. The number of texels in the buffer texture’s texel array is given by
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\[
\frac{\text{buffer_size}}{\text{components} \times \text{sizeof(base_type)}}.
\]

where buffer_size is the size of the buffer object, in basic machine units and components and base_type are the element count and base data type for elements, as specified in table 3.15. The number of texels in the texel array is then clamped to the implementation-dependent limit MAX_TEXTURE_BUFFER_SIZE. When a buffer texture is accessed in a shader, the results of a texel fetch are undefined if the specified texel coordinate is negative, or greater than or equal to the clamped number of texels in the texel array.

When a buffer texture is accessed in a shader, an integer is provided to indicate the texel coordinate being accessed. If no buffer object is bound to the buffer texture, the results of the texel access are undefined. Otherwise, the attached buffer object’s data store is interpreted as an array of elements of the GL data type corresponding to internalformat. Each texel consists of one to four elements that are mapped to texture components (R, G, B, and A). Element m of the texel numbered n is taken from element \( n \times \text{components} + m \) of the attached buffer object’s data store. Elements and texels are both numbered starting with zero. For texture formats with signed or unsigned normalized fixed-point components, the extracted values are converted to floating-point using equations 2.1 or 2.3, respectively. The components of the texture are then converted to an (R,G,B,A) vector according to table 3.15, and returned to the shader as a four-component result vector with components of the appropriate data type for the texture’s internal format. The base data type, component count, normalized component information, and mapping of data store elements to texture components is specified in table 3.15.

<table>
<thead>
<tr>
<th>Sized Internal Format</th>
<th>Base Type</th>
<th>Components</th>
<th>Norm</th>
<th>Component 0</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8</td>
<td>ubyte</td>
<td>1</td>
<td>Yes</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16</td>
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<td>Yes</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16F</td>
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<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R32F</td>
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<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8I</td>
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<td>1</td>
<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16I</td>
<td>short</td>
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<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R32I</td>
<td>int</td>
<td>1</td>
<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8UI</td>
<td>ubyte</td>
<td>1</td>
<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>No</td>
<td>R 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Continued on next page)
### Internal formats for buffer textures (continued)

<table>
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<tr>
<th>Sized Internal Format</th>
<th>Base Type</th>
<th>Components</th>
<th>Norm</th>
<th>Component 0</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
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<td>0</td>
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<td>G</td>
<td>0</td>
<td>1</td>
</tr>
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<td>RG16F</td>
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<td>No</td>
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<td>G</td>
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<td>1</td>
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</tr>
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<tr>
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<td>No</td>
<td>R</td>
<td>G</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
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</tr>
<tr>
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<td>No</td>
<td>R</td>
<td>G</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>RG16UI</td>
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<td>No</td>
<td>R</td>
<td>G</td>
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<td>1</td>
</tr>
<tr>
<td>RG32UI</td>
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<td>R</td>
<td>G</td>
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<td>G</td>
<td>B</td>
<td>A</td>
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<td>G</td>
<td>B</td>
<td>A</td>
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<td>R</td>
<td>G</td>
<td>B</td>
<td>A</td>
</tr>
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<td>No</td>
<td>R</td>
<td>G</td>
<td>B</td>
<td>A</td>
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<td>R</td>
<td>G</td>
<td>B</td>
<td>A</td>
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<td>No</td>
<td>R</td>
<td>G</td>
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<td>RGBA32I</td>
<td>int</td>
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<td>R</td>
<td>G</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>RGBA8UI</td>
<td>ubyte</td>
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<td>No</td>
<td>R</td>
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<td>B</td>
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<td>R</td>
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<td>A</td>
</tr>
<tr>
<td>RGBA32UI</td>
<td>uint</td>
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<td>No</td>
<td>R</td>
<td>G</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 3.15: Internal formats for buffer textures. For each format, the data type of each element is indicated in the “Base Type” column and the element count is in the “Components” column. The “Norm” column indicates whether components should be treated as normalized floating-point values. The “Component 0, 1, 2, and 3” columns indicate the mapping of each element of a texel to texture components.

In addition to attaching buffer objects to textures, buffer objects can be bound to the buffer object target named TEXTURE_BUFFER, in order to specify, modify, or...
read the buffer object’s data store. The buffer object bound to TEXTURE_BUFFER has no effect on rendering. A buffer object is bound to TEXTURE_BUFFER by calling 

`BindBuffer` with `target` set to `TEXTURE_BUFFER`, as described in section 2.9.

### 3.8.8 Texture Parameters

Various parameters control how the texel array is treated when specified or changed, and when applied to a fragment. Each parameter is set by calling

```c
void TexParameter{if}(enum target, enum pname, T param);
void TexParameter{if}v(enum target, enum pname, const T *params);
void TexParameterI{i u}v(enum target, enum pname, const T *params);
```

*target* is the target, either `TEXTURE_1D`, `TEXTURE_2D`, `TEXTURE_3D`, `TEXTURE_1D_ARRAY`, `TEXTURE_2D_ARRAY`, `TEXTURE_RECTANGLE`, `TEXTURE_CUBE_MAP`, or `TEXTURE_CUBE_MAP_ARRAY`, *params* is a symbolic constant indicating the parameter to be set; the possible constants and corresponding parameters are summarized in table 3.16. In the first form of the command, *param* is a value to which to set a single-valued parameter; in the remaining forms, *params* is an array of parameters whose type depends on the parameter being set.

If the values for `TEXTURE_BORDER_COLOR` are specified with `TexParameterIiv` or `TexParameterIuiv`, the values are unmodified and stored with an internal data type of integer. If specified with `TexParameteriv`, they are converted to floating-point using equation 2.2. Otherwise the values are unmodified and stored as floating-point.

If *pname* is `TEXTURE_SWIZZLE_RGBA`, *params* is an array of four enums which respectively set the `TEXTURE_SWIZZLE_R`, `TEXTURE_SWIZZLE_G`, `TEXTURE_SWIZZLE_B`, and `TEXTURE_SWIZZLE_A` parameters simultaneously.

The error `INVALID_ENUM` is generated if the type of the parameter specified by *pname* is enum, and the value(s) specified by *param* or *params* are not among the legal values shown in table 3.16.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Legal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEXTURE_BASE_LEVEL</td>
<td>int</td>
<td>any non-negative integer</td>
</tr>
<tr>
<td>TEXTURE_BORDER_COLOR</td>
<td>4 floats, ints, or uints</td>
<td>any 4 values</td>
</tr>
</tbody>
</table>

Texture parameters continued on next page
### 3.8. TEXTURING

Texture parameters continued from previous page

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Legal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEXTURE_COMPARE_MODE</td>
<td>enum</td>
<td>NONE, COMPARE_REF_TO_TEXTURE</td>
</tr>
<tr>
<td>TEXTURE_COMPARE_FUNC</td>
<td>enum</td>
<td>LEQUAL, GEQUAL, LESS, GREATER, EQUAL, NOTEQUAL, ALWAYS, NEVER</td>
</tr>
<tr>
<td>TEXTURE_LOD_BIAS</td>
<td>float</td>
<td>any value</td>
</tr>
<tr>
<td>TEXTURE_MAG_FILTER</td>
<td>enum</td>
<td>NEAREST, LINEAR</td>
</tr>
<tr>
<td>TEXTURE_MAX_LEVEL</td>
<td>int</td>
<td>any non-negative integer</td>
</tr>
<tr>
<td>TEXTURE_MAX_LOD</td>
<td>float</td>
<td>any value</td>
</tr>
<tr>
<td>TEXTURE_MIN_FILTER</td>
<td>enum</td>
<td>NEAREST, LINEAR, NEAREST_MIPMAP_NEAREST, NEAREST_MIPMAP_LINEAR, LINEAR_MIPMAP_NEAREST, LINEAR_MIPMAP_LINEAR,</td>
</tr>
<tr>
<td>TEXTURE_MIN_LOD</td>
<td>float</td>
<td>any value</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_R</td>
<td>enum</td>
<td>RED, GREEN, BLUE, ALPHA, ZERO, ONE</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_G</td>
<td>enum</td>
<td>RED, GREEN, BLUE, ALPHA, ZERO, ONE</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_B</td>
<td>enum</td>
<td>RED, GREEN, BLUE, ALPHA, ZERO, ONE</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_A</td>
<td>enum</td>
<td>RED, GREEN, BLUE, ALPHA, ZERO, ONE</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_RGBA</td>
<td>4 enums</td>
<td>RED, GREEN, BLUE, ALPHA, ZERO, ONE</td>
</tr>
<tr>
<td>TEXTURE_WRAP_S</td>
<td>enum</td>
<td>CLAMP_TO_EDGE, REPEAT, CLAMP_TO_BORDER, MIRRORED_REPEAT</td>
</tr>
<tr>
<td>TEXTURE_WRAP_T</td>
<td>enum</td>
<td>CLAMP_TO_EDGE, REPEAT, CLAMP_TO_BORDER, MIRRORED_REPEAT</td>
</tr>
<tr>
<td>TEXTURE_WRAP_R</td>
<td>enum</td>
<td>CLAMP_TO_EDGE, REPEAT, CLAMP_TO_BORDER, MIRRORED_REPEAT</td>
</tr>
</tbody>
</table>

Table 3.16: Texture parameters and their values.
In the remainder of section 3.8, denote by \( \text{lod}_{\text{min}} \), \( \text{lod}_{\text{max}} \), \( \text{level}_{\text{base}} \), and \( \text{level}_{\text{max}} \) the values of the texture parameters \( \text{TEXTURE\_MIN\_LOD} \), \( \text{TEXTURE\_MAX\_LOD} \), \( \text{TEXTURE\_BASE\_LEVEL} \), and \( \text{TEXTURE\_MAX\_LEVEL} \) respectively.

Texture parameters for a cube map texture apply to the cube map as a whole; the six distinct two-dimensional texture images use the texture parameters of the cube map itself.

When \( \text{target} \) is \( \text{TEXTURE\_RECTANGLE} \), certain texture parameter values may not be specified. In this case, the error \( \text{INVALID\_ENUM} \) is generated if the \( \text{TEXTURE\_WRAP\_S} \), \( \text{TEXTURE\_WRAP\_T} \), or \( \text{TEXTURE\_WRAP\_R} \) parameter is set to \( \text{REPEAT} \) or \( \text{MIRRORED\_REPEAT} \). The error \( \text{INVALID\_ENUM} \) is generated if \( \text{TEXTURE\_MIN\_FILTER} \) is set to a value other than \( \text{NEAREST} \) or \( \text{LINEAR} \) (no mipmap filtering is permitted). The error \( \text{INVALID\_VALUE} \) is generated if \( \text{TEXTURE\_BASE\_LEVEL} \) is set to any value other than zero.

### 3.8.9 Depth Component Textures

Depth textures and the depth components of depth/stencil textures can be treated as \( \text{RED} \) textures during texture filtering and application (see section 3.8.16). The initial state for depth and depth/stencil textures treats them as \( \text{RED} \) textures.

### 3.8.10 Cube Map Texture Selection

When cube map texturing is enabled, the \((s \ t \ r)\) texture coordinates are treated as a direction vector \((r_x \ r_y \ r_z)\) emanating from the center of a cube (the \(q\) coordinate can be ignored, since it merely scales the vector without affecting the direction.) At texture application time, the interpolated per-fragment direction vector selects one of the cube map face’s two-dimensional images based on the largest magnitude coordinate direction (the major axis direction). If two or more coordinates have the identical magnitude, the implementation may define the rule to disambiguate this situation. The rule must be deterministic and depend only on \((r_x \ r_y \ r_z)\). The target column in table 3.17 explains how the major axis direction maps to the two-dimensional image of a particular cube map target.

Using the \(s_c\), \(t_c\), and \(m_a\) determined by the major axis direction as specified in table 3.17, an updated \((s \ t)\) is calculated as follows:

\[
\begin{align*}
  s &= \frac{1}{2} \left( \frac{s_c}{|m_a|} + 1 \right) \\
  t &= \frac{1}{2} \left( \frac{t_c}{|m_a|} + 1 \right)
\end{align*}
\]
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<table>
<thead>
<tr>
<th>Major Axis Direction</th>
<th>Target</th>
<th>( s_c )</th>
<th>( t_c )</th>
<th>( m_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+r_x)</td>
<td>TEXTURE_CUBE_MAP_POSITIVE_X</td>
<td>(-r_z)</td>
<td>(-r_y)</td>
<td>(+r_x)</td>
</tr>
<tr>
<td>(-r_x)</td>
<td>TEXTURE_CUBE_MAP_NEGATIVE_X</td>
<td>(+r_z)</td>
<td>(-r_y)</td>
<td>(-r_x)</td>
</tr>
<tr>
<td>(+r_y)</td>
<td>TEXTURE_CUBE_MAP_POSITIVE_Y</td>
<td>(+r_x)</td>
<td>( r_z)</td>
<td>(+r_y)</td>
</tr>
<tr>
<td>(-r_y)</td>
<td>TEXTURE_CUBE_MAP_NEGATIVE_Y</td>
<td>(+r_x)</td>
<td>( r_z)</td>
<td>(-r_y)</td>
</tr>
<tr>
<td>(+r_z)</td>
<td>TEXTURE_CUBE_MAP_POSITIVE_Z</td>
<td>(+r_x)</td>
<td>(-r_y)</td>
<td>(+r_z)</td>
</tr>
<tr>
<td>(-r_z)</td>
<td>TEXTURE_CUBE_MAP_NEGATIVE_Z</td>
<td>(-r_x)</td>
<td>(-r_y)</td>
<td>(-r_z)</td>
</tr>
</tbody>
</table>

Table 3.17: Selection of cube map images based on major axis direction of texture coordinates.

**Seamless Cube Map Filtering**

Seamless cube map filtering is enabled or disabled by calling `Enable` or `Disable`, respectively, with the symbolic constant `TEXTURE_CUBE_MAP_SEAMLESS`.

When seamless cube map filtering is disabled, the new \((s\ t)\) is used to find a texture value in the determined face’s two-dimensional image using the rules given in sections 3.8.11 through 3.8.12.

When seamless cube map filtering is enabled, the rules for texel selection in sections 3.8.11 through 3.8.12 are modified so that texture wrap modes are ignored. Instead,

- If **NEAREST** filtering is done within a mipmap level, always apply wrap mode `CLAMP_TO_EDGE`.
- If **LINEAR** filtering is done within a mipmap level, always apply wrap mode `CLAMP_TO_BORDER`. Then,
  - If a texture sample location would lie in the texture border in either \(u\) or \(v\), instead select the corresponding texel from the appropriate neighboring face.
  - If a texture sample location would lie in the texture border in both \(u\) and \(v\) (in one of the corners of the cube), there is no unique neighboring face from which to extract one texel. The recommended method to generate this texel is to average the values of the three available samples. However, implementations are free to construct this fourth texel in another way, so long as, when the three available samples have the same value, this texel also has that value.
The required state is one bit indicating whether seamless cube map filtering is enabled or disabled. Initially, it is disabled.

### 3.8.11 Texture Minification

Applying a texture to a primitive implies a mapping from texture image space to framebuffer image space. In general, this mapping involves a reconstruction of the sampled texture image, followed by a homogeneous warping implied by the mapping to framebuffer space, then a filtering, followed finally by a resampling of the filtered, warped, reconstructed image before applying it to a fragment. In the GL this mapping is approximated by one of two simple filtering schemes. One of these schemes is selected based on whether the mapping from texture space to framebuffer space is deemed to magnify or minify the texture image.

#### Scale Factor and Level of Detail

The choice is governed by a scale factor $\rho(x, y)$ and the level-of-detail parameter $\lambda(x, y)$, defined as

$$\lambda_{base}(x, y) = \log_2[\rho(x, y)]$$

$$\lambda'(x, y) = \lambda_{base}(x, y) + \text{clamp}(\text{bias}_{\text{texobj}} + \text{bias}_{\text{shader}})$$

$$\lambda = \begin{cases} 
\text{lod}_{\max}, & \lambda' > \text{lod}_{\max} \\
\lambda', & \text{lod}_{\min} \leq \lambda' \leq \text{lod}_{\max} \\
\text{lod}_{\min}, & \lambda' < \text{lod}_{\min} \\
\text{undefined}, & \text{lod}_{\min} > \text{lod}_{\max}
\end{cases}$$

$\text{bias}_{\text{texobj}}$ is the value of $\text{TEXTURE_LOD_BIAS}$ for the bound texture object (as described in section 3.8.8). $\text{bias}_{\text{shader}}$ is the value of the optional bias parameter in the texture lookup functions available to fragment shaders. If the texture access is performed in a fragment shader without a provided bias, or outside a fragment shader, then $\text{bias}_{\text{shader}}$ is zero. The sum of these values is clamped to the range $[-\text{bias}_{\max}, \text{bias}_{\max}]$ where $\text{bias}_{\max}$ is the value of the implementation defined constant $\text{MAX_TEXTURE_LOD_BIAS}$.

If $\lambda(x, y)$ is less than or equal to the constant $c$ (see section 3.8.12) the texture is said to be magnified; if it is greater, the texture is minified. Sampling of minified textures is described in the remainder of this section, while sampling of magnified textures is described in section 3.8.12.
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The initial values of \( \text{lod}_{\min} \) and \( \text{lod}_{\max} \) are chosen so as to never clamp the normal range of \( \lambda \). They may be respecified for a specific texture by calling \text{TexParameter} with \( \text{pname} \) set to \text{TEXTURE_MIN_LOD} or \text{TEXTURE_MAX_LOD} respectively.

Let \( s(x, y) \) be the function that associates an \( s \) texture coordinate with each set of window coordinates \( (x, y) \) that lie within a primitive; define \( t(x, y) \) and \( r(x, y) \) analogously. Let

\[
\begin{align*}
  u(x, y) &= \begin{cases} 
    s(x, y) + \delta_u, & \text{rectangular texture} \\
    w_t \times s(x, y) + \delta_u, & \text{otherwise} 
  \end{cases} \\
  v(x, y) &= \begin{cases} 
    t(x, y) + \delta_v, & \text{rectangular texture} \\
    h_t \times t(x, y) + \delta_v, & \text{otherwise} 
  \end{cases} \\
  w(x, y) &= d_t \times r(x, y) + \delta_w 
\end{align*}
\]  

(3.20)

where \( w_t, h_t, \) and \( d_t \) are as defined by equation 3.16 with \( w_s, h_s, \) and \( d_s \) equal to the width, height, and depth of the image array whose level is \( \text{level}_{\text{base}} \). For a one-dimensional or one-dimensional array texture, define \( v(x, y) = 0 \) and \( w(x, y) = 0 \); for a two-dimensional, two-dimensional array, rectangular, cube map, or cube map array texture, define \( w(x, y) = 0 \).

\((\delta_u, \delta_v, \delta_w)\) are the texel offsets specified in the OpenGL Shading Language texture lookup functions that support offsets. If the texture function used does not support offsets, all three shader offsets are taken to be zero.

If the value of any non-ignored component of the offset vector operand is outside implementation-dependent limits, the results of the texture lookup are undefined. For all instructions except \text{textureGather}, the limits are the values of \text{MIN_PROGRAM_TEXEL_OFFSET} and \text{MAX_PROGRAM_TEXEL_OFFSET}. For the \text{textureGather} instruction, the limits are the values of \text{MIN_PROGRAM_TEXTURE_GATHER_OFFSET} and \text{MAX_PROGRAM_TEXTURE_GATHER_OFFSET}.

For a polygon or point, \( \rho \) is given at a fragment with window coordinates \( (x, y) \) by

\[
\rho = \max \left\{ \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2}, \sqrt{\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2} \right\}
\]  

(3.21)

where \( \partial u/\partial x \) indicates the derivative of \( u \) with respect to window \( x \), and similarly for the other derivatives.
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For a line, the formula is

\[
\rho = \sqrt{\left(\frac{\partial u}{\partial x} \Delta x + \frac{\partial u}{\partial y} \Delta y\right)^2 + \left(\frac{\partial v}{\partial x} \Delta x + \frac{\partial v}{\partial y} \Delta y\right)^2 + \left(\frac{\partial w}{\partial x} \Delta x + \frac{\partial w}{\partial y} \Delta y\right)^2 / l,}
\]

where \( \Delta x = x_2 - x_1 \) and \( \Delta y = y_2 - y_1 \) with \((x_1, y_1)\) and \((x_2, y_2)\) being the segment’s window coordinate endpoints and \( l = \sqrt{\Delta x^2 + \Delta y^2} \).

While it is generally agreed that equations 3.21 and 3.22 give the best results when texturing, they are often impractical to implement. Therefore, an implementation may approximate the ideal \( \rho \) with a function \( f(x, y) \) subject to these conditions:

1. \( f(x, y) \) is continuous and monotonically increasing in each of \(|\partial u/\partial x|, |\partial u/\partial y|, |\partial v/\partial x|, |\partial v/\partial y|, |\partial w/\partial x|, \) and \( |\partial w/\partial y| \)

2. Let

\[
m_u = \max\left\{|\frac{\partial u}{\partial x}|, |\frac{\partial u}{\partial y}|\right\},
\]

\[
m_v = \max\left\{|\frac{\partial v}{\partial x}|, |\frac{\partial v}{\partial y}|\right\},
\]

\[
m_w = \max\left\{|\frac{\partial w}{\partial x}|, |\frac{\partial w}{\partial y}|\right\}.
\]

Then \( \max\{m_u, m_v, m_w\} \leq f(x, y) \leq m_u + m_v + m_w. \)

Coordinate Wrapping and Texel Selection

After generating \( u(x, y), v(x, y), \) and \( w(x, y) \), they may be clamped and wrapped before sampling the texture, depending on the corresponding texture wrap modes.

Let \( u'(x, y) = u(x, y), v'(x, y) = v(x, y), \) and \( w'(x, y) = w(x, y) \).

The value assigned to TEXTURE_MIN_FILTER is used to determine how the texture value for a fragment is selected.

When the value of TEXTURE_MIN_FILTER is NEAREST, the texel in the image array of level levelbase that is nearest (in Manhattan distance) to \((u', v', w')\) is obtained. Let \((i, j, k)\) be integers such that

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i = \text{wrap}(\lfloor u'(x,y) \rfloor)

j = \text{wrap}(\lfloor v'(x,y) \rfloor)

k = \text{wrap}(\lfloor w'(x,y) \rfloor)

and the value returned by \text{wrap}(\ ) is defined in table 3.18. For a three-dimensional texture, the texel at location \((i, j, k)\) becomes the texture value. For two-dimensional, two-dimensional array, rectangular, or cube map textures, \(k\) is irrelevant, and the texel at location \((i, j)\) becomes the texture value. For one-dimensional texture or one-dimensional array textures, \(j\) and \(k\) are irrelevant, and the texel at location \(i\) becomes the texture value.

For one- and two-dimensional array textures, the texel is obtained from image layer \(l\), where

\[
l = \begin{cases} 
\text{clamp}(\lfloor t + 0.5 \rfloor, 0, h_t - 1), & \text{for one-dimensional array textures} \\
\text{clamp}(\lfloor r + 0.5 \rfloor, 0, d_t - 1), & \text{for two-dimensional array textures}
\end{cases}
\]

<table>
<thead>
<tr>
<th>Wrap mode</th>
<th>Result of (\text{wrap}(\text{coord}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAMP_TO_EDGE</td>
<td>\text{clamp}(\text{coord}, 0, \text{size} - 1)</td>
</tr>
<tr>
<td>CLAMP_TO_BORDER</td>
<td>\text{clamp}(\text{coord}, -1, \text{size})</td>
</tr>
<tr>
<td>REPEAT</td>
<td>\text{fmod}(\text{coord}, \text{size})</td>
</tr>
<tr>
<td>MIRRORED_REPEAT</td>
<td>((\text{size} - 1) - \text{mirror}(\text{fmod}(\text{coord}, 2 \times \text{size}) - \text{size}))</td>
</tr>
</tbody>
</table>

Table 3.18: Texel location wrap mode application. \text{fmod}(a,b)\) returns \(a - b \times \lfloor \frac{a}{b} \rfloor\). \text{mirror}(a)\) returns \(a\) if \(a \geq 0\), and \(-(1 + a)\) otherwise. The values of \texttt{mode} and \texttt{size} are \texttt{TEXTURE_WRAP_S} and \(w_t\), \texttt{TEXTURE_WRAP_T} and \(h_t\), and \texttt{TEXTURE_WRAP_R} and \(d_t\) when wrapping \(i\), \(j\), or \(k\) coordinates, respectively.

If the selected \((i, j, k), (i, j), \) or \(i\) location refers to a border texel that satisfies any of the conditions

\[
i < -b_s \quad i \geq w_t + b_s \\
j < -b_s \quad j \geq h_t + b_s \\
k < -b_s \quad k \geq d_t + b_s
\]

then the border values defined by \texttt{TEXTURE_BORDER_COLOR} are used in place of the non-existent texel. If the texture contains color components, the values of

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TEXTURE_BORDER_COLOR are interpreted as an RGBA color to match the texture’s internal format in a manner consistent with table 3.11. The internal data type of the border values must be consistent with the type returned by the texture as described in section 3.8, or the result is undefined. Border values are clamped before they are used, according to the format in which texture components are stored. For signed and unsigned normalized fixed-point formats, border values are clamped to $[-1, 1]$ and $[0, 1]$, respectively. For floating-point and integer formats, border values are clamped to the representable range of the format. If the texture contains depth components, the first component of TEXTURE_BORDER_COLOR is interpreted as a depth value.

When the value of TEXTURE_MIN_FILTER is LINEAR, a $2 \times 2 \times 2$ cube of texels in the image array of level levelbase is selected. Let

\[
\begin{align*}
  i_0 &= \text{wrap}(\lfloor u' - 0.5 \rfloor) \\
  j_0 &= \text{wrap}(\lfloor v' - 0.5 \rfloor) \\
  k_0 &= \text{wrap}(\lfloor w' - 0.5 \rfloor) \\
  i_1 &= \text{wrap}(\lfloor u' - 0.5 \rfloor + 1) \\
  j_1 &= \text{wrap}(\lfloor v' - 0.5 \rfloor + 1) \\
  k_1 &= \text{wrap}(\lfloor w' - 0.5 \rfloor + 1) \\
  \alpha &= \text{frac}(u' - 0.5) \\
  \beta &= \text{frac}(v' - 0.5) \\
  \gamma &= \text{frac}(w' - 0.5)
\end{align*}
\]

where frac($x$) denotes the fractional part of $x$.

For a three-dimensional texture, the texture value $\tau$ is found as

\[
\tau = (1 - \alpha)(1 - \beta)(1 - \gamma)\tau_{i_0j_0k_0} + \alpha(1 - \beta)(1 - \gamma)\tau_{i_1j_0k_0} \\
+ (1 - \alpha)\beta(1 - \gamma)\tau_{i_0j_1k_0} + \alpha\beta(1 - \gamma)\tau_{i_1j_1k_0} \\
+ (1 - \alpha)(1 - \beta)\gamma\tau_{i_0j_0k_1} + \alpha(1 - \beta)\gamma\tau_{i_1j_0k_1} \\
+ (1 - \alpha)\beta\gamma\tau_{i_0j_1k_1} + \alpha\beta\gamma\tau_{i_1j_1k_1}
\]

(3.23)

where $\tau_{ijk}$ is the texel at location $(i, j, k)$ in the three-dimensional texture image.

For a two-dimensional, two-dimensional array, rectangular, or cube map texture,

\[
\tau = (1 - \alpha)(1 - \beta)\tau_{i_0j_0} + \alpha(1 - \beta)\tau_{i_1j_0} \\
+ (1 - \alpha)\beta\tau_{i_0j_1} + \alpha\beta\tau_{i_1j_1}
\]

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where $\tau_{ij}$ is the texel at location $(i, j)$ in the two-dimensional texture image. For two-dimensional array textures, all texels are obtained from layer $l$, where

$$l = \text{clamp}([r + 0.5], 0, d_t - 1).$$

For a \text{textureGather} built-in function (see OpenGL Shading Language), a $2 \times 2$ set of texels in the image array of level $\text{level}_{\text{base}}$ is selected. These texels are selected in the same way as when the value of \text{TEXTURE_MIN_FILTER} is \text{LINEAR}, but instead of the texels being filtered to generate the texture value, the R, G, B and A texture values are derived directly from these four texels:

$$\tau_R = \tau_{i0j1}$$
$$\tau_G = \tau_{i1j1}$$
$$\tau_B = \tau_{i1j0}$$
$$\tau_A = \tau_{i0j0}$$

And for a one-dimensional or one-dimensional array texture,

$$\tau = (1 - \alpha)\tau_{i0} + \alpha\tau_{i1}$$

where $\tau_i$ is the texel at location $i$ in the one-dimensional texture. For one-dimensional array textures, both texels are obtained from layer $l$, where

$$l = \text{clamp}([t + 0.5], 0, h_t - 1).$$

For any texel in the equation above that refers to a border texel outside the defined range of the image, the texel value is taken from the texture border color as with \text{NEAREST} filtering.

**Rendering Feedback Loops**

If all of the following conditions are satisfied, then the value of the selected $\tau_{ijk}$, $\tau_{ij}$, or $\tau_i$ in the above equations is undefined instead of referring to the value of the texel at location $(i, j, k)$, $(i, j)$, or $(i)$ respectively. This situation is discussed in more detail in the description of feedback loops in section 4.4.3.

- The current \text{DRAW_FRAMEBUFFER_BINDING} names a framebuffer object $F$.
- The texture is attached to one of the attachment points, $A$, of framebuffer object $F$. 

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Figure 3.7. An example of an $8 \times 8$ texture image and the components returned for `textureGather`.
• The value of `TEXTURE_MIN_FILTER` is `NEAREST` or `LINEAR`, and the value of `FRAMEBUFFER_ATTACHMENT_TEXTURE_LEVEL` for attachment point $A$ is equal to the value of `TEXTURE_BASE_LEVEL`.

- or -

The value of `TEXTURE_MIN_FILTER` is `NEAREST_MIPMAP_NEAREST`, `NEAREST_MIPMAP_LINEAR`, `LINEAR_MIPMAP_NEAREST`, or `LINEAR_MIPMAP_LINEAR`, and the value of `FRAMEBUFFER_ATTACHMENT_TEXTURE_LEVEL` for attachment point $A$ is within the inclusive range from `TEXTURE_BASE_LEVEL` to $q$.

**Mipmapping**

`TEXTURE_MIN_FILTER` values `NEAREST_MIPMAP_NEAREST`, `NEAREST_MIPMAP_LINEAR`, `LINEAR_MIPMAP_NEAREST`, and `LINEAR_MIPMAP_LINEAR` each require the use of a *mipmap*. Rectangular textures do not support mipmapping (it is an error to specify a minification filter that requires mipmapping). A mipmap is an ordered set of arrays representing the same image; each array has a resolution lower than the previous one. If the image array of level $level_{base}$ has dimensions $w_t \times h_t \times d_t$, then there are $\lceil \log_2(maxsize) \rceil + 1$ levels in the mipmap. where

$$maxsize = \begin{cases} w_t, & \text{for 1D and 1D array textures} \\ \max(w_t, h_t), & \text{for 2D, 2D array, cube map, and cube map array textures} \\ \max(w_t, h_t, d_t), & \text{for 3D textures} \end{cases}$$

Numbering the levels such that level $level_{base}$ is the 0th level, the $i$th array has dimensions

$$\max(1, \lfloor \frac{w_t}{w_d} \rfloor) \times \max(1, \lfloor \frac{h_t}{h_d} \rfloor) \times \max(1, \lfloor \frac{d_t}{d_d} \rfloor)$$

where

$$w_d = 2^i$$

$$h_d = \begin{cases} 1, & \text{for 1D and 1D array textures} \\ 2^i, & \text{otherwise} \end{cases}$$

$$d_d = \begin{cases} 2^i, & \text{for 3D textures} \\ 1, & \text{otherwise} \end{cases}$$

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until the last array is reached with dimension $1 \times 1 \times 1$.

Each array in a mipmap is defined using \texttt{TexImage3D}, \texttt{TexImage2D}, \texttt{CopyTexImage2D}, \texttt{TexImage1D}, or \texttt{CopyTexImage1D}; the array being set is indicated with the level-of-detail argument \texttt{level}. Level-of-detail numbers proceed from \texttt{levelbase} for the original texel array through $p = \lceil \log_2(\text{maxsize}) \rceil + \texttt{levelbase}$ with each unit increase indicating an array of half the dimensions of the previous one (rounded down to the next integer if fractional) as already described. All arrays from \texttt{levelbase} through $q = \min\{p, \texttt{levelmax}\}$ must be defined, as discussed in section 3.8.14.

The values of \texttt{levelbase} and \texttt{levelmax} may be respecified for a specific texture by calling \texttt{TexParameter} with \texttt{pname} set to \texttt{TEXTURE_BASE_LEVEL} or \texttt{TEXTURE_MAX_LEVEL} respectively.

The error \texttt{INVALID_VALUE} is generated if either value is negative.

The mipmap is used in conjunction with the level of detail to approximate the application of an appropriately filtered texture to a fragment. Let $c$ be the value of $\lambda$ at which the transition from minification to magnification occurs (since this discussion pertains to minification, we are concerned only with values of $\lambda$ where $\lambda > c$).

For mipmap filters \texttt{NEAREST_MIPMAP_NEAREST} and \texttt{LINEAR_MIPMAP_NEAREST}, the $d$th mipmap array is selected, where

$$d = \begin{cases} 
\texttt{levelbase}, & \lambda \leq \frac{1}{2} \\
\lceil \texttt{levelbase} + \lambda + \frac{1}{2} \rceil - 1, & \lambda > \frac{1}{2}, \texttt{levelbase} + \lambda \leq q + \frac{1}{2} \\
q, & \lambda > \frac{1}{2}, \texttt{levelbase} + \lambda > q + \frac{1}{2}
\end{cases} \quad (3.24)$$

The rules for \texttt{NEAREST} or \texttt{LINEAR} filtering are then applied to the selected array. Specifically, the coordinate $(u, v, w)$ is computed as in equation 3.20, with $w_s, h_s,$ and $d_s$ equal to the width, height, and depth of the image array whose level is $d$.

For mipmap filters \texttt{NEAREST_MIPMAP_LINEAR} and \texttt{LINEAR_MIPMAP_LINEAR}, the level $d_1$ and $d_2$ mipmap arrays are selected, where

$$d_1 = \begin{cases} 
q, & \texttt{levelbase} + \lambda \geq q \\
\lceil \texttt{levelbase} + \lambda \rceil, & \text{otherwise}
\end{cases} \quad (3.25)$$

$$d_2 = \begin{cases} 
q, & \texttt{levelbase} + \lambda \geq q \\
d_1 + 1, & \text{otherwise}
\end{cases} \quad (3.26)$$

The rules for \texttt{NEAREST} or \texttt{LINEAR} filtering are then applied to each of the selected arrays, yielding two corresponding texture values $\tau_1$ and $\tau_2$. Specifically,
for level \( d_1 \), the coordinate \((u, v, w)\) is computed as in equation 3.20, with \( w_s, h_s, \) and \( d_s \) equal to the width, height, and depth of the image array whose level is \( d_1 \). For level \( d_2 \) the coordinate \((u', v', w')\) is computed as in equation 3.20, with \( w_s, h_s, \) and \( d_s \) equal to the width, height, and depth of the image array whose level is \( d_2 \).

The final texture value is then found as

\[
\tau = [1 - \frac{\lambda}{\lambda}]\tau_1 + \frac{\lambda}{\lambda}\tau_2.
\]

**Manual Mipmap Generation**

Mipmaps can be generated manually with the command

```c
void GenerateMipmap(enum target);
```

where `target` is one of `TEXTURE_1D`, `TEXTURE_2D`, `TEXTURE_3D`, `TEXTURE_1D_ARRAY`, `TEXTURE_2D_ARRAY`, `TEXTURE_CUBE_MAP`, or `TEXTURE_CUBE_MAP_ARRAY`. Mipmap generation affects the texture image attached to `target`. For cube map and cube map array textures, an `INVALID_OPERATION` error is generated if the texture bound to `target` is not cube complete or cube array complete, respectively, as defined in section 3.8.14.

Mipmap generation replaces texel array levels \( \text{level}_{\text{base}} + 1 \) through \( q \) with arrays derived from the \( \text{level}_{\text{base}} \) array, regardless of their previous contents. All other mipmap arrays, including the \( \text{level}_{\text{base}} \) array, are left unchanged by this computation.

The internal formats of the derived mipmap arrays all match those of the \( \text{level}_{\text{base}} \) array, and the dimensions of the derived arrays follow the requirements described in section 3.8.14.

The contents of the derived arrays are computed by repeated, filtered reduction of the \( \text{level}_{\text{base}} \) array. For one- and two-dimensional array and cube map array textures, each layer is filtered independently. No particular filter algorithm is required, though a box filter is recommended as the default filter.

**3.8.12 Texture Magnification**

When \( \lambda \) indicates magnification, the value assigned to `TEXTURE_MAG_FILTER` determines how the texture value is obtained. There are two possible values for `TEXTURE_MAG_FILTER`: `NEAREST` and `LINEAR`. `NEAREST` behaves exactly as `NEAREST` for `TEXTURE_MIN_FILTER` and `LINEAR` behaves exactly as `LINEAR` for
TEXTURE_MIN_FILTER as described in section 3.8.11, including the texture coordinate wrap modes specified in table 3.18. The level-of-detail level<sub>base</sub> texel array is always used for magnification.

Implementations may either unconditionally assume \( c = 0 \) for the minification vs. magnification switch-over point, or may choose to make \( c \) depend on the combination of minification and magnification modes as follows: if the magnification filter is given by LINEAR and the minification filter is given by NEAREST_MIPMAP_NEAREST or NEAREST_MIPMAP_LINEAR, then \( c = 0.5 \). This is done to ensure that a minified texture does not appear “sharper” than a magnified texture. Otherwise \( c = 0 \).

3.8.13 Combined Depth/Stencil Textures

If the texture image has a base internal format of DEPTH_STENCIL, then the stencil index texture component is ignored. The texture value \( \tau \) does not include a stencil index component, but includes only the depth component.

3.8.14 Texture Completeness

A texture is said to be complete if all the image arrays and texture parameters required to utilize the texture for texture application are consistently defined. The definition of completeness varies depending on texture dimensionality and type.

For one-, two-, and three-dimensional and one-and two-dimensional array textures, a texture is mipmap complete if all of the following conditions hold true:

- The set of mipmap arrays level<sub>base</sub> through \( q \) (where \( q \) is defined in the Mipmapping discussion of section 3.8.11) were each specified with the same internal format.
- The dimensions of the arrays follow the sequence described in the Mipmapping discussion of section 3.8.11.
- level<sub>base</sub> \( \leq \) level<sub>max</sub>

Array levels \( k \) where \( k < level<sub>base</sub> \) or \( k > q \) are insignificant to the definition of completeness.

A cube map texture is mipmap complete if each of the six texture images, considered individually, is mipmap complete. Additionally, a cube map texture is cube complete if the following conditions all hold true:

- The level<sub>base</sub> arrays of each of the six texture images making up the cube map have identical, positive, and square dimensions.
The \textit{level} arrays were each specified with the same internal format.

A cube map array texture is \textit{cube array complete} if it is complete when treated as a two-dimensional array and cube complete for every cube map slice within the array texture.

Using the preceding definitions, a texture is complete unless any of the following conditions hold true:

- Any dimension of the \textit{level} array is not positive. For a rectangular or multisample texture, \textit{level} is always zero.
- The texture is a cube map texture, and is not cube complete.
- The texture is a cube map array texture, and is not cube array complete.
- The minification filter requires a mipmap (is neither \texttt{NEAREST} nor \texttt{LINEAR}), and the texture is not mipmap complete.
- The internal format of the texture arrays is integer (see table 3.12), and either the magnification filter is not \texttt{NEAREST}, or the minification filter is neither \texttt{NEAREST} nor \texttt{NEAREST_MIPMAP_NEAREST}.

\textbf{Effects of Sampler Objects on Texture Completeness}

If a sampler object and a texture object are simultaneously bound to the same texture unit, then the sampling state for that unit is taken from the sampler object (see section 3.8.2). This can have an effect on the effective completeness of the texture. In particular, if the texture is not mipmap complete and the sampler object specifies a \texttt{TEXTURE_MIN_FILTER} requiring mipmaps, the texture will be considered incomplete for the purposes of that texture unit. However, if the sampler object does not require mipmaps, the texture object will be considered complete. This means that a texture can be considered both complete and incomplete simultaneously if it is bound to two or more texture units along with sampler objects with different states.

\textbf{Effects of Completeness on Texture Application}

Texture lookup and texture fetch operations performed in vertex, geometry, and fragment shaders are affected by completeness of the texture being sampled as described in sections 2.11.8 and 3.9.2.
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Effects of Completeness on Texture Image Specification

An implementation may allow a texture image array of level 1 or greater to be created only if a mipmap complete set of image arrays consistent with the requested array can be supported with $level_{base} = 0$ and $level_{max} = 1000$.

3.8.15 Texture State and Proxy State

The state necessary for texture can be divided into two categories. First, there are the multiple sets of texel arrays (a single array for the rectangular texture target; one set of mipmap arrays each for the one-, two-, and three-dimensional and one- and two-dimensional array texture targets; and six sets of mipmap arrays for the cube map texture targets) and their number. Each array has associated with it a width, height (two- and three-dimensional, rectangular, one-dimensional array, cube map, and cube map array only), and depth (three-dimensional, two-dimensional array, and cube map array only), an integer describing the internal format of the image, integer values describing the resolutions of each of the red, green, blue, alpha, depth, and stencil components of the image, integer values describing the type (unsigned normalized, integer, floating-point, etc.) of each of the components, a boolean describing whether the image is compressed or not, and an integer size of a compressed image. Each initial texel array is null (zero width, height, and depth, internal format RGBA, component sizes set to zero and component types set to NONE, the compressed flag set to FALSE, and a zero compressed size). Multi-sample textures contain an integer identifying the number of samples in each texel, and a boolean indicating whether identical sample locations and the same number of samples will be used for all texels in the image. The buffer texture target has associated an integer containing the name of the buffer object that provided the data store for the texture, initially zero, and an integer identifying the internal format of the texture, initially R8.

Next, there are the four sets of texture properties, corresponding to the one-, two-, three-dimensional, and cube map texture targets. Each set consists of the selected minification and magnification filters, the wrap modes for s, t (two- and three-dimensional and cube map only), and r (three-dimensional only), the TEXTURE_BORDER_COLOR, two floating-point numbers describing the minimum and maximum level of detail, two integers describing the base and maximum mipmap array, a boolean flag indicating whether the texture is resident, and three integers describing the depth texture mode, compare mode, and compare function. In the initial state, the value assigned to TEXTURE_MIN_FILTER is NEAREST_MIPMAP_LINEAR (except for rectangular textures, where the initial value is LINEAR), and the value for TEXTURE_MAG_FILTER is LINEAR. s, t, and r
wrap modes are all set to REPEAT (except for rectangular textures, where the initial value is CLAMP_TO_EDGE). The values of TEXTURE_MIN_LOD and TEXTURE_MAX_LOD are -1000 and 1000 respectively. The values of TEXTURE_BASE_LEVEL and TEXTURE_MAX_LEVEL are 0 and 1000 respectively. The value of TEXTURE_BORDER_COLOR is (0,0,0,0). The values of TEXTURE_COMPARE_MODE and TEXTURE_COMPARE_FUNC are NONE, and LEQUAL respectively.

In addition to image arrays for the non-proxy texture targets described above, partially instantiated image arrays are maintained for one-, two-, and three-dimensional, rectangular, one- and two-dimensional array, and cube map array textures. Additionally, a single proxy image array is maintained for the cube map texture. Each proxy image array includes width, height, depth, and internal format state values, as well as state for the red, green, blue, alpha, depth, and stencil component resolutions and types. Proxy arrays do not include image data nor texture parameters. When TexImage3D is executed with target specified as PROXY_TEXTURE_3D, the three-dimensional proxy state values of the specified level-of-detail are recomputed and updated. If the image array would not be supported by TexImage3D called with target set to TEXTURE_3D, no error is generated, but the proxy width, height, depth, and component resolutions are set to zero, and the component types are set to NONE. If the image array would be supported by such a call to TexImage3D, the proxy state values are set exactly as though the actual image array were being specified. No pixel data are transferred or processed in either case.

Proxy arrays for one-and two-dimensional textures, one-and two-dimensional array textures, and cube map array textures are operated on in the same way when TexImage1D is executed with target specified as PROXY_TEXTURE_1D, TexImage2D is executed with target specified as PROXY_TEXTURE_2D, PROXY_TEXTURE_1D_ARRAY, or PROXY_TEXTURE_RECTANGLE, or TexImage3D is executed with target specified as PROXY_TEXTURE_2D_ARRAY, or PROXY_TEXTURE_CUBE_MAP_ARRAY.

Proxy arrays for two-dimensional multisample and two-dimensional multisample array textures are operated on in the same way when TexImage2DMultisample is called with target specified as PROXY_TEXTURE_2D_MULTI_SAMPLE, or TexImage3DMultisample is called with target specified as PROXY_TEXTURE_2D_MULTI_SAMPLE_ARRAY.

The cube map proxy arrays are operated on in the same manner when TexImage2D is executed with the target field specified as PROXY_TEXTURE_CUBE_MAP, with the addition that determining that a given cube map texture is supported with PROXY_TEXTURE_CUBE_MAP indicates that all six of the cube map 2D images are supported. Likewise, if the specified PROXY_TEXTURE_CUBE_MAP is not supported, none of the six cube map 2D images are supported.
There is no image or non-level-related state associated with proxy textures. Therefore they may not be used as textures, and calling `BindTexture`, `GetTexImage`, `GetTexParameteriv`, or `GetTexParameterfv` with a proxy texture target generates an `INVALID_ENUM` error.

### 3.8.16 Texture Comparison Modes

Texture values can also be computed according to a specified comparison function. Texture parameter `TEXTURE_COMPARE_MODE` specifies the comparison operands, and parameter `TEXTURE_COMPARE_FUNC` specifies the comparison function.

**Depth Texture Comparison Mode**

If the currently bound texture’s base internal format is `DEPTH_COMPONENT` or `DEPTH_STENCIL`, then `TEXTURE_COMPARE_MODE` and `TEXTURE_COMPARE_FUNC` control the output of the texture unit as described below. Otherwise, the texture unit operates in the normal manner and texture comparison is bypassed.

Let $D_t$ be the depth texture value and $D_{ref}$ be the reference value, provided by the shader’s texture lookup function. If the texture’s internal format indicates a fixed-point depth texture, then $D_t$ and $D_{ref}$ are clamped to the range $[0, 1]$; otherwise no clamping is performed.

Then the effective texture value is computed as follows:

- If the value of `TEXTURE_COMPARE_MODE` is `NONE`, then
  
  $$ r = D_t $$

- If the value of `TEXTURE_COMPARE_MODE` is `COMPARE_REF_TO_TEXTURE`, then $r$ depends on the texture comparison function as shown in table 3.19.

  The resulting $r$ is assigned to $R_t$.

  - If the value of `TEXTURE_MAG_FILTER` is not `NEAREST`, or the value of `TEXTURE_MIN_FILTER` is not `NEAREST` or `NEAREST_MIPMAP_NEAREST`, then $r$ may be computed by comparing more than one depth texture value to the texture reference value. The details of this are implementation-dependent, but $r$ should be a value in the range $[0, 1]$ which is proportional to the number of comparison passes or failures.

### 3.8.17 sRGB Texture Color Conversion

If the currently bound texture’s internal format is one of `SRGB`, `SRGB8`, `SRGB_ALPHA`, `SRGB8_ALPHA`, `COMPRESSED_SRGB`, or `COMPRESSED_SRGB_ALPHA`, the red, green, and blue components are converted from an sRGB color space to an sRGB color space.
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<table>
<thead>
<tr>
<th>Texture Comparison Function</th>
<th>Computed result ( r )</th>
</tr>
</thead>
</table>
| LEQUAL                     | \( r = \begin{cases} 
1.0, & D_{\text{ref}} \leq D_t \\
0.0, & D_{\text{ref}} > D_t 
\end{cases} \) |
| GEQUAL                     | \( r = \begin{cases} 
1.0, & D_{\text{ref}} \geq D_t \\
0.0, & D_{\text{ref}} < D_t 
\end{cases} \) |
| LESS                       | \( r = \begin{cases} 
1.0, & D_{\text{ref}} < D_t \\
0.0, & D_{\text{ref}} \geq D_t 
\end{cases} \) |
| GREATER                    | \( r = \begin{cases} 
1.0, & D_{\text{ref}} > D_t \\
0.0, & D_{\text{ref}} \leq D_t 
\end{cases} \) |
| EQUAL                      | \( r = \begin{cases} 
1.0, & D_{\text{ref}} = D_t \\
0.0, & D_{\text{ref}} \neq D_t 
\end{cases} \) |
| NOTEQUAL                   | \( r = \begin{cases} 
1.0, & D_{\text{ref}} \neq D_t \\
0.0, & D_{\text{ref}} = D_t 
\end{cases} \) |
| ALWAYS                     | \( r = 1.0 \) |
| NEVER                      | \( r = 0.0 \) |

Table 3.19: Depth texture comparison functions.

linear color space as part of filtering described in sections 3.8.11 and 3.8.12. Any alpha component is left unchanged. Ideally, implementations should perform this color conversion on each sample prior to filtering but implementations are allowed to perform this conversion after filtering (though this post-filtering approach is inferior to converting from sRGB prior to filtering).

The conversion from an sRGB encoded component, \( c_s \), to a linear component, \( c_l \), is as follows.

\[
c_l = \begin{cases} 
\frac{c_s - 12.92}{1.055}, & c_s \leq 0.04045 \\
\left(\frac{c_s + 0.055}{1.055}\right)^{2.4}, & c_s > 0.04045 
\end{cases}
\]  

(3.27)

Assume \( c_s \) is the sRGB component in the range \([0, 1]\).

3.8.18 Shared Exponent Texture Color Conversion

If the currently bound texture’s internal format is RGB9_E5, the red, green, blue, and shared bits are converted to color components (prior to filtering) using shared exponent decoding. The component \( \text{red}_s, \text{green}_s, \text{blue}_s, \) and \( \text{exp}_{\text{shared}} \) values (see
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section 3.8.3) are treated as unsigned integers and are converted to red, green, and blue as follows:

\[
\begin{align*}
\text{red} &= \text{red}_s 2^{\text{exp} \text{shared} - B} \\
\text{green} &= \text{green}_s 2^{\text{exp} \text{shared} - B} \\
\text{blue} &= \text{blue}_s 2^{\text{exp} \text{shared} - B}
\end{align*}
\]

3.9 Fragment Shaders

The sequence of operations that are applied to fragments that result from rasterizing a point, line segment, or polygon are described using a fragment shader.

A fragment shader is an array of strings containing source code for the operations that are meant to occur on each fragment that results from rasterization. The language used for fragment shaders is described in the OpenGL Shading Language Specification.

Fragment shaders are created as described in section 2.11.1 using a type parameter of FRAGMENT_SHADER. They are attached to and used in program objects as described in section 2.11.2.

When the program object currently in use includes a fragment shader, its fragment shader is considered active, and is used to process fragments. If the program object has no fragment shader, or no program object is currently in use, the results of fragment shader execution are undefined.

3.9.1 Shader Variables

Fragment shaders can access uniforms belonging to the current shader object. The amount of storage available for fragment shader uniform variables in the default uniform block is specified by the value of the implementation-dependent constant MAX_FRAGMENT_UNIFORM_COMPONENTS. The total amount of combined storage available for fragment shader uniform variables in all uniform blocks (including the default uniform block) is specified by the value of the implementation-dependent constant MAX_COMBINED_FRAGMENT_UNIFORM_COMPONENTS. These values represent the numbers of individual floating-point, integer, or boolean values that can be held in uniform variable storage for a fragment shader. A uniform matrix will consume no more than \(4 \times \min(r, c)\) such values, where \(r\) and \(c\) are the number of rows and columns in the matrix. A link error will be generated if an attempt is made to utilize more than the space available for fragment shader uniform variables.
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Fragment shaders can read varying variables that correspond to the attributes of the fragments produced by rasterization. The OpenGL Shading Language Specification defines a set of built-in varying variables that can be accessed by a fragment shader. These built-in varying variables include data associated with a fragment such as the fragment’s position.

Additionally, when a vertex shader is active, it may define one or more varying variables (see section 2.11.7 and the OpenGL Shading Language Specification). These values are, if not flat shaded, interpolated across the primitive being rendered. The results of these interpolations are available when varying variables of the same name are defined in the fragment shader.

When interpolating built-in and user-defined varying variables, the default screen-space location at which these variables are sampled is defined in previous rasterization sections. The default location may be overridden by interpolation qualifiers. When interpolating variables declared using `centroid in`, the variable is sampled at a location within the pixel covered by the primitive generating the fragment. When interpolating variables declared using `sample in` when `MULTISAMPLE` is enabled, the fragment shader will be invoked separately for each covered sample and the variable will be sampled at the corresponding sample point.

Additionally, built-in fragment shader functions provide further fine-grained control over interpolation. The built-in functions `interpolateAtCentroid` and `interpolateAtSample` will sample variables as though they were declared with the `centroid` or `sample` qualifiers, respectively. The built-in function `interpolateAtOffset` will sample variables at a specified \((x, y)\) offset relative to the center of the pixel. The range and granularity of offsets supported by this function is implementation-dependent. If either component of the specified offset is less than the value of `MIN_FRAGMENT_INTERPOLATION_OFFSET` or greater than the value of `MAX_FRAGMENT_INTERPOLATION_OFFSET`, the position used to interpolate the variable is undefined. Not all values of offset may be supported; \(x\) and \(y\) offsets may be rounded to fixed-point values with the number of fraction bits given by the value of the implementation-dependent constant `FRAGMENT_-INTERPOLATION_OFFSET_BITS`.

A fragment shader can also write to varying out variables. Values written to these variables are used in the subsequent per-fragment operations. Varying out variables can be used to write floating-point, integer or unsigned integer values destined for buffers attached to a framebuffer object, or destined for color buffers attached to the default framebuffer. The **Shader Outputs** subsection of section 3.9.2 describes how to direct these values to buffers.
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3.9.2 Shader Execution

The executable version of the fragment shader is used to process incoming fragment values that are the result of rasterization.

Texture Access

The Shader Only Texturing subsection of section 2.11.8 describes texture lookup functionality accessible to a vertex shader. The texel fetch and texture size query functionality described there also applies to fragment shaders.

When a texture lookup is performed in a fragment shader, the GL computes the filtered texture value \( \tau \) in the manner described in sections 3.8.11 and 3.8.12, and converts it to a texture base color \( C_b \) as shown in Table 3.20, followed by swizzling the components of \( C_b \), controlled by the values of the texture parameters TEXTURE_SWIZZLE_R, TEXTURE_SWIZZLE_G, TEXTURE_SWIZZLE_B, and TEXTURE_SWIZZLE_A. If the value of TEXTURE_SWIZZLE_R is denoted by swizzle\(_r\), swizzling computes the first component of \( C_s \) according to

\[
\text{if (swizzle\(_r\) == RED)} \\
C_s[0] = C_b[0]; \\
\text{else if (swizzle\(_r\) == GREEN)} \\
C_s[0] = C_b[1]; \\
\text{else if (swizzle\(_r\) == BLUE)} \\
C_s[0] = C_b[2]; \\
\text{else if (swizzle\(_r\) == ALPHA)} \\
C_s[0] = A_b; \\
\text{else if (swizzle\(_r\) == ZERO)} \\
C_s[0] = 0; \\
\text{else if (swizzle\(_r\) == ONE)} \\
C_s[0] = 1; // float or int depending on texture component type}
\]

Swizzling of \( C_s[1] \), \( C_s[2] \), and \( A_s \) are similarly controlled by the values of TEXTURE_SWIZZLE_G, TEXTURE_SWIZZLE_B, and TEXTURE_SWIZZLE_A, respectively.

The resulting four-component vector \( (R_s, G_s, B_s, A_s) \) is returned to the fragment shader. For the purposes of level-of-detail calculations, the derivatives \( \frac{du}{dx} \), \( \frac{du}{dy} \), \( \frac{dv}{dx} \), \( \frac{dv}{dy} \), \( \frac{dw}{dx} \), and \( \frac{dw}{dy} \) may be approximated by a differencing algorithm as detailed in section 8.8 of the OpenGL Shading Language Specification.

Texture lookups involving textures with depth component data can either return the depth data directly or return the results of a comparison with the \( D_{ref} \) value (see section 3.8.16) used to perform the lookup. The comparison operation is requested...
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<table>
<thead>
<tr>
<th>Texture Base Internal Format</th>
<th>Texture base color $C_b$</th>
<th>$A_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED</td>
<td>$(R_t, 0, 0)$</td>
<td>1</td>
</tr>
<tr>
<td>RG</td>
<td>$(R_t, G_t, 0)$</td>
<td>1</td>
</tr>
<tr>
<td>RGB</td>
<td>$(R_t, G_t, B_t)$</td>
<td>1</td>
</tr>
<tr>
<td>RGBA</td>
<td>$(R_t, G_t, B_t)$</td>
<td>$A_t$</td>
</tr>
</tbody>
</table>

Table 3.20: Correspondence of filtered texture components to texture base components.

in the shader by using any of the shadow sampler types (sampler1DShadow, sampler2DShadow, or sampler2DRectShadow), and in the texture using the TEXTURE_COMPARE_MODE parameter. These requests must be consistent; the results of a texture lookup are undefined if:

- The sampler used in a texture lookup function is not one of the shadow sampler types, the texture object’s internal format is `DEPTH_COMPONENT` or `DEPTH_STENCIL`, and the TEXTURE_COMPARE_MODE is not `NONE`.

- The sampler used in a texture lookup function is one of the shadow sampler types, the texture object’s internal format is `DEPTH_COMPONENT` or `DEPTH_STENCIL`, and the TEXTURE_COMPARE_MODE is `NONE`.

- The sampler used in a texture lookup function is one of the shadow sampler types, and the texture object’s internal format is not `DEPTH_COMPONENT` or `DEPTH_STENCIL`.

The stencil index texture internal component is ignored if the base internal format is `DEPTH_STENCIL`.

Texture lookups using `textureGather` must only be performed on textures with supported formats. The value of `MAX_PROGRAM_TEXTURE_GATHER_COMPONENTS` determines which formats are supported. If the value is one, only `RED`, `DEPTH`, and `DEPTH_STENCIL` are supported. If the value is four, all internal formats are supported. When `textureGather` is used to sample a texture with an unsupported format, the results are undefined.

Using a sampler in a fragment shader will return $(R, G, B, A) = (0, 0, 0, 1)$ if the sampler’s associated texture is not complete, as defined in section 3.8.14.

The number of separate texture units that can be accessed from within a fragment shader during the rendering of a single primitive is specified by the implementation-dependent constant `MAX_TEXTURE_IMAGE_UNITS`.  

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3.9. FRAGMENT SHADERS

Shader Inputs

The OpenGL Shading Language Specification describes the values that are available as inputs to the fragment shader.

The built-in variable \texttt{gl\_FragCoord} holds the fragment coordinate \((x_f, y_f, z_f, w_f)\) for the fragment. Computing the fragment coordinate depends on the fragment processing pixel-center and origin conventions (discussed below) as follows:

\[
\begin{align*}
x_f &= \begin{cases} 
x_w - \frac{1}{2}, & \text{pixel-center convention is integer} 
x_w, & \text{otherwise} 
\end{cases} \\
y'_f &= \begin{cases} 
H - y_w, & \text{origin convention is upper-left} 
y_w, & \text{otherwise} 
\end{cases} \\
y_f &= \begin{cases} 
y'_f - \frac{1}{2}, & \text{pixel-center convention is integer} 
y'_f, & \text{otherwise} 
\end{cases} \\
z_f &= z_w \\
w_f &= \frac{1}{w_c}
\end{align*}
\]

where \((x_w, y_w, z_w)\) is the fragment’s window-space position, \(w_c\) is the \(w\) component of the fragment’s clip-space position, and \(H\) is the window’s height in pixels. Note that \(z_w\) already has a polygon offset added in, if enabled (see section 3.6.4). \(z_f\) must be precisely 0 or 1 in the case where \(z_w\) is either 0 or 1, respectively. The \(\frac{1}{w}\) value is computed from the \(w_c\) coordinate (see section 2.14).

Unless otherwise specified by layout qualifiers in the fragment shader (see section 4.3.8.1 of the OpenGL Shading Language Specification), the fragment processing pixel-center convention is half-integer and the fragment processing origin convention is lower-left.

The built-in variable \texttt{gl\_FrontFacing} is set to \texttt{TRUE} if the fragment is generated from a front-facing primitive, and \texttt{FALSE} otherwise. For fragments generated from triangle primitives (including ones resulting from primitives rendered as points or lines), the determination is made by examining the sign of the area computed by equation 3.8 of section 3.6.1 (including the possible reversal of this sign controlled by \texttt{FrontFace}). If the sign is positive, fragments generated by the primitive are front-facing; otherwise, they are back-facing. All other fragments are considered front-facing.

If a geometry shader is active, the built-in variable \texttt{gl\_PrimitiveID} contains the ID value emitted by the geometry shader for the provoking vertex. If no
3.9. **FRAGMENT SHADERS**

geometry shader is active, `gl_PrimitiveID` contains the number of primitives processed by the rasterizer since the last drawing command was called. The first primitive generated by a drawing command is numbered zero, and the primitive ID counter is incremented after every individual point, line, or polygon primitive is processed. For polygons drawn in point or line mode, the primitive ID counter is incremented only once, even though multiple points or lines may be drawn.

Restarting a primitive using the primitive restart index (see section 2.8) has no effect on the primitive ID counter.

`gl_PrimitiveID` is only defined under the same conditions that `gl_VertexID` is defined, as described under “Shader Inputs” in section 2.11.8.

Similarly to the limit on geometry shader output components (see section 2.13.4), there is a limit on the number of components of built-in and user-defined input varying variables that can be read by the fragment shader, given by the value of the implementation-dependent constant `MAX_FRAGMENT_INPUT_COMPONENTS`.

The built-in variable `gl_SampleMaskIn` is an integer array holding bitfields indicating the set of fragment samples covered by the primitive corresponding to the fragment shader invocation. The number of elements in the array is

$$\left\lceil \frac{s}{32} \right\rceil,$$

where `s` is the maximum number of color samples supported by the implementation. Bit `n` of element `w` in the array is set if and only if the sample numbered `32w + n` is considered covered for this fragment shader invocation. When rendering to a non-multisample buffer, or if multisample rasterization is disabled, all bits are zero except for bit zero of the first array element. That bit will be one if the pixel is covered and zero otherwise. Bits in the sample mask corresponding to covered samples that will be killed due to `SAMPLE_COVERAGE` or `SAMPLE_MASK` will not be set (see section 4.1.3). When per-sample shading is active due to the use of a fragment input qualified by `sample`, only the bit for the current sample is set in `gl_SampleMaskIn`. When GL state specifies multiple fragment shader invocations for a given fragment, the sample mask for any single fragment shader invocation may specify a subset of the covered samples for the fragment. In this case, the bit corresponding to each covered sample will be set in exactly one fragment shader invocation.

The built-in read-only variable `gl_SampleID` is filled with the sample number of the sample currently being processed. This variable is in the range 0 to `gl_NumSamples` minus one, where `gl_NumSamples` is the total number of samples in the framebuffer, or one if rendering to a non-multisample framebuffer. Using this variable in a fragment shader causes the entire shader to be evaluated per-sample.
When rendering to a non-multisample buffer, or if multisample rasterization is dis-
abled, \texttt{gl_SampleID} will always be zero. \texttt{gl_NumSamples} is the sample count
of the framebuffer regardless of whether multisample rasterization is enabled or
not.

The built-in read-only variable \texttt{gl_SamplePosition} contains the position of
the current sample within the multi-sample draw buffer. The \texttt{x} and \texttt{y} components
of \texttt{gl_SamplePosition} contain the sub-pixel coordinate of the current sample
and will have values in the range $[0, 1]$. The sub-pixel coordinates of the center of
the pixel are always $(0.5, 0.5)$. Using this variable in a fragment shader causes
the entire shader to be evaluated per-sample. When rendering to a non-multisample
buffer, or if multisample rasterization is disabled, \texttt{gl_SamplePosition} will al-
ways be $(0.5, 0.5)$.

When a program is linked, all components of any varying and special variable
read by a fragment shader will count against this limit. A program whose fragment
shader exceeds this limit may fail to link, unless device-dependent optimizations
are able to make the program fit within available hardware resources.

Component counting rules for different variable types and variable declarations
are the same as for \texttt{MAX_VERTEX_OUTPUT_COMPONENTS}. (see section 2.11.7).

\textbf{Shader Outputs}

The OpenGL Shading Language Specification describes the values that may be
output by a fragment shader. These outputs are split into two categories, user-
defined varying out variables and the built-in variables \texttt{gl_SampleMask}, \texttt{gl_-}
\texttt{FragColor}, \texttt{gl_FragData[n]}, and \texttt{gl_FragDepth}. For fixed-point depth
buffers, the final fragment depth written by a fragment shader is first clamped to
$[0, 1]$ and then converted to fixed-point as if it were a window \texttt{z} value (see sec-
tion 2.14.1). For floating-point depth buffers, conversion is not performed but
clamping is. Note that the depth range computation is not applied here, only the
conversion to fixed-point.

The built-in integer array \texttt{gl_SampleMask} can be used to change the sample
coverage for a fragment from within the shader. The number of elements in the
array is

$$s \left\lceil \frac{s}{32} \right\rceil,$$

where \texttt{s} is the maximum number of color samples supported by the implemen-
tation. If bit \texttt{n} of element \texttt{w} in the array is set to zero, sample $32w + n$ should
be considered uncovered for the purposes of multisample fragment operations (see
section 4.1.3). Modifying the sample mask in this way may exclude covered sam-
pies from being processed further at a per-fragment granularity. However, setting
sample mask bits to one will never enable samples not covered by the original primitive. If the fragment shader is being evaluated at any frequency other than per-fragment, bits of the sample mask not corresponding to the current fragment shader invocation are ignored.

Color values written by a fragment shader may be floating-point, signed integer, or unsigned integer. If the color buffer has an signed or unsigned normalized fixed-point format, color values are assumed to be floating-point and are converted to fixed-point as described in equations 2.6 or 2.4, respectively; otherwise no type conversion is applied. If the values written by the fragment shader do not match the format(s) of the corresponding color buffer(s), the result is undefined.

Writing to gl_FragColor specifies the fragment color (color number zero) that will be used by subsequent stages of the pipeline. Writing to gl_FragData[n] specifies the value of fragment color number n. Any colors, or color components, associated with a fragment that are not written by the fragment shader are undefined. A fragment shader may not statically assign values to more than one of gl_FragColor, gl_FragData, and any user-defined varying out variable. In this case, a compile or link error will result. A shader statically assigns a value to a variable if, after pre-processing, it contains a statement that would write to the variable, whether or not run-time flow of control will cause that statement to be executed.

Writing to gl_FragDepth specifies the depth value for the fragment being processed. If the active fragment shader does not statically assign a value to gl_FragDepth, then the depth value generated during rasterization is used by subsequent stages of the pipeline. Otherwise, the value assigned to gl_FragDepth is used, and is undefined for any fragments where statements assigning a value to gl_FragDepth are not executed. Thus, if a shader statically assigns a value to gl_FragDepth, then it is responsible for always writing it.

The binding of a user-defined varying out variable to a fragment color number can be specified explicitly. The command

```c
void BindFragDataLocationIndexed( uint program,
        uint colorNumber, uint index, const char * name );
```

specifies that the varying out variable name in program should be bound to fragment color colorNumber when the program is next linked. index may be zero or one to specify that the color be used as either the first or second color input to the blend equation, respectively, as described in section 4.1.7.

If name was bound previously, its assigned binding is replaced with colorNumber. name must be a null-terminated string. The error INVALID_VALUE is generated if index is greater than one, if colorNumber is greater than or equal to
the value of MAX_DRAW_BUFFERS and index is zero, or if colorNumber is greater than or equal to the value of MAX_DUAL_SOURCE_DRAW_BUFFERS and index is greater than or equal to one. The command

```c
void BindFragDataLocation( uint program,
    uint colorNumber, const char *name );
```

is equivalent to calling

```c
BindFragDataLocationIndexed (program, colorNumber, 0, name );
```

`BindFragDataLocation` has no effect until the program is linked. In particular, it doesn’t modify the bindings of varying out variables in a program that has already been linked. The error INVALID_OPERATION is generated if name starts with the reserved gl_prefix.

When a program is linked, any varying out variables without a binding specified either through `BindFragDataLocationIndexed` or `BindFragDataLocation`, or explicitly set within the shader text will automatically be bound to fragment colors and indices by the GL. All such assignments will use color indices of zero. Such bindings can be queried using the commands `GetFragDataLocation` and `GetFragDataIndex`. If a varying out variable has a binding explicitly set within the shader text and a different binding assigned by `BindFragDataLocationIndexed` or `BindFragDataLocation`, the assignment in the shader text is used. Output binding assignments will cause `LinkProgram` to fail:

- if the number of active outputs is greater than the value of MAX_DRAW_BUFFERS;
- if the program has an active output assigned to a location greater than or equal to the value of MAX_DUAL_SOURCE_DRAW_BUFFERS and has an active output assigned an index greater than or equal to one;
- if more than one varying out variable is bound to the same number and index; or
- if the explicit binding assignments do not leave enough space for the linker to automatically assign a location for a varying out array, which requires multiple contiguous locations.

`BindFragDataLocationIndexed` may be issued before any shader objects are attached to a program object. Hence it is allowed to bind any name (except a name starting with gl_) to a color number and index, including a name that is never used.
as a varying out variable in any fragment shader object. Assigned bindings for
variables that do not exist are ignored.

After a program object has been linked successfully, the bindings of varying
out variable names to color numbers can be queried. The command

```c
int GetFragDataLocation( uint program, const
char *name );
```
returns the number of the fragment color to which the varying out variable name
was bound when the program object program was last linked. name must be
a null-terminated string. If program has not been successfully linked, the error
INVALID_OPERATION is generated. If name is not a varying out variable, or if an
error occurs, -1 will be returned.

The command

```c
int GetFragDataIndex( uint program, const char *
name );
```
returns the index of the fragment color to which the variable name was bound when
the program object program was last linked. If program has not been successfully
linked, the error INVALID_OPERATION is generated. If name is not a varying out
variable, or if an error occurs, -1 will be returned.

### 3.10 Antialiasing Application

If antialiasing is enabled for the primitive from which a rasterized fragment was
produced, then the computed coverage value is applied to the fragment. The value
is multiplied by the fragment’s alpha (A) value to yield a final alpha value. The
coverage value is applied separately to each fragment color, and only applied if the
corresponding color buffer in the framebuffer has a fixed- or floating-point format.

### 3.11 Multisample Point Fade

Finally, if multisampling is enabled and the rasterized fragment results from a point
primitive, then the computed fade factor from equation 3.2 is applied to the frag-
ment. The fade factor is multiplied by the fragment’s alpha value to yield a final
alpha value. The fade factor is applied separately to each fragment color, and
only applied if the corresponding color buffer in the framebuffer has a fixed- or
floating-point format.
Chapter 4

Per-Fragment Operations and the Framebuffer

The framebuffer, whether it is the default framebuffer or a framebuffer object (see section 2.1), consists of a set of pixels arranged as a two-dimensional array. For purposes of this discussion, each pixel in the framebuffer is simply a set of some number of bits. The number of bits per pixel may vary depending on the GL implementation, the type of framebuffer selected, and parameters specified when the framebuffer was created. Creation and management of the default framebuffer is outside the scope of this specification, while creation and management of framebuffer objects is described in detail in section 4.4.

Corresponding bits from each pixel in the framebuffer are grouped together into a bitplane; each bitplane contains a single bit from each pixel. These bitplanes are grouped into several logical buffers. These are the color, depth, and stencil buffers. The color buffer actually consists of a number of buffers, and these color buffers serve related but slightly different purposes depending on whether the GL is bound to the default framebuffer or a framebuffer object.

For the default framebuffer, the color buffers are the front left buffer, the front right buffer, the back left buffer, and the back right buffer. Typically the contents of the front buffers are displayed on a color monitor while the contents of the back buffers are invisible. (Monoscopic contexts display only the front left buffer; stereoscopic contexts display both the front left and the front right buffers.) All color buffers must have the same number of bitplanes, although an implementation or context may choose not to provide right buffers, or back buffers at all. Further, an implementation or context may choose not to provide depth or stencil buffers. If no default framebuffer is associated with the GL context, the framebuffer is incomplete except when a framebuffer object is bound (see sections 4.4.1 and 4.4.4).
Framebuffer objects are not visible, and do not have any of the color buffers present in the default framebuffer. Instead, the buffers of an framebuffer object are specified by attaching individual textures or renderbuffers (see section 4.4) to a set of attachment points. A framebuffer object has an array of color buffer attachment points, numbered zero through \( n \), a depth buffer attachment point, and a stencil buffer attachment point. In order to be used for rendering, a framebuffer object must be complete, as described in section 4.4.4. Not all attachments of a framebuffer object need to be populated.

Each pixel in a color buffer consists of up to four color components. The four color components are named R, G, B, and A, in that order; color buffers are not required to have all four color components. R, G, B, and A components may be represented as signed or unsigned normalized fixed-point, floating-point, or signed or unsigned integer values; all components must have the same representation. Each pixel in a depth buffer consists of a single unsigned integer value in the format described in section 2.14.1 or a floating-point value. Each pixel in a stencil buffer consists of a single unsigned integer value.

The number of bitplanes in the color, depth, and stencil buffers is dependent on the currently bound framebuffer. For the default framebuffer, the number of bitplanes is fixed. For framebuffer objects, the number of bitplanes in a given logical buffer may change if the image attached to the corresponding attachment point changes.

The GL has two active framebuffers; the draw framebuffer is the destination for rendering operations, and the read framebuffer is the source for readback operations. The same framebuffer may be used for both drawing and reading. Section 4.4.1 describes the mechanism for controlling framebuffer usage.

The default framebuffer is initially used as the draw and read framebuffer and the initial state of all provided bitplanes is undefined. The format and encoding of buffers in the draw and read framebuffers can be queried as described in section 6.1.3.

## 4.1 Per-Fragment Operations

A fragment produced by rasterization with window coordinates of \((x_w, y_w)\) modifies the pixel in the framebuffer at that location based on a number of parameters and conditions. We describe these modifications and tests, diagrammed in figure 4.1, in the order in which they are performed. Figure 4.1 diagrams these

---

\(^1\)The window system binding API may allow associating a GL context with two separate “default framebuffers” provided by the window system as the draw and read framebuffers, but if so, both default framebuffers are referred to by the name zero at their respective binding points.
modifications and tests.

4.1.1 Pixel Ownership Test

The first test is to determine if the pixel at location \((x_w, y_w)\) in the framebuffer is currently owned by the GL (more precisely, by this GL context). If it is not, the window system decides the fate the incoming fragment. Possible results are that the fragment is discarded or that some subset of the subsequent per-fragment operations are applied to the fragment. This test allows the window system to control the GL’s behavior, for instance, when a GL window is obscured.

If the draw framebuffer is a framebuffer object (see section 4.2.1), the pixel ownership test always passes, since the pixels of framebuffer objects are owned by the GL, not the window system. If the draw framebuffer is the default framebuffer, the window system controls pixel ownership.

4.1.2 Scissor Test

The scissor test determines if \((x_w, y_w)\) lies within the scissor rectangle defined by four values. These values are set with
4.1. PER-FRAGMENT OPERATIONS

```c
void Scissor( int left, int bottom, sizei width, sizei height );
```

If \( \text{left} \leq x < \text{left} + \text{width} \) and \( \text{bottom} \leq y < \text{bottom} + \text{height} \), then the scissor test passes. Otherwise, the test fails and the fragment is discarded. The test is enabled or disabled using `Enable` or `Disable` using the constant `SCISSOR_TEST`. When disabled, it is as if the scissor test always passes. If either `width` or `height` is less than zero, then the error `INVALID_VALUE` is generated. The state required consists of four integer values and a bit indicating whether the test is enabled or disabled. In the initial state, \( \text{left} = \text{bottom} = 0 \). `width` and `height` are set to the width and height, respectively, of the window into which the GL is to do its rendering. If the default framebuffer is bound but no default framebuffer is associated with the GL context (see chapter 4), then `width` and `height` are initially set to zero. Initially, the scissor test is disabled.

4.1.3 Multisample Fragment Operations

This step modifies fragment alpha and coverage values based on the values of `SAMPLE_ALPHA_TO_COVERAGE`, `SAMPLE_ALPHA_TO_ONE`, `SAMPLE_COVERAGE`, `SAMPLE_COVERAGE_VALUE`, `SAMPLE_COVERAGE_INVERT`, `SAMPLE_MASK`, `SAMPLE_MASK_VALUE`, and an output sample mask optionally written by the fragment shader. No changes to the fragment alpha or coverage values are made at this step if `MULTISAMPLE` is disabled, or if the value of `SAMPLE_BUFFERS` is not one.

All alpha values in this section refer only to the alpha component of the fragment shader output linked to color number zero, index zero (see section 3.9.2) if a fragment shader is in use, or the alpha component of the result of fixed-function fragment shading. If the fragment shader does not write to this output, the alpha value is undefined.

`SAMPLE_ALPHA_TO_COVERAGE`, `SAMPLE_ALPHA_TO_ONE`, and `SAMPLE_COVERAGE` are enabled and disabled by calling `Enable` and `Disable` with `cap` specified as one of the three the desired token value. All three values are queried by calling `IsEnabled` with `cap` set to the desired token value. If drawbuffer zero is not `NONE` and the buffer it references has an integer format, the `SAMPLE_ALPHA_TO_COVERAGE` and `SAMPLE_ALPHA_TO_ONE` operations are skipped.

If `SAMPLE_ALPHA_TO_COVERAGE` is enabled, and the color buffer has a fixed-point or floating-point format, a temporary coverage value is generated where each bit is determined by the alpha value at the corresponding sample location. The temporary coverage value is then ANDed with the fragment coverage value to generate a new fragment coverage value. If the fragment shader outputs

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an integer to color number zero, index zero when not rendering to an integer format, the coverage value is undefined. Otherwise the fragment coverage value is unchanged at this point. If multiple colors are written by a fragment shader, the alpha value of fragment color zero is used to determine the temporary coverage value.

No specific algorithm is required for converting the sample alpha values to a temporary coverage value. It is intended that the number of 1's in the temporary coverage be proportional to the set of alpha values for the fragment, with all 1’s corresponding to the maximum of all alpha values, and all 0’s corresponding to all alpha values being 0. The alpha values used to generate a coverage value are clamped to the range $[0, 1]$. It is also intended that the algorithm be pseudo-random in nature, to avoid image artifacts due to regular coverage sample locations. The algorithm can and probably should be different at different pixel locations. If it does differ, it should be defined relative to window, not screen, coordinates, so that rendering results are invariant with respect to window position.

Next, if SAMPLE_ALPHA_TO_ONE is enabled, each alpha value is replaced by the maximum representable alpha value for fixed-point color buffers, or by 1.0 for floating-point buffers. Otherwise, the alpha values are not changed.

Next, if a fragment shader is active and statically assigns to the built-in output variable gl_SampleMask, the fragment coverage is ANDed with the bits of the sample mask. If such a fragment shader did not assign a value to gl_SampleMask due to flow control, the value ANDed with the fragment coverage is undefined. If no fragment shader is active, or if the active fragment shader does not statically assign values to gl_SampleMask, the fragment coverage is not modified.

Next, if SAMPLE_COVERAGE is enabled, the fragment coverage is ANDed with another temporary coverage. This temporary coverage is generated in the same manner as the one described above, but as a function of the value of SAMPLE_COVERAGE_VALUE. The function need not be identical, but it must have the same properties of proportionality and invariance. If SAMPLE_COVERAGE_INVERT is TRUE, the temporary coverage is inverted (all bit values are inverted) before it is ANDed with the fragment coverage.

The values of SAMPLE_COVERAGE_VALUE and SAMPLE_COVERAGE_INVERT are specified by calling

```c
    void SampleCoverage( clampf value, boolean invert );
```

with value set to the desired coverage value, and invert set to TRUE or FALSE. value is clamped to $[0,1]$ before being stored as SAMPLE_COVERAGE_VALUE. SAMPLE_COVERAGE_VALUE is queried by calling GetFloatv with pname set to SAMPLE_COVERAGE_VALUE. SAMPLE_COVERAGE_INVERT is queried by calling GetBooleanv with pname set to SAMPLE_COVERAGE_INVERT.
Finally, if \texttt{SAMPLE\_MASK} is enabled, the fragment coverage is ANDed with the coverage value \texttt{SAMPLE\_MASK\_VALUE}. The value of \texttt{SAMPLE\_MASK\_VALUE} is specified using

\begin{verbatim}
void SampleMaski(uint maskNumber, bitfield mask);
\end{verbatim}

with \texttt{mask} set to the desired mask for mask word \texttt{maskNumber}. \texttt{SAMPLE\_MASK\_VALUE} is queried by calling \texttt{GetIntegeri} with \texttt{pname} set to \texttt{SAMPLE\_MASK\_VALUE} and the index set to \texttt{maskNumber}. Bit \texttt{B} of mask word \texttt{M} corresponds to sample $32 \times M + B$ as described in section 3.3.1. The error \texttt{INVALID\_VALUE} is generated if the mask word indexed is greater than or equal to the value of \texttt{MAX\_SAMPLE\_MASK\_WORDS}.

### 4.1.4 Stencil Test

The stencil test conditionally discards a fragment based on the outcome of a comparison between the value in the stencil buffer at location $(x_w, y_w)$ and a reference value. The test is enabled or disabled with the \texttt{Enable} and \texttt{Disable} commands, using the symbolic constant \texttt{STENCIL\_TEST}. When disabled, the stencil test and associated modifications are not made, and the fragment is always passed.

The stencil test is controlled with

\begin{verbatim}
void StencilFunc(enum func, int ref, uint mask);
void StencilFuncSeparate(enum face, enum func, int ref, uint mask);
void StencilOp(enum sfail, enum dpfail, enum dpass);
void StencilOpSeparate(enum face, enum sfail, enum dpfail, enum dpass);
\end{verbatim}

There are two sets of stencil-related state, the front stencil state set and the back stencil state set. Stencil tests and writes use the front set of stencil state when processing fragments rasterized from non-polygon primitives (points and lines) and front-facing polygon primitives while the back set of stencil state is used when processing fragments rasterized from back-facing polygon primitives. For the purposes of stencil testing, a primitive is still considered a polygon even if the polygon is to be rasterized as points or lines due to the current polygon mode. Whether a polygon is front- or back-facing is determined in the same manner used for two-sided lighting and face culling (see section 3.6.1).

\texttt{StencilFuncSeparate} and \texttt{StencilOpSeparate} take a \texttt{face} argument which can be \texttt{FRONT}, \texttt{BACK}, or \texttt{FRONT\_AND\_BACK} and indicates which set of state is affected. \texttt{StencilFunc} and \texttt{StencilOp} set front and back stencil state to identical values.
StencilFunc and StencilFuncSeparate take three arguments that control whether the stencil test passes or fails. \( \text{ref} \) is an integer reference value that is used in the unsigned stencil comparison. Stencil comparison operations and queries of \( \text{ref} \) clamp its value to the range \([0, 2^s - 1]\), where \( s \) is the number of bits in the stencil buffer attached to the draw framebuffer. The \( s \) least significant bits of \( \text{mask} \) are bitwise ANDed with both the reference and the stored stencil value, and the resulting masked values are those that participate in the comparison controlled by \( \text{func} \). \( \text{func} \) is a symbolic constant that determines the stencil comparison function; the eight symbolic constants are \text{NEVER}, \text{ALWAYS}, \text{LESS}, \text{LEQUAL}, \text{EQUAL}, \text{GEQUAL}, \text{GREATER}, \text{or} \text{NOTEQUAL}. Accordingly, the stencil test passes never, always, and if the masked reference value is less than, less than or equal to, equal to, greater than or equal to, greater than, or not equal to the masked stored value in the stencil buffer.

StencilOp and StencilOpSeparate take three arguments that indicate what happens to the stored stencil value if this or certain subsequent tests fail or pass. \( \text{sfail} \) indicates what action is taken if the stencil test fails. The symbolic constants are \text{KEEP}, \text{ZERO}, \text{REPLACE}, \text{INCR}, \text{DECR}, \text{INVERT}, \text{INCR_WRAP}, \text{and} \text{DECR_WRAP}. These correspond to keeping the current value, setting to zero, replacing with the reference value, incrementing with saturation, decrementing with saturation, bitwise inverting it, incrementing without saturation, and decrementing without saturation.

For purposes of increment and decrement, the stencil bits are considered as an unsigned integer. Incrementing or decrementing with saturation clamps the stencil value at 0 and the maximum representable value. Incrementing or decrementing without saturation will wrap such that incrementing the maximum representable value results in 0, and decrementing 0 results in the maximum representable value.

The same symbolic values are given to indicate the stencil action if the depth buffer test (see section 4.1.5) fails \( (dpfail) \), or if it passes \( (dpass) \).

If the stencil test fails, the incoming fragment is discarded. The state required consists of the most recent values passed to StencilFunc or StencilFuncSeparate and to StencilOp or StencilOpSeparate, and a bit indicating whether stenciling is enabled or disabled. In the initial state, stenciling is disabled, the front and back stencil reference value are both zero, the front and back stencil comparison functions are both \text{ALWAYS}, and the front and back stencil mask are both set to the value \( 2^s - 1 \), where \( s \) is greater than or equal to the number of bits in the deepest stencil buffer supported by the GL implementation. Initially, all three front and back stencil operations are \text{KEEP}.

If there is no stencil buffer, no stencil modification can occur, and it is as if the stencil tests always pass, regardless of any calls to StencilFunc.
4.1.5 Depth Buffer Test

The depth buffer test discards the incoming fragment if a depth comparison fails. The comparison is enabled or disabled with the generic Enable and Disable commands using the symbolic constant DEPTH_TEST. When disabled, the depth comparison and subsequent possible updates to the depth buffer value are bypassed and the fragment is passed to the next operation. The stencil value, however, is modified as indicated below as if the depth buffer test passed. If enabled, the comparison takes place and the depth buffer and stencil value may subsequently be modified.

The comparison is specified with

```c
void DepthFunc(enum func);
```

This command takes a single symbolic constant: one of NEVER, ALWAYS, LESS, LEQUAL, EQUAL, GREATER, GEQUAL, NOTEQUAL. Accordingly, the depth buffer test passes never, always, if the incoming fragment’s \( z_w \) value is less than, less than or equal to, equal to, greater than, greater than or equal to, or not equal to the depth value stored at the location given by the incoming fragment’s \((x_w, y_w)\) coordinates.

If depth clamping (see section 2.20) is enabled, before the incoming fragment’s \( z_w \) is compared \( z_w \) is clamped to the range \([\min(n, f), \max(n, f)]\), where \( n \) and \( f \) are the current near and far depth range values (see section 2.14.1).

If the depth buffer test fails, the incoming fragment is discarded. The stencil value at the fragment’s \((x_w, y_w)\) coordinates is updated according to the function currently in effect for depth buffer test failure. Otherwise, the fragment continues to the next operation and the value of the depth buffer at the fragment’s \((x_w, y_w)\) location is set to the fragment’s \( z_w \) value. In this case the stencil value is updated according to the function currently in effect for depth buffer test success.

The necessary state is an eight-valued integer and a single bit indicating whether depth buffering is enabled or disabled. In the initial state the function is LESS and the test is disabled.

If there is no depth buffer, it is as if the depth buffer test always passes.

4.1.6 Occlusion Queries

Occlusion queries use query objects to track the number of fragments or samples that pass the depth test. An occlusion query can be started and finished by calling BeginQuery and EndQuery, respectively, with a target of SAMPLES_PASSED or ANY_SAMPLES_PASSED.

When an occlusion query is started with target SAMPLES_PASSED, the samples-passed count maintained by the GL is set to zero. When an occlusion
query is active, the samples-passed count is incremented for each fragment that passes the depth test. If the value of `SAMPLE_BUFFERS` is 0, then the samples-passed count is incremented by 1 for each fragment. If the value of `SAMPLE_BUFFERS` is 1, then the samples-passed count is incremented by the number of samples whose coverage bit is set. However, implementations, at their discretion, may instead increase the samples-passed count by the value of `SAMPLES` if any sample in the fragment is covered.

When an occlusion query finishes and all fragments generated by commands issued prior to `EndQuery` have been generated, the samples-passed count is written to the corresponding query object as the query result value, and the query result for that object is marked as available.

If the samples-passed count overflows (exceeds the value $2^n - 1$, where $n$ is the number of bits in the samples-passed count), its value becomes undefined. It is recommended, but not required, that implementations handle this overflow case by saturating at $2^n - 1$ and incrementing no further.

When an occlusion query is started with the target `ANY_SAMPLES_PASSED`, the samples-boolean state maintained by the GL is set to `FALSE`. While that occlusion query is active, the samples-boolean state is set to `TRUE` if any fragment or sample passes the depth test. When the occlusion query finishes, the samples-boolean state of `FALSE` or `TRUE` is written to the corresponding query object as the query result value, and the query result for that object is marked as available.

### 4.1.7 Blending

Blending combines the incoming source fragment’s R, G, B, and A values with the destination R, G, B, and A values stored in the framebuffer at the fragment’s $(x_w, y_w)$ location.

Source and destination values are combined according to the blend equation, quadruplets of source and destination weighting factors determined by the blend functions, and a constant blend color to obtain a new set of R, G, B, and A values, as described below.

If the color buffer is fixed-point, the components of the source and destination values and blend factors are clamped to $[0, 1]$ prior to evaluating the blend equation. If the color buffer is floating-point, no clamping occurs. The resulting four values are sent to the next operation.

Blending applies only if the color buffer has a fixed-point or floating-point format. If the color buffer has an integer format, proceed to the next operation.

Blending is enabled or disabled for an individual draw buffer with the commands.
4.1. PER-FRAGMENT OPERATIONS

```c
void Enablei( enum target, uint index );
void Disablei( enum target, uint index );
```

target is the symbolic constant BLEND and index is an integer i specifying the draw buffer associated with the symbolic constant DRAW_BUFFERi. If the color buffer associated with DRAW_BUFFERi is one of FRONT, BACK, LEFT, RIGHT, or FRONT_AND_BACK (specifying multiple color buffers), then the state enabled or disabled is applicable for all of the buffers. Blending can be enabled or disabled for all draw buffers using Enable or Disable with the symbolic constant BLEND. If blending is disabled for a particular draw buffer, or if logical operation on color values is enabled (section 4.1.10), proceed to the next operation.

An INVALID_VALUE error is generated if index is greater than the value of MAX_DRAW_BUFFERS minus one.

If multiple fragment colors are being written to multiple buffers (see section 4.2.1), blending is computed and applied separately for each fragment color and the corresponding buffer.

**Blend Equation**

Blending is controlled by the blend equation. This equation can be simultaneously set to the same value for all draw buffers using the commands

```c
void BlendEquation( enum mode );
void BlendEquationSeparate( enum modeRGB, 
                         enum modeAlpha );
```

or for an individual draw buffer using the indexed commands

```c
void BlendEquation( uint buf, enum mode );
void BlendEquationSeparate( uint buf, enum modeRGB, 
                           enum modeAlpha );
```

BlendEquationSeparate and BlendEquationSeparatei argument modeRGB determines the RGB blend equation while modeAlpha determines the alpha blend equation. BlendEquation and BlendEquationi argument mode determines both the RGB and alpha blend equations. mode, modeRGB, and modeAlpha must be one of FUNC_ADD, FUNC_SUBTRACT, FUNC_REVERSE_SUBTRACT, MIN, or MAX. BlendEquation and BlendEquationSeparate modify the blend equations for all draw buffers. BlendEquationi and BlendEquationSeparatei modify the blend equations associated with an individual draw buffer. The buf argument is an integer i that indicates that the blend equations should be modified for DRAW_BUFFERi.

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4.1. **PER-FRAGMENT OPERATIONS**

Signed or unsigned normalized fixed-point destination (framebuffer) components are represented as described in section 2.1.5. Constant color components, floating-point destination components, and source (fragment) components are taken to be floating point values. If source components are represented internally by the GL as fixed-point values, they are also interpreted according to section 2.1.5.

Prior to blending, signed and unsigned normalized fixed-point color components undergo an implied conversion to floating-point using equations 2.1 and 2.3, respectively. This conversion must leave the values 0 and 1 invariant. Blending computations are treated as if carried out in floating-point.

If `FRAMEBUFFER_SRGB` is enabled and the value of `FRAMEBUFFER_ATTACHMENT_COLOR_ENCODING` for the framebuffer attachment corresponding to the destination buffer is `SRGB` (see section 6.1.3), the R, G, and B destination color values (after conversion from fixed-point to floating-point) are considered to be encoded for the sRGB color space and hence must be linearized prior to their use in blending. Each R, G, and B component is converted in the same fashion described for sRGB texture components in section 3.8.17.

If `FRAMEBUFFER_SRGB` is disabled or the value of `FRAMEBUFFER_ATTACHMENT_COLOR_ENCODING` is not `SRGB`, no linearization is performed.

The resulting linearized R, G, and B and unmodified A values are recombined as the destination color used in blending computations.

Table 4.1 provides the corresponding per-component blend equations for each mode, whether acting on RGB components for `modeRGB` or the alpha component for `modeAlpha`.

In the table, the `s` subscript on a color component abbreviation (R, G, B, or A) refers to the source color component for an incoming fragment, the `d` subscript on a color component abbreviation refers to the destination color component at the corresponding framebuffer location, and the `c` subscript on a color component abbreviation refers to the constant blend color component. A color component abbreviation without a subscript refers to the new color component resulting from blending. Additionally, `Sr`, `Sg`, `Sb`, and `Sa` are the red, green, blue, and alpha components of the source weighting factors determined by the source blend function, and `Dr`, `Dg`, `Db`, and `Da` are the red, green, blue, and alpha components of the destination weighting factors determined by the destination blend function. Blend functions are described below.

### Blend Functions

The weighting factors used by the blend equation are determined by the blend functions. There are four possible sources for weighting factors. These are the
4.1. PER-FRAGMENT OPERATIONS

<table>
<thead>
<tr>
<th>Mode</th>
<th>RGB Components</th>
<th>Alpha Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUNC_ADD</td>
<td>( R = R_s S_r + R_d D_r )</td>
<td>( A = A_s S_a + A_d D_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_s S_g + G_d D_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_s S_b + B_d D_b )</td>
<td></td>
</tr>
<tr>
<td>FUNC_SUBTRACT</td>
<td>( R = R_s S_r - R_d D_r )</td>
<td>( A = A_s S_a - A_d D_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_s S_g - G_d D_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_s S_b - B_d D_b )</td>
<td></td>
</tr>
<tr>
<td>FUNC_REVERSE_SUBTRACT</td>
<td>( R = R_d D_r - R_s S_r )</td>
<td>( A = A_d D_a - A_s S_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_d D_g - G_s S_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_d D_b - B_s S_b )</td>
<td></td>
</tr>
<tr>
<td>MIN</td>
<td>( R = \min(R_s, R_d) )</td>
<td>( A = \min(A_s, A_d) )</td>
</tr>
<tr>
<td></td>
<td>( G = \min(G_s, G_d) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = \min(B_s, B_d) )</td>
<td></td>
</tr>
<tr>
<td>MAX</td>
<td>( R = \max(R_s, R_d) )</td>
<td>( A = \max(A_s, A_d) )</td>
</tr>
<tr>
<td></td>
<td>( G = \max(G_s, G_d) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = \max(B_s, B_d) )</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: RGB and alpha blend equations.

constant color \((R_c, G_c, B_c, A_c)\) set with BlendColor (see below), the first source color \((R_{s0}, G_{s0}, B_{s0}, A_{s0})\), the second source color \((R_{s1}, G_{s1}, B_{s1}, A_{s1})\), and the destination color (the existing content of the draw buffer). Additionally the special constants \texttt{ZERO} and \texttt{ONE} are available as weighting factors.

Blend functions are simultaneously specified for all draw buffers using the commands

```c
void BlendFunc( enum src, enum dst );
void BlendFuncSeparate( enum srcRGB, enum dstRGB,
                        enum srcAlpha, enum dstAlpha );
```

or for an individual draw buffer using the indexed commands

```c
void BlendFunci( uint buf, enum src, enum dst );
void BlendFuncSeparatei( uint buf, enum srcRGB,
                         enum dstRGB, enum srcAlpha, enum dstAlpha );
```

BlendFuncSeparate and BlendFuncSeparatei arguments \texttt{srcRGB} and \texttt{dstRGB} determine the source and destination RGB blend functions, respectively, while \texttt{srcAlpha} and \texttt{dstAlpha} determine the source and destination alpha blend.
### Table 4.2: RGB and Alpha source and destination blending functions and the corresponding blend factors.

Addition and subtraction of triplets is performed component-wise.

\[ f = \min(A_s, 1 - A_d). \]

<table>
<thead>
<tr>
<th>Function</th>
<th>RGB Blend Factors</th>
<th>Alpha Blend Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZERO</td>
<td>((0, 0, 0))</td>
<td>0</td>
</tr>
<tr>
<td>ONE</td>
<td>((1, 1, 1))</td>
<td>1</td>
</tr>
<tr>
<td>SRC_COLOR</td>
<td>((R_s, G_s, B_s))</td>
<td>(A_s)</td>
</tr>
<tr>
<td>ONE_MINUS_SRC_COLOR</td>
<td>((1, 1, 1) - (R_s, G_s, B_s))</td>
<td>1 - (A_s)</td>
</tr>
<tr>
<td>DST_COLOR</td>
<td>((R_d, G_d, B_d))</td>
<td>(A_d)</td>
</tr>
<tr>
<td>ONE_MINUS_DST_COLOR</td>
<td>((1, 1, 1) - (R_d, G_d, B_d))</td>
<td>1 - (A_d)</td>
</tr>
<tr>
<td>SRC_ALPHA</td>
<td>((A_s, A_s, A_s))</td>
<td>(A_s)</td>
</tr>
<tr>
<td>ONE_MINUS_SRC_ALPHA</td>
<td>((1, 1, 1) - (A_s, A_s, A_s))</td>
<td>1 - (A_s)</td>
</tr>
<tr>
<td>DST_ALPHA</td>
<td>((A_d, A_d, A_d))</td>
<td>(A_d)</td>
</tr>
<tr>
<td>ONE_MINUS_DST_ALPHA</td>
<td>((1, 1, 1) - (A_d, A_d, A_d))</td>
<td>1 - (A_d)</td>
</tr>
<tr>
<td>CONSTANT_COLOR</td>
<td>((R_c, G_c, B_c))</td>
<td>(A_c)</td>
</tr>
<tr>
<td>ONE_MINUS_CONSTANT_COLOR</td>
<td>((1, 1, 1) - (R_c, G_c, B_c))</td>
<td>1 - (A_c)</td>
</tr>
<tr>
<td>CONSTANT_ALPHA</td>
<td>((A_c, A_c, A_c))</td>
<td>(A_c)</td>
</tr>
<tr>
<td>ONE_MINUS_CONSTANT_ALPHA</td>
<td>((1, 1, 1) - (A_c, A_c, A_c))</td>
<td>1 - (A_c)</td>
</tr>
<tr>
<td>SRC_ALPHA_SATURATE</td>
<td>((f, f, f))^1</td>
<td>1</td>
</tr>
<tr>
<td>SRC_COLOR_SATURATE</td>
<td>((R_s, G_s, B_s))</td>
<td>(A_s)</td>
</tr>
<tr>
<td>ONE_MINUS_SRC_COLOR_SATURATE</td>
<td>((1, 1, 1) - (R_s, G_s, B_s))</td>
<td>1 - (A_s)</td>
</tr>
<tr>
<td>SRC1_ALPHA</td>
<td>((A_s, A_s, A_s))</td>
<td>(A_s)</td>
</tr>
<tr>
<td>ONE_MINUS_SRC_COLOR_ALPHA</td>
<td>((1, 1, 1) - (A_s, A_s, A_s))</td>
<td>1 - (A_s)</td>
</tr>
</tbody>
</table>

functions. \texttt{BlendFunc} and \texttt{BlendFunci} argument src determines both RGB and alpha source functions, while dst determines both RGB and alpha destination functions. \texttt{BlendFuncSeparate} and \texttt{BlendFunc} modify the blend functions for all draw buffers. \texttt{BlendFuncSeparatei} and \texttt{BlendFunci} modify the blend functions associated with an individual draw buffer. The \texttt{buf} argument is an integer \(i\) that indicates that the blend equations should be modified for \texttt{DRAW\_BUFFER\_i}.

The possible source and destination blend functions and their corresponding computed blend factors are summarized in table 4.2.
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Dual Source Blending and Multiple Draw Buffers

Blend functions that require the second color input, \((R_{s1}, G_{s1}, B_{s1}, A_{s1})\) \((\text{SRC1}_\text{-COLOR}, \text{SRC1}_\text{-ALPHA}, \text{ONE_MINUS_SRC1}_\text{-COLOR}, \text{or} \ \text{ONE_MINUS_SRC1}_\text{-ALPHA})\) may consume hardware resources that could otherwise be used for rendering to multiple draw buffers. Therefore, the number of draw buffers that can be attached to a frame buffer may be lower when using dual-source blending.

The maximum number of draw buffers that may be attached to a single frame buffer when using dual-source blending functions is implementation dependent and can be queried by calling `GetIntegerv` with the symbolic constant `MAX_-DUAL_SOURCE_DRAW_BUFFERS`. When using dual-source blending, `MAX_DUAL_-SOURCE_DRAW_BUFFERS` should be used in place of `MAX_DRAW_BUFFERS` to determine the maximum number of draw buffers that may be attached to a single frame buffer. The value of `MAX_DUAL_SOURCE_DRAW_BUFFERS` must be at least 1. If the value of `MAX_DUAL_SOURCE_DRAW_BUFFERS` is 1, then dual-source blending and multiple draw buffers cannot be used simultaneously.

If either blend function requires the second color input for any draw buffer, and any draw buffers greater than or equal to the value of `MAX_DUAL_SOURCE_DRAW_BUFFERS` have values other than `NONE`, the error `INVALID_OPERATION` is generated by `DrawArrays` and the other drawing commands defined in section 2.8.3.

Generation of Second Color Source for Blending

When using a fragment shader with dual-source blending functions, the color output varyings are bound to the first and second inputs of a draw buffer using `BindFragDataLocationIndexed` as described in the Shader Outputs subsection of section 3.9.2. Data written to the first of these outputs becomes the first source color input to the blender (corresponding to `SRC_COLOR` and `SRC_ALPHA`). Data written to the second of these outputs generates the second source color input to the blender (corresponding to `SRC1_COLOR` and `SRC1_ALPHA`).

If the second color input to the blender is not written in the shader, or if no output is bound to the second input of a blender, the result of the blending operation is not defined.

Blend Color

The constant color \(C_c\) to be used in blending is specified with the command

\[
\text{void BlendColor} ( \text{clampf red}, \text{clampf green}, \text{clampf blue}, \text{clampf alpha} );
\]
The constant color can be used in both the source and destination blending functions.

### Blending State

The state required for blending, for each draw buffer, is two integers for the RGB and alpha blend equations, four integers indicating the source and destination RGB and alpha blending functions, and a bit indicating whether blending is enabled or disabled. Additionally, four floating-point values to store the RGBA constant blend color are required.

For all draw buffers, the initial blend equations for RGB and alpha are both `FUNC_ADD`, and the initial blending functions are `ONE` for the source RGB and alpha functions and `ZERO` for the destination RGB and alpha functions. Initially, blending is disabled for all draw buffers. The initial constant blend color is \((R, G, B, A) = (0, 0, 0, 0)\).

The value of the blend enable for draw buffer \(i\) can be queried by calling `IsEnabled\(i\)` with `target BLEND` and `index \(i\)`, and the values of the blend equations and functions can be queried by calling `GetInteger\(i\)\(v\)` with the corresponding `target` as shown in table 6.21 and `index \(i\)`.

The value of the blend enable, or the blend equations and functions for draw buffer zero may also be queried by calling `IsEnabled`, or `GetInteger`, respectively, with the same symbolic constants but no `index` parameter.

Blending occurs once for each color buffer currently enabled for blending and for writing (section 4.2.1) using each buffer’s color for \(C_d\). If a color buffer has no A value, then \(A_d\) is taken to be 1.

### 4.1.8 sRGB Conversion

If `FRAMEBUFFER_SRGB` is enabled and the value of `FRAMEBUFFER_ATTACHMENT_COLOR_ENCODING` for the framebuffer attachment corresponding to the destination buffer is `SRGB` (see section 6.1.3), the R, G, and B values after blending are converted into the non-linear sRGB color space by computing

\[
  c_s = \begin{cases} 
  0.0, & c_l \leq 0 \\
  12.92c_l, & 0 < c_l < 0.0031308 \\
  1.055c_l^{0.41666} - 0.055, & 0.0031308 \leq c_l < 1 \\
  1.0, & c_l \geq 1
  \end{cases}
\]

(4.1)

where \(c_l\) is the R, G, or B element and \(c_s\) is the result (effectively converted into an sRGB color space).
4.1. PER-FRAGMENT OPERATIONS

FRAMEBUFFER_ATTACHMENT_COLOR_ENCODING is not SRGB, then

\[ c_s = c_l. \]

The resulting \( c_s \) values for R, G, and B, and the unmodified A form a new RGBA color value. If the color buffer is fixed-point, each component is clamped to the range \([0, 1]\) and then converted to a fixed-point value using equation 2.4. The resulting four values are sent to the subsequent dithering operation.

4.1.9 Dithering

Dithering selects between two representable color values or indices. A representable value is a value that has an exact representation in the color buffer. Dithering selects, for each color component, either the largest representable color value (for that particular color component) that is less than or equal to the incoming color component value, \( c \), or the smallest representable color value that is greater than or equal to \( c \). The selection may depend on the \( x_w \) and \( y_w \) coordinates of the pixel, as well as on the exact value of \( c \). If one of the two values does not exist, then the selection defaults to the other value.

Many dithering selection algorithms are possible, but an individual selection must depend only on the incoming component value and the fragment’s \( x \) and \( y \) window coordinates. If dithering is disabled, then each incoming color component \( c \) is replaced with the largest positive representable color value (for that particular component) that is less than or equal to \( c \), or by the smallest negative representable value, if no representable value is less than or equal to \( c \).

Dithering is enabled with Enable and disabled with Disable using the symbolic constant DITHER. The state required is thus a single bit. Initially, dithering is enabled.

4.1.10 Logical Operation

Finally, a logical operation is applied between the incoming fragment’s color values and the color values stored at the corresponding location in the framebuffer. The result replaces the values in the framebuffer at the fragment’s \( (x_w, y_w) \) coordinates. If the selected draw buffers refer to the same framebuffer-attachable image more than once, then the values stored in that image are undefined.

The logical operation on color values is enabled or disabled with Enable or Disable using the symbolic constant COLOR_LOGIC_OP. If the logical operation is enabled for color values, it is as if blending were disabled, regardless of the value of BLEND. If multiple fragment colors are being written to multiple buffers (see
### 4.1. PER-FRAGMENT OPERATIONS

<table>
<thead>
<tr>
<th>Argument value</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEAR</td>
<td>0</td>
</tr>
<tr>
<td>AND</td>
<td>( s \land d )</td>
</tr>
<tr>
<td>AND_REVERSE</td>
<td>( s \land \neg d )</td>
</tr>
<tr>
<td>COPY</td>
<td>( s )</td>
</tr>
<tr>
<td>AND_INVERTED</td>
<td>( \neg s \land d )</td>
</tr>
<tr>
<td>NOOP</td>
<td>( d )</td>
</tr>
<tr>
<td>XOR</td>
<td>( s \text{xor} d )</td>
</tr>
<tr>
<td>OR</td>
<td>( s \lor d )</td>
</tr>
<tr>
<td>NOR</td>
<td>( \neg(s \lor d) )</td>
</tr>
<tr>
<td>EQUIV</td>
<td>( \neg(s \text{xor} d) )</td>
</tr>
<tr>
<td>INVERT</td>
<td>( \neg d )</td>
</tr>
<tr>
<td>OR_REVERSE</td>
<td>( s \lor \neg d )</td>
</tr>
<tr>
<td>COPY_INVERTED</td>
<td>( \neg s )</td>
</tr>
<tr>
<td>OR_INVERTED</td>
<td>( \neg s \lor d )</td>
</tr>
<tr>
<td>NAND</td>
<td>( \neg(s \land d) )</td>
</tr>
<tr>
<td>SET</td>
<td>all 1’s</td>
</tr>
</tbody>
</table>

Table 4.3: Arguments to \texttt{LogicOp} and their corresponding operations.

In section 4.2.1, the logical operation is computed and applied separately for each fragment color and the corresponding buffer.

Logical operation has no effect on a floating-point destination color buffer. However, if logical operation is enabled, blending is still disabled.

The logical operation is selected by

```c
void LogicOp(enum op);
```

\( op \) is a symbolic constant; the possible constants and corresponding operations are enumerated in table 4.3. In this table, \( s \) is the value of the incoming fragment and \( d \) is the value stored in the framebuffer. The numeric values assigned to the symbolic constants are the same as those assigned to the corresponding symbolic values in the X window system.

Logical operations are performed independently for each red, green, blue, and alpha value of each color buffer that is selected for writing. The required state is an integer indicating the logical operation, and a bit indicating whether the logical operation is enabled or disabled. The initial state is for the logic operation to be given by \texttt{COPY}, and to be disabled.
4.1.11 Additional Multisample Fragment Operations

If the DrawBuffer mode is NONE, no change is made to any multisample or color buffer. Otherwise, fragment processing is as described below.

If MULTISAMPLE is enabled, and the value of SAMPLE_BUFFERS is one, the stencil test, depth test, blending, dithering, and logical operations are performed for each pixel sample, rather than just once for each fragment. Failure of the stencil or depth test results in termination of the processing of that sample, rather than discarding of the fragment. All operations are performed on the color, depth, and stencil values stored in the multisample buffer (to be described in a following section). The contents of the color buffers are not modified at this point.

Stencil, depth, blending, dithering, and logical operations are performed for a pixel sample only if that sample’s fragment coverage bit is a value of 1. If the corresponding coverage bit is 0, no operations are performed for that sample.

If MULTISAMPLE is disabled, and the value of SAMPLE_BUFFERS is one, the fragment may be treated exactly as described above, with optimization possible because the fragment coverage must be set to full coverage. Further optimization is allowed, however. An implementation may choose to identify a centermost sample, and to perform stencil and depth tests on only that sample. Regardless of the outcome of the stencil test, all multisample buffer stencil sample values are set to the appropriate new stencil value. If the depth test passes, all multisample buffer depth sample values are set to the depth of the fragment’s centermost sample’s depth value, and all multisample buffer color sample values are set to the color value of the incoming fragment. Otherwise, no change is made to any multisample buffer color or depth value.

After all operations have been completed on the multisample buffer, the sample values for each color in the multisample buffer are combined to produce a single color value, and that value is written into the corresponding color buffers selected by DrawBuffer or DrawBuffers. An implementation may defer the writing of the color buffers until a later time, but the state of the framebuffer must behave as if the color buffers were updated as each fragment was processed. The method of combination is not specified. If the framebuffer contains sRGB values, then it is recommended that the average of sample values is computed in a linearized space, as for blending (see section 4.1.7). Otherwise, a simple average computed independently for each color component is recommended.

4.2 Whole Framebuffer Operations

The preceding sections described the operations that occur as individual fragments are sent to the framebuffer. This section describes operations that control or affect
4.2. WHOLE FRAMEBUFFER OPERATIONS

the whole framebuffer.

4.2.1 Selecting a Buffer for Writing

The first such operation is controlling the color buffers into which each of the fragment color values is written. This is accomplished with either DrawBuffer or DrawBuffers.

The command

```c
void DrawBuffer( enum buf );
```

defines the set of color buffers to which fragment color zero is written. `buf` must be one of the values from tables 4.4 or 4.5. In addition, acceptable values for `buf` depend on whether the GL is using the default framebuffer (i.e., DRAW_FRAMEBUFFER_BINDING is zero), or a framebuffer object (i.e., DRAW_-FRAMEBUFFER_BINDING is non-zero). In the initial state, the GL is bound to the default framebuffer. For more information about framebuffer objects, see section 4.4.

If the GL is bound to the default framebuffer, then `buf` must be one of the values listed in table 4.4, which summarizes the constants and the buffers they indicate. In this case, `buf` is a symbolic constant specifying zero, one, two, or four buffers for writing. These constants refer to the four potentially visible buffers (front left, front right, back left, and back right). Arguments that omit reference to LEFT or RIGHT refer to both left and right buffers. Arguments that omit reference to FRONT or BACK refer to both front and back buffers.

If the GL is bound to a framebuffer object, `buf` must be one of the values listed in table 4.5, which summarizes the constants and the buffers they indicate. In this case, `buf` is a symbolic constant specifying a single color buffer for writing. Specifying COLOR_ATTACHMENT enables drawing only to the image attached to the framebuffer at COLOR_ATTACHMENTi. Each COLOR_ATTACHMENTi adheres to COLOR_ATTACHMENTi = COLOR_ATTACHMENT0 + i. The intial value of DRAW_-BUFFER for framebuffer objects is COLOR_ATTACHMENT0.

If the GL is bound to the default framebuffer and DrawBuffer is supplied with a constant (other than NONE) that does not indicate any of the color buffers allocated to the GL context, the error INVALID_OPERATION results.

If the GL is bound to a framebuffer object and `buf` is one of the constants from table 4.4, then the error INVALID_OPERATION results. If `buf` is COLOR_-ATTACHMENTm and m is greater than or equal to the value of MAX_COLOR_-ATTACHMENTS, then the error INVALID_VALUE results.

If DrawBuffer is supplied with a constant that is legal for neither the default framebuffer nor a framebuffer object, then the error INVALID_ENUM results.
4.2. WHOLE FRAMEBUFFER OPERATIONS

<table>
<thead>
<tr>
<th>Symbolic Constant</th>
<th>Front Left</th>
<th>Front Right</th>
<th>Back Left</th>
<th>Back Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRONT_LEFT</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRONT_RIGHT</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK_LEFT</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK_RIGHT</td>
<td></td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>FRONT</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>LEFT</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RIGHT</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>FRONT_AND_BACK</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Table 4.4: Arguments to `DrawBuffer(s)` and `ReadBuffer` when the context is bound to a default framebuffer, and the buffers they indicate.

<table>
<thead>
<tr>
<th>Symbolic Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td>No buffer</td>
</tr>
<tr>
<td>COLOR_ATTACHMENT(i) (see caption)</td>
<td>Output fragment color to image attached at color attachment point (i)</td>
</tr>
</tbody>
</table>

Table 4.5: Arguments to `DrawBuffer(s)` and `ReadBuffer` when the context is bound to a framebuffer object, and the buffers they indicate. \(i\) in `COLOR_ATTACHMENT\(i\)` may range from zero to the value of `MAX_COLOR_ATTACHMENTS` - 1.
4.2. WHOLE FRAMEBUFFER OPERATIONS

Table 4.6: Arguments to DrawBuffers when the context is bound to the default framebuffer, and the buffers they indicate.

<table>
<thead>
<tr>
<th>Symbolic Constant</th>
<th>Front Left</th>
<th>Front Right</th>
<th>Back Left</th>
<th>Back Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRONT_LEFT</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRONT_RIGHT</td>
<td></td>
<td>•</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK_LEFT</td>
<td></td>
<td></td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>BACK_RIGHT</td>
<td></td>
<td></td>
<td></td>
<td>•</td>
</tr>
</tbody>
</table>

**DrawBuffer** will set the draw buffer for fragment colors other than zero to **NONE**.

The command

```c
void DrawBuffers(sizei n, const enum *bufs);
```

defines the draw buffers to which all fragment colors are written. \( n \) specifies the number of buffers in \( bufs \). \( bufs \) is a pointer to an array of symbolic constants specifying the buffer to which each fragment color is written.

Each buffer listed in \( bufs \) must be one of the values from tables 4.5 or 4.6. Otherwise, an **INVALID_ENUM** error is generated. Further, acceptable values for the constants in \( bufs \) depend on whether the GL is using the default framebuffer (i.e., \( DRAW_FRAMEBUFFER_BINDING \) is zero), or a framebuffer object (i.e., \( DRAW_FRAMEBUFFER_BINDING \) is non-zero). For more information about framebuffer objects, see section 4.4.

If the GL is bound to the default framebuffer, then each of the constants must be one of the values listed in table 4.6.

If the GL is bound to a framebuffer object, then each of the constants must be one of the values listed in table 4.5.

In both cases, the draw buffers being defined correspond in order to the respective fragment colors. The draw buffer for fragment colors beyond \( n \) is set to **NONE**.

The maximum number of draw buffers is implementation-dependent. The number of draw buffers supported can be queried by calling **GetInteger** with the symbolic constant **MAX_DRAW_BUFFERS**. An **INVALID_VALUE** error is generated if \( n \) is greater than **MAX_DRAW_BUFFERS**.

Except for **NONE**, a buffer may not appear more than once in the array pointed...
4.2. WHOLE FRAMEBUFFER OPERATIONS

to by *bufs*. specifying a buffer more then once will result in the error **INVALID_OPERATION**.

If a fragment shader writes to *gl_FragColor*, **DrawBuffers** specifies a set of draw buffers into which the single fragment color defined by *gl_FragColor* is written. If a fragment shader writes to *gl_FragData*, or a user-defined varying out variable, **DrawBuffers** specifies a set of draw buffers into which each of the multiple output colors defined by these variables are separately written. If a fragment shader writes to none of *gl_FragColor*, *gl_FragData*, nor any user-defined varying out variables, the values of the fragment colors following shader execution are undefined, and may differ for each fragment color.

For both the default framebuffer and framebuffer objects, the constants **FRONT**, **BACK**, **LEFT**, **RIGHT**, and **FRONT_AND_BACK** are not valid in the *bufs* array passed to **DrawBuffers**, and will result in the error **INVALID_ENUM**. This restriction is because these constants may themselves refer to multiple buffers, as shown in table 4.4.

If the GL is bound to the default framebuffer and **DrawBuffers** is supplied with a constant (other than **NONE**) that does not indicate any of the color buffers allocated to the GL context by the window system, the error **INVALID_OPERATION** will be generated.

If the GL is bound to a framebuffer object and **DrawBuffers** is supplied with a constant from table 4.6, or **COLOR_ATTACHMENTm** where *m* is greater than or equal to the value of **MAX_COLOR_ATTACHMENTS**, then the error **INVALID_OPERATION** results.

Indicating a buffer or buffers using **DrawBuffer** or **DrawBuffers** causes subsequent pixel color value writes to affect the indicated buffers.

Specifying **NONE** as the draw buffer for a fragment color will inhibit that fragment color from being written to any buffer.

Monoscopic contexts include only left buffers, while stereoscopic contexts include both left and right buffers. Likewise, single buffered contexts include only front buffers, while double buffered contexts include both front and back buffers. The type of context is selected at GL initialization.

The state required to handle color buffer selection for each framebuffer is an integer for each supported fragment color. For the default framebuffer, in the initial state the draw buffer for fragment color zero is **BACK** if there is a back buffer; **FRONT** if there is no back buffer; and **NONE** if no default framebuffer is associated with the context. For framebuffer objects, in the initial state the draw buffer for fragment color zero is **COLOR_ATTACHMENT0**. For both the default framebuffer and framebuffer objects, the initial state of draw buffers for fragment colors other then zero is **NONE**.

The value of the draw buffer selected for fragment color *i* can be queried by
calling \texttt{GetIntegerv} with the symbolic constant \texttt{DRAW_BUFFER} \texttt{i}. \texttt{DRAW_BUFFER} is equivalent to \texttt{DRAW_BUFFER}0.

### 4.2.2 Fine Control of Buffer Updates

Writing of bits to each of the logical framebuffers after all per-fragment operations have been performed may be masked. The commands

\begin{verbatim}
void ColorMask( boolean r, boolean g, boolean b, boolean a );  
void ColorMaski( uint buf, boolean r, boolean g, boolean b, boolean a );
\end{verbatim}

control writes to the active draw buffers. \texttt{ColorMask} and \texttt{ColorMaski} are used to mask the writing of R, G, B and A values to the draw buffer or buffers. \texttt{ColorMaski} sets the mask for a particular draw buffer. The mask for \texttt{DRAW_BUFFER} \texttt{i} is modified by passing \texttt{i} as the parameter \texttt{buf}. \texttt{r}, \texttt{g}, \texttt{b}, and \texttt{a} indicate whether R, G, B, or A values, respectively, are written or not (a value of \texttt{TRUE} means that the corresponding value is written). The mask specified by \texttt{r}, \texttt{g}, \texttt{b}, and \texttt{a} is applied to the color buffer associated with \texttt{DRAW_BUFFER} \texttt{i}. If \texttt{DRAW_BUFFER} \texttt{i} is one of \texttt{FRONT}, \texttt{BACK}, \texttt{LEFT}, \texttt{RIGHT}, or \texttt{FRONT_AND_BACK} (specifying multiple color buffers) then the mask is applied to all of the buffers.

\texttt{ColorMask} sets the mask for all draw buffers to the same values as specified by \texttt{r}, \texttt{g}, \texttt{b}, and \texttt{a}.

An \texttt{INVALID_VALUE} error is generated if \texttt{index} is greater than the value of \texttt{MAX_DRAW_BUFFERS} minus one.

In the initial state, all color values are enabled for writing for all draw buffers.

The value of the color writemask for draw buffer \texttt{i} can be queried by calling \texttt{GetBooleani} with \texttt{target} \texttt{COLOR_WRITEMASK} and \texttt{index} \texttt{i}. The value of the color writemask for draw buffer zero may also be queried by calling \texttt{GetBooleanv} with the symbolic constant \texttt{COLOR_WRITEMASK}.

The depth buffer can be enabled or disabled for writing \texttt{zw} values using

\begin{verbatim}
void DepthMask( boolean mask );
\end{verbatim}

If \texttt{mask} is non-zero, the depth buffer is enabled for writing; otherwise, it is disabled.

In the initial state, the depth buffer is enabled for writing. The commands

\begin{verbatim}
void StencilMask( uint mask );
\end{verbatim}

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void StencilMaskSeparate(enum face, uint mask);

control the writing of particular bits into the stencil planes.

The least significant \( s \) bits of \( mask \), where \( s \) is the number of bits in the stencil buffer, specify an integer mask. Where a 1 appears in this mask, the corresponding bit in the stencil buffer is written; where a 0 appears, the bit is not written. The \( face \) parameter of StencilMaskSeparate can be FRONT, BACK, or FRONT_AND_BACK and indicates whether the front or back stencil mask state is affected. StencilMask sets both front and back stencil mask state to identical values.

Fragments generated by front-facing primitives use the front mask and fragments generated by back-facing primitives use the back mask (see section 4.1.4). The clear operation always uses the front stencil write mask when clearing the stencil buffer.

The state required for the various masking operations is two integers for the front and back stencil values, and a bit for depth values. A set of four bits is also required indicating which color components of an RGBA value should be written. In the initial state, the integer masks are all ones, as are the bits controlling depth value and RGBA component writing.

Fine Control of Multisample Buffer Updates

When the value of SAMPLE_BUFFERS is one, ColorMask, DepthMask, and StencilMask or StencilMaskSeparate control the modification of values in the multisample buffer. The color mask has no effect on modifications to the color buffers. If the color mask is entirely disabled, the color sample values must still be combined (as described above) and the result used to replace the color values of the buffers enabled by DrawBuffer.

4.2.3 Clearing the Buffers

The GL provides a means for setting portions of every pixel in a particular buffer to the same value. The argument to

    void Clear(bitfield buf);

is zero or the bitwise OR of one or more values indicating which buffers are to be cleared. The values are COLOR_BUFFER_BIT, DEPTH_BUFFER_BIT, and STENCIL_BUFFER_BIT, indicating the buffers currently enabled for color writing, the depth buffer, and the stencil buffer (see below), respectively. The value to which each buffer is cleared depends on the setting of the clear value for that buffer.
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If buf is zero, no buffers are cleared. If buf contains any bits other than COLOR_BUFFER_BIT, DEPTH_BUFFER_BIT, or STENCIL_BUFFER_BIT, then the error INVALID_VALUE is generated.

```c
void ClearColor(clampf r, clampf g, clampf b, clampf a);
```

sets the clear value for fixed- and floating-point color buffers. The specified components are stored as floating-point values.

The command

```c
void ClearDepth(clampd d);
```

sets the depth value used when clearing the depth buffer. d is clamped to the range [0, 1]. When clearing a fixed-point depth buffer, d is converted to fixed-point according to the rules for a window z value given in section 2.14.1. No conversion is applied when clearing a floating-point depth buffer.

The command

```c
void ClearStencil(int s);
```

takes a single integer argument that is the value to which to clear the stencil buffer. s is masked to the number of bitplanes in the stencil buffer.

When Clear is called, the only per-fragment operations that are applied (if enabled) are the pixel ownership test, the scissor test, and dithering. The masking operations described in section 4.2.2 are also applied. If a buffer is not present, then a Clear directed at that buffer has no effect. Unsigned normalized fixed-point and signed normalized fixed-point RGBA color buffers are cleared to color values derived by clamping each component of the clear color to the range [0, 1] or [-1, 1] respectively, then converting to fixed-point using equations 2.4 or 2.6, respectively. The result of clearing integer color buffers is undefined.

The state required for clearing is a clear value for each of the color buffer, the depth buffer, and the stencil buffer. Initially, the RGBA color clear value is (0, 0, 0, 0), the depth buffer clear value is 1.0, and the stencil buffer clear index is 0.

Individual buffers of the currently bound draw framebuffer may be cleared with the command

```c
void ClearBuffer(if ui)\{ enum buffer, int drawbuffer, 
    const T *value \};
```
where `buffer` and `drawbuffer` identify a buffer to clear, and `value` specifies the value or values to clear it to.

If `buffer` is `COLOR`, a particular draw buffer `DRAW_BUFFER_i` is specified by passing `i` as the parameter `drawbuffer`, and `value` points to a four-element vector specifying the R, G, B, and A color to clear that draw buffer to. If the draw buffer is one of `FRONT`, `BACK`, `LEFT`, `RIGHT`, or `FRONT_AND_BACK`, identifying multiple buffers, each selected buffer is cleared to the same value. The `ClearBufferfv`, `ClearBufferiv`, and `ClearBufferuiv` commands should be used to clear fixed- and floating-point, signed integer, and unsigned integer color buffers respectively. Clamping and conversion for fixed-point color buffers are performed in the same fashion as `ClearColor`.

If `buffer` is `DEPTH`, `drawbuffer` must be zero, and `value` points to the single depth value to clear the depth buffer to. Clamping and type conversion for fixed-point depth buffers are performed in the same fashion as `ClearDepth`. Only `ClearBufferfv` should be used to clear depth buffers.

If `buffer` is `STENCIL`, `drawbuffer` must be zero, and `value` points to the single stencil value to clear the stencil buffer to. Masking and type conversion are performed in the same fashion as `ClearStencil`. Only `ClearBufferiv` should be used to clear stencil buffers.

The command

```c
void ClearBufferfi( enum buffer, int drawbuffer, 
                    float depth, int stencil );
```

clears both depth and stencil buffers of the currently bound draw framebuffer. `buffer` must be `DEPTH_STENCIL` and `drawbuffer` must be zero. `depth` and `stencil` are the values to clear the depth and stencil buffers to, respectively. Clamping and type conversion of `depth` for fixed-point depth buffers is performed in the same fashion as `ClearDepth`. Masking of `stencil` for stencil buffers is performed in the same fashion as `ClearStencil`. `ClearBufferfi` is equivalent to clearing the depth and stencil buffers separately, but may be faster when a buffer of internal format `DEPTH_STENCIL` is being cleared.

The result of `ClearBuffer` is undefined if no conversion between the type of the specified `value` and the type of the buffer being cleared is defined (for example, if `ClearBufferiv` is called for a fixed- or floating-point buffer, or if `ClearBufferfv` is called for a signed or unsigned integer buffer). This is not an error.

When `ClearBuffer` is called, the same per-fragment and masking operations defined for `Clear` are applied.

Errors
ClearBuffer{if ui}y generates an INVALID_ENUM error if buffer is not COLOR, DEPTH, or STENCIL. ClearBuffer{if} generates an INVALID_ENUM error if buffer is not DEPTH_STENCIL.

ClearBuffer generates an INVALID_VALUE error if buffer is COLOR and drawbuffer is less than zero, or greater than the value of MAX_DRAW_BUFFERS minus one; or if buffer is DEPTH, STENCIL, or DEPTH_STENCIL and drawbuffer is not zero.

Clearing the Multisample Buffer

The color samples of the multisample buffer are cleared when one or more color buffers are cleared, as specified by the Clear mask bit COLOR_BUFFER_BIT and the DrawBuffer mode. If the DrawBuffer mode is NONE, the color samples of the multisample buffer cannot be cleared using Clear.

If the Clear mask bits DEPTH_BUFFER_BIT or STENCIL_BUFFER_BIT are set, then the corresponding depth or stencil samples, respectively, are cleared.

The ClearBuffer commands also clear color, depth, or stencil samples of multisample buffers corresponding to the specified buffer.

4.3 Reading and Copying Pixels

Pixels may be read from the framebuffer using ReadPixels. BlitFramebuffer can be used to copy a block of pixels from one portion of the framebuffer to another.

4.3.1 Reading Pixels

The method for reading pixels from the framebuffer and placing them in pixel pack buffer or client memory is diagrammed in figure 4.2. We describe the stages of the pixel reading process in the order in which they occur.

Initially, zero is bound for the PIXEL_PACK_BUFFER, indicating that image read and query commands such as ReadPixels return pixel results into client memory pointer parameters. However, if a non-zero buffer object is bound as the current pixel pack buffer, then the pointer parameter is treated as an offset into the designated buffer object.

Pixels are read using

```c
void ReadPixels( int x, int y, sizei width, sizei height,
    enum format, enum type, void *data );
```

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4.3. READING AND COPYING PIXELS

The arguments after \(x\) and \(y\) to \texttt{ReadPixels} are described in section 3.7.2. The pixel storage modes that apply to \texttt{ReadPixels} and other commands that query images (see section 6.1) are summarized in table 4.7.

\texttt{ReadPixels} generates an \texttt{INVALID_OPERATION} error if \texttt{READ_FRAMEBUFFER_BINDING} (see section 4.4) is non-zero, the read framebuffer is framebuffer complete, and the value of \texttt{SAMPLE_BUFFERS} for the read framebuffer is greater than zero.

Obtaining Pixels from the Framebuffer

If the \texttt{format} is \texttt{DEPTH_COMPONENT}, then values are obtained from the depth buffer. If there is no depth buffer, the error \texttt{INVALID_OPERATION} occurs.

If there is a multisample buffer (the value of \texttt{SAMPLE_BUFFERS} is one), then values are obtained from the depth samples in this buffer. It is recommended that the depth value of the centermost sample be used, though implementations may choose any function of the depth sample values at each pixel.

If the \texttt{format} is \texttt{DEPTH_STENCIL}, then values are taken from both the depth buffer and the stencil buffer. If there is no depth buffer or if there is no stencil buffer, then the error \texttt{INVALID_OPERATION} occurs. If the \texttt{type} parameter is not
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<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Type</th>
<th>Initial Value</th>
<th>Valid Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACK_SWAP_BYTES</td>
<td>boolean</td>
<td>FALSE</td>
<td>TRUE/FALSE</td>
</tr>
<tr>
<td>PACK_LSB_FIRST</td>
<td>boolean</td>
<td>FALSE</td>
<td>TRUE/FALSE</td>
</tr>
<tr>
<td>PACK_ROW_LENGTH</td>
<td>integer</td>
<td>0</td>
<td>(0, ∞)</td>
</tr>
<tr>
<td>PACK_SKIP_ROWS</td>
<td>integer</td>
<td>0</td>
<td>(0, ∞)</td>
</tr>
<tr>
<td>PACK_SKIP_PIXELS</td>
<td>integer</td>
<td>0</td>
<td>(0, ∞)</td>
</tr>
<tr>
<td>PACK_ALIGNMENT</td>
<td>integer</td>
<td>4</td>
<td>1,2,4,8</td>
</tr>
<tr>
<td>PACK_IMAGE_HEIGHT</td>
<td>integer</td>
<td>0</td>
<td>(0, ∞)</td>
</tr>
<tr>
<td>PACK_SKIP_IMAGES</td>
<td>integer</td>
<td>0</td>
<td>(0, ∞)</td>
</tr>
</tbody>
</table>

Table 4.7: PixelStore parameters pertaining to ReadPixels, and GetTexImage.

UNSIGNED_INT_24_8 or FLOAT_32_UNSIGNED_INT_24_8_REV, then the error INVALID_ENUM occurs.

If there is a multisample buffer, then values are obtained from the depth and stencil samples in this buffer. It is recommended that the depth and stencil values of the centermost sample be used, though implementations may choose any function of the depth and stencil sample values at each pixel.

If the format is STENCIL_INDEX, then values are taken from the stencil buffer; again, if there is no stencil buffer, the error INVALID_OPERATION occurs.

If there is a multisample buffer, then values are obtained from the stencil samples in this buffer. It is recommended that the stencil value of the centermost sample be used, though implementations may choose any function of the stencil sample values at each pixel.

For all other formats, the read buffer from which values are obtained is one of the color buffers; the selection of color buffer is controlled with ReadBuffer.

The command

```c
void ReadBuffer( enum src );
```

takes a symbolic constant as argument. src must be one of the values from tables 4.4 or 4.5. Otherwise, an INVALID_ENUM error is generated. Further, the acceptable values for src depend on whether the GL is using the default framebuffer (i.e., READ_FRAMEBUFFER_BINDING is zero), or a framebuffer object (i.e., READ_FRAMEBUFFER_BINDING is non-zero). For more information about framebuffer objects, see section 4.4.

If the object bound to READ_FRAMEBUFFER_BINDING is not framebuffer complete (as defined in section 4.4.4), then ReadPixels generates the error INVALID_FRAMEBUFFER_OPERATION. If ReadBuffer is supplied with a constant that is nei-
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ther legal for the default framebuffer, nor legal for a framebuffer object, then the error INVALID_ENUM results.

When READ_FRAMEBUFFER_BINDING is zero, i.e. the default framebuffer, src must be one of the values listed in table 4.4, including NONE, FRONT_AND_BACK, FRONT, and LEFT refer to the front left buffer, BACK refers to the back left buffer, and RIGHT refers to the front right buffer. The other constants correspond directly to the buffers that they name. If the requested buffer is missing, then the error INVALID_OPERATION is generated. For the default framebuffer, the initial setting for ReadBuffer is FRONT if there is no back buffer and BACK otherwise.

When the GL is using a framebuffer object, src must be one of the values listed in table 4.5, including NONE. In a manner analogous to how the DRAW_BUFFERS state is handled, specifying COLOR_ATTACHMENT enables reading from the image attached to the framebuffer at COLOR_ATTACHMENTi. For framebuffer objects, the initial setting for ReadBuffer is COLOR_ATTACHMENT0.

ReadPixels generates an INVALID_OPERATION error if it attempts to select a color buffer while READ_BUFFER is NONE.

ReadPixels obtains values from the selected buffer from each pixel with lower left hand corner at (x + i, y + j) for 0 ≤ i < width and 0 ≤ j < height; this pixel is said to be the ith pixel in the jth row. If any of these pixels lies outside of the window allocated to the current GL context, or outside of the image attached to the currently bound framebuffer object, then the values obtained for those pixels are undefined. When READ_FRAMEBUFFER_BINDING is zero, values are also undefined for individual pixels that are not owned by the current context. Otherwise, ReadPixels obtains values from the selected buffer, regardless of how those values were placed there.

If format is one of RED, GREEN, BLUE, ALPHA, RG, RGB, RGBA, BGR, or BGRA, then red, green, blue, and alpha values are obtained from the selected buffer at each pixel location. If the framebuffer does not support alpha values then the A that is obtained is 1.0.

If format is an integer format and the color buffer is not an integer format; if the color buffer is an integer format and format is not an integer format; or if format is an integer format and type is FLOAT or HALF_FLOAT, the error INVALID_OPERATION occurs.

When READ_FRAMEBUFFER_BINDING is non-zero, the red, green, blue, and alpha values are obtained by first reading the internal component values of the corresponding value in the image attached to the selected logical buffer. Internal components are converted to an RGBA color by taking each R, G, B, and A component present according to the base internal format of the buffer (as shown in table 3.11). If G, B, or A values are not present in the internal format, they are taken to be zero, zero, and one respectively.
Conversion of RGBA values

This step applies only if format is not STENCIL_INDEX, DEPTH_COMPONENT, or DEPTH_STENCIL. The R, G, B, and A values form a group of elements.

For a signed or unsigned normalized fixed-point color buffer, each element is converted to floating-point using equations 2.3 or 2.1, respectively. For an integer or floating-point color buffer, the elements are unmodified.

Conversion of Depth values

This step applies only if format is DEPTH_COMPONENT or DEPTH_STENCIL and the depth buffer uses a fixed-point representation. An element is taken to be a fixed-point value in \([0, 1]\) with \(m\) bits, where \(m\) is the number of bits in the depth buffer (see section 2.14.1). No conversion is necessary if the depth buffer uses a floating-point representation.

Final Conversion

For an index, if the type is not FLOAT or HALF_FLOAT, final conversion consists of masking the index with the value given in table 4.8; if the type is FLOAT or HALF_FLOAT, then the integer index is converted to a GL float or half data value.

Read color clamping is controlled by calling

```c
void ClampColor( enum target, enum clamp );
```

with target set to CLAMP_READ_COLOR. If clamp is TRUE, read color clamping is enabled; if clamp is FALSE, read color clamping is disabled. If clamp is FIXED_ONLY, read color clamping is enabled if the selected read color buffer has fixed-point components.

For a floating-point RGBA color, if type is not one of FLOAT, HALF_FLOAT, UNSIGNED_INT_5_9_9_9_REV, or UNSIGNED_INT_10F_11F_11F_REV; or if read color clamping is enabled, each component is first clamped to \([0, 1]\). Then the appropriate conversion formula from table 4.9 is applied to the component.

In the special case of calling ReadPixels with type of UNSIGNED_INT_10F_11F_11F_REV and format of RGB, conversion is performed as follows: the returned data are packed into a series of uint values. The red, green, and blue components are converted to unsigned 11-bit floating-point, unsigned 11-bit floating-point, and unsigned 10-bit floating point as described in sections 2.1.3 and 2.1.4. The resulting red 11 bits, green 11 bits, and blue 10 bits are then packed as the 1st, 2nd, and

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<table>
<thead>
<tr>
<th>type Parameter</th>
<th>Index Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSIGNED_BYTE</td>
<td>$2^8 - 1$</td>
</tr>
<tr>
<td>BYTE</td>
<td>$2^7 - 1$</td>
</tr>
<tr>
<td>UNSIGNED_SHORT</td>
<td>$2^{16} - 1$</td>
</tr>
<tr>
<td>SHORT</td>
<td>$2^{15} - 1$</td>
</tr>
<tr>
<td>UNSIGNED_INT</td>
<td>$2^{32} - 1$</td>
</tr>
<tr>
<td>INT</td>
<td>$2^{31} - 1$</td>
</tr>
<tr>
<td>UNSIGNED_INT_24_8</td>
<td>$2^8 - 1$</td>
</tr>
<tr>
<td>FLOAT_32_UNSIGNED_INT_24_8</td>
<td>$2^8 - 1$</td>
</tr>
</tbody>
</table>

Table 4.8: Index masks used by ReadPixels. Floating point data are not masked.

3rd components of the UNSIGNED_INT_10F_11F_11F_REV format as shown in table 3.8.

In the special case of calling ReadPixels with type of UNSIGNED_INT_5_9_9_9_REV and format RGB, the conversion is performed as follows: the returned data are packed into a series of uint values. The red, green, and blue components are converted to reds, greens, blues, and expshared integers as described in section 3.8.3 when internalformat is RGB9_E5. The reds, greens, blues, and expshared are then packed as the 1st, 2nd, 3rd, and 4th components of the UNSIGNED_INT_5_9_9_9_REV format as shown in table 3.8.

For an integer RGBA color, each component is clamped to the representable range of type.

Placement in Pixel Pack Buffer or Client Memory

If a pixel pack buffer is bound (as indicated by a non-zero value of PIXEL_PACK_BUFFER_BINDING), data is an offset into the pixel pack buffer and the pixels are packed into the buffer relative to this offset; otherwise, data is a pointer to a block client memory and the pixels are packed into the client memory relative to the pointer. If a pixel pack buffer object is bound and packing the pixel data according to the pixel pack storage state would access memory beyond the size of the pixel pack buffer’s memory size, an INVALID_OPERATION error results. If a pixel pack buffer object is bound and data is not evenly divisible by the number of basic machine units needed to store in memory the corresponding GL data type from table 3.2 for the type parameter, an INVALID_OPERATION error results.

Groups of elements are placed in memory just as they are taken from memory when transferring pixel rectangles to the GL. That is, the $i$th group of the $j$th
### 4.3. READING AND COPYING PIXELS

Table 4.9: Reversed component conversions, used when component data are being returned to client memory. Color, normal, and depth components are converted from the internal floating-point representation \((f)\) to a datum of the specified GL data type \((c)\) using the specified equation. All arithmetic is done in the internal floating point format. These conversions apply to component data returned by GL query commands and to components of pixel data returned to client memory. The equations remain the same even if the implemented ranges of the GL data types are greater than the minimum required ranges. (See table 2.2.) Equations with \(N\) as the exponent are performed for each bitfield of the packed data type, with \(N\) set to the number of bits in the bitfield.

<table>
<thead>
<tr>
<th>type Parameter</th>
<th>GL Data Type</th>
<th>Component Conversion Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSIGNED_BYTE</td>
<td>ubyte</td>
<td>(c = (2^8 - 1)f)</td>
</tr>
<tr>
<td>BYTE</td>
<td>byte</td>
<td>(c = (2^7 - 1)f - 1)</td>
</tr>
<tr>
<td>UNSIGNED_SHORT</td>
<td>ushort</td>
<td>(c = (2^{16} - 1)f)</td>
</tr>
<tr>
<td>SHORT</td>
<td>short</td>
<td>(c = (2^{15} - 1)f - 1)</td>
</tr>
<tr>
<td>UNSIGNED_INT</td>
<td>uint</td>
<td>(c = (2^{32} - 1)f)</td>
</tr>
<tr>
<td>INT</td>
<td>int</td>
<td>(c = (2^{31} - 1)f - 1)</td>
</tr>
<tr>
<td>HALF_FLOAT</td>
<td>half</td>
<td>(c = f)</td>
</tr>
<tr>
<td>FLOAT</td>
<td>float</td>
<td>(c = f)</td>
</tr>
<tr>
<td>UNSIGNED_BYTE_3_3_2</td>
<td>ubyte</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_BYTE_2_3_3_REV</td>
<td>ubyte</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_6_5</td>
<td>ushort</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_5_6_5_REV</td>
<td>ushort</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_4_4_4</td>
<td>ushort</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_4_4_4_REV</td>
<td>ushort</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_SHORT_1_5_5_5_REV</td>
<td>ushort</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_INT_8_8_8_8</td>
<td>uint</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_INT_8_8_8_8_REV</td>
<td>uint</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_INT_10_10_10_2</td>
<td>uint</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_INT_2_10_10_10_REV</td>
<td>uint</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_INT_24_8</td>
<td>uint</td>
<td>(c = (2^N - 1)f)</td>
</tr>
<tr>
<td>UNSIGNED_INT_10F_11F_11F_REV</td>
<td>uint</td>
<td>Special</td>
</tr>
<tr>
<td>UNSIGNED_INT_5_9_9_9_REV</td>
<td>uint</td>
<td>Special</td>
</tr>
<tr>
<td>FLOAT_32_UNSIGNED_INT_24_8_REV</td>
<td>float</td>
<td>(c = f) (depth only)</td>
</tr>
</tbody>
</table>

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row (corresponding to the $i$th pixel in the $j$th row) is placed in memory just where the $i$th group of the $j$th row would be taken from when transferring pixels. See Unpacking under section 3.7.2. The only difference is that the storage mode parameters whose names begin with PACK_ are used instead of those whose names begin with UNPACK_. If the format is RED, GREEN, BLUE, or ALPHA, only the corresponding single element is written. Likewise if the format is RG, RGB, or BGR, only the corresponding two or three elements are written. Otherwise all the elements of each group are written.

4.3.2 Copying Pixels

The command

```c
void BlitFramebuffer( int srcX0, int srcY0, int srcX1,
int srcY1, int dstX0, int dstY0, int dstX1, int dstY1,
bitfield mask, enum filter );
```

transfers a rectangle of pixel values from one region of the read framebuffer to another in the draw framebuffer.

`mask` is the bitwise OR of a number of values indicating which buffers are to be copied. The values are COLOR_BUFFER_BIT, DEPTH_BUFFER_BIT, and STENCIL_BUFFER_BIT, which are described in section 4.2.3. The pixels corresponding to these buffers are copied from the source rectangle bounded by the locations $(srcX0, srcY0)$ and $(srcX1, srcY1)$ to the destination rectangle bounded by the locations $(dstX0, dstY0)$ and $(dstX1, dstY1)$. The lower bounds of the rectangle are inclusive, while the upper bounds are exclusive.

When the color buffer is transferred, values are taken from the read buffer of the read framebuffer and written to each of the draw buffers of the draw framebuffer.

The actual region taken from the read framebuffer is limited to the intersection of the source buffers being transferred, which may include the color buffer selected by the read buffer, the depth buffer, and/or the stencil buffer depending on `mask`. The actual region written to the draw framebuffer is limited to the intersection of the destination buffers being written, which may include multiple draw buffers, the depth buffer, and/or the stencil buffer depending on `mask`. Whether or not the source or destination regions are altered due to these limits, the scaling and offset applied to pixels being transferred is performed as though no such limits were present.

If the source and destination rectangle dimensions do not match, the source image is stretched to fit the destination rectangle. `filter` must be LINEAR or NEAREST, and specifies the method of interpolation to be applied if the image is stretched.
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LINEAR filtering is allowed only for the color buffer; if \textit{mask} includes \texttt{DEPTH_-BUFFER_BIT} or \texttt{STENCIL_BUFFER_BIT}, and filter is not \texttt{NEAREST}, no copy is performed and an \texttt{INVALID_OPERATION} error is generated. If the source and destination dimensions are identical, no filtering is applied. If either the source or destination rectangle specifies a negative width or height ($X1 < X0$ or $Y1 < Y0$), the image is reversed in the corresponding direction. If both the source and destination rectangles specify a negative width or height for the same direction, no reversal is performed. If a linear filter is selected and the rules of \texttt{LINEAR} sampling would require sampling outside the bounds of a source buffer, it is as though \texttt{CLAMP_TO_EDGE} texture sampling were being performed. If a linear filter is selected and sampling would be required outside the bounds of the specified source region, but within the bounds of a source buffer, the implementation may choose to clamp while sampling or not.

If the source and destination buffers are identical, and the source and destination rectangles overlap, the result of the blit operation is undefined.

Blit operations bypass the fragment pipeline. The only fragment operations which affect a blit are the pixel ownership test and the scissor test.

If the read framebuffer is layered (see section 4.4.7), pixel values are read from layer zero. If the draw framebuffer is layered, pixel values are written to layer zero. If both read and draw framebuffers are layered, the blit operation is still performed only on layer zero.

If a buffer is specified in \textit{mask} and does not exist in both the read and draw framebuffers, the corresponding bit is silently ignored.

If the color formats of the read and draw buffers do not match, and \textit{mask} includes \texttt{COLOR_BUFFER_BIT}, pixel groups are converted to match the destination format. However, colors are clamped only if all draw color buffers have fixed-point components. Format conversion is not supported for all data types, and an \texttt{INVALID_OPERATION} error is generated under any of the following conditions:

- The read buffer contains fixed-point or floating-point values and any draw buffer contains neither fixed-point nor floating-point values.
- The read buffer contains unsigned integer values and any draw buffer does not contain unsigned integer values.
- The read buffer contains signed integer values and any draw buffer does not contain signed integer values.

Calling \texttt{BlitFramebuffer} will result in an \texttt{INVALID_FRAMEBUFFER_OPERATION} error if the objects bound to \texttt{DRAW_FRAMEBUFFER_BINDING} and \texttt{READ_FRAMEBUFFER_BINDING} are not framebuffer complete (section 4.4.4).
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Calling **BlitFramebuffer** will result in an `INVALID_OPERATION` error if `mask` includes `DEPTH_BUFFER_BIT` or `STENCIL_BUFFER_BIT`, and the source and destination depth and stencil buffer formats do not match.

Calling **BlitFramebuffer** will result in an `INVALID_OPERATION` error if `filter` is `LINEAR` and read buffer contains integer data.

If `SAMPLE_BUFFERS` for the read framebuffer is greater than zero and `SAMPLE_BUFFERS` for the draw framebuffer is zero, the samples corresponding to each pixel location in the source are converted to a single sample before being written to the destination.

If `SAMPLE_BUFFERS` for the read framebuffer is zero and `SAMPLE_BUFFERS` for the draw framebuffer is greater than zero, the value of the source sample is replicated in each of the destination samples.

If `SAMPLE_BUFFERS` for either the read framebuffer or draw framebuffer is greater than zero, no copy is performed and an `INVALID_OPERATION` error is generated if the dimensions of the source and destination rectangles provided to **BlitFramebuffer** are not identical, if the formats of the read and draw framebuffers are not identical, or if the values of `SAMPLES` for the read and draw buffers are not identical.

If `SAMPLE_BUFFERS` for both the read and draw framebuffers are greater than zero, and the values of `SAMPLES` for the read and draw framebuffers are identical, the samples are copied without modification from the read framebuffer to the draw framebuffer. Otherwise, no copy is performed and an `INVALID_OPERATION` error is generated. Note that the samples in the draw buffer are not guaranteed to be at the same sample location as the read buffer, so rendering using this newly created buffer can potentially have geometry cracks or incorrect antialiasing. This may occur if the sizes of the framebuffers do not match, if the formats differ, or if the source and destination rectangles are not defined with the same `((X0, Y0), (X1, Y1))` bounds.

### 4.3.3 Pixel Draw/Read State

The state required for pixel operations consists of the parameters that are set with **PixelStore**. This state has been summarized in tables 3.1. Additional state includes an integer indicating the current setting of **ReadBuffer**, and a three-valued integer controlling clamping during final conversion. For the default framebuffer, in the initial state the read buffer is `BACK` if there is a back buffer; `FRONT` if there is no back buffer; and `NONE` if no default framebuffer is associated with the context. The initial value of read color clamping is `FIXED_ONLY`. State set with **PixelStore** is GL client state.
4.4 Framebuffer Objects

As described in chapter 1 and section 2.1, the GL renders into (and reads values from) a framebuffer. GL defines two classes of framebuffers: window system-provided and application-created.

Initially, the GL uses the default framebuffer. The storage, dimensions, allocation, and format of the images attached to this framebuffer are managed entirely by the window system. Consequently, the state of the default framebuffer, including its images, can not be changed by the GL, nor can the default framebuffer be deleted by the GL.

The routines described in the following sections, however, can be used to create, destroy, and modify the state and attachments of framebuffer objects.

Framebuffer objects encapsulate the state of a framebuffer in a similar manner to the way texture objects encapsulate the state of a texture. In particular, a framebuffer object encapsulates state necessary to describe a collection of color, depth, and stencil logical buffers (other types of buffers are not allowed). For each logical buffer, a framebuffer-attachable image can be attached to the framebuffer to store the rendered output for that logical buffer. Examples of framebuffer-attachable images include texture images and renderbuffer images. Renderbuffers are described further in section 4.4.2.

By allowing the images of a renderbuffer to be attached to a framebuffer, the GL provides a mechanism to support off-screen rendering. Further, by allowing the images of a texture to be attached to a framebuffer, the GL provides a mechanism to support render to texture.

4.4.1 Binding and Managing Framebuffer Objects

The default framebuffer for rendering and readback operations is provided by the window system. In addition, named framebuffer objects can be created and operated upon. The namespace for framebuffer objects is the unsigned integers, with zero reserved by the GL for the default framebuffer.

A framebuffer object is created by binding a name returned by GenFramebuffers (see below) to DRAW_FRAMEBUFFER or READ_FRAMEBUFFER. The binding is effected by calling

```c
void BindFramebuffer(enum target, uint framebuffer);
```

with `target` set to the desired framebuffer target and `framebuffer` set to the framebuffer object name. The resulting framebuffer object is a new state vector, comprising all the state values listed in table 6.24, as well as one set of the state values
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listed in table 6.25 for each attachment point of the framebuffer, set to the same initial values. There are MAX_COLOR_ATTACHMENTS color attachment points, plus one each for the depth and stencil attachment points.

BindFramebuffer may also be used to bind an existing framebuffer object to DRAW_FRAMEBUFFER and/or READ_FRAMEBUFFER. If the bind is successful no change is made to the state of the bound framebuffer object, and any previous binding to target is broken.

BindFramebuffer fails and an INVALID_OPERATION error is generated if framebuffer is not zero or a name returned from a previous call to GenFramebuffers, or if such a name has since been deleted with DeleteFramebuffers.

If a framebuffer object is bound to DRAW_FRAMEBUFFER or READ_FRAMEBUFFER, it becomes the target for rendering or readback operations, respectively, until it is deleted or another framebuffer is bound to the corresponding bind point. Calling BindFramebuffer with target set to FRAMEBUFFER binds framebuffer to both the draw and read targets.

While a framebuffer object is bound, GL operations on the target to which it is bound affect the images attached to the bound framebuffer object, and queries of the target to which it is bound return state from the bound object. Queries of the values specified in tables 6.53 and 6.27 are derived from the framebuffer object bound to DRAW_FRAMEBUFFER.

The initial state of DRAW_FRAMEBUFFER and READ_FRAMEBUFFER refers to the default framebuffer. In order that access to the default framebuffer is not lost, it is treated as a framebuffer object with the name of zero. The default framebuffer is therefore rendered to and read from while zero is bound to the corresponding targets. On some implementations, the properties of the default framebuffer can change over time (e.g., in response to window system events such as attaching the context to a new window system drawable.)

Framebuffer objects (those with a non-zero name) differ from the default framebuffer in a few important ways. First and foremost, unlike the default framebuffer, framebuffer objects have modifiable attachment points for each logical buffer in the framebuffer. Framebuffer-attachable images can be attached to and detached from these attachment points, which are described further in section 4.4.2. Also, the size and format of the images attached to framebuffer objects are controlled entirely within the GL interface, and are not affected by window system events, such as pixel format selection, window resizes, and display mode changes.

Additionally, when rendering to or reading from an application created-framebuffer object,

- The pixel ownership test always succeeds. In other words, framebuffer objects own all of their pixels.
There are no visible color buffer bitplanes. This means there is no color buffer corresponding to the back, front, left, or right color bitplanes.

The only color buffer bitplanes are the ones defined by the framebuffer attachment points named \texttt{COLOR\_ATTACHMENT0} through \texttt{COLOR\_ATTACHMENTn}.

The only depth buffer bitplanes are the ones defined by the framebuffer attachment point \texttt{DEPTH\_ATTACHMENT}.

The only stencil buffer bitplanes are the ones defined by the framebuffer attachment point \texttt{STENCIL\_ATTACHMENT}.

If the attachment sizes are not all identical, rendering will be limited to the largest area that can fit in all of the attachments (an intersection of rectangles having a lower left of \((0, 0)\) and an upper right of \((width, height)\) for each attachment).

If the number of layers of each attachment are not all identical, rendering will be limited to the smallest number of layers of any attachment.

If the attachment sizes are not all identical, the values of pixels outside the common intersection area after rendering are undefined.

Framebuffer objects are deleted by calling

\begin{verbatim}
void DeleteFramebuffers( sizei n, const uint *framebuffers );
\end{verbatim}

\texttt{framebuffers} contains \(n\) names of framebuffer objects to be deleted. After a framebuffer object is deleted, it has no attachments, and its name is again unused. If a framebuffer that is currently bound to one or more of the targets \texttt{DRAW\_-FRAMEBUFFER} or \texttt{READ\_FRAMEBUFFER} is deleted, it is as though \texttt{BindFramebuffer} had been executed with the corresponding \texttt{target} and \texttt{framebuffer} zero. Unused names in \texttt{framebuffers} are silently ignored, as is the value zero.

The command

\begin{verbatim}
void GenFramebuffers( sizei n, uint *ids );
\end{verbatim}

returns \(n\) previously unused framebuffer object names in \texttt{ids}. These names are marked as used, for the purposes of \texttt{GenFramebuffers} only, but they acquire state and type only when they are first bound.
The names bound to the draw and read framebuffer bindings can be queried by calling `GetIntegerv` with the symbolic constants `DRAW_FRAMEBUFFER_BINDING` and `READ_FRAMEBUFFER_BINDING`, respectively. `FRAMEBUFFER_BINDING` is equivalent to `DRAW_FRAMEBUFFER_BINDING`.

### 4.4.2 Attaching Images to Framebuffer Objects

Framebuffer-attachable images may be attached to, and detached from, framebuffer objects. In contrast, the image attachments of the default framebuffer may not be changed by the GL.

A single framebuffer-attachable image may be attached to multiple framebuffer objects, potentially avoiding some data copies, and possibly decreasing memory consumption.

For each logical buffer, a framebuffer object stores a set of state which defines the logical buffer’s *attachment point*. The attachment point state contains enough information to identify the single image attached to the attachment point, or to indicate that no image is attached. The per-logical buffer attachment point state is listed in table 6.25.

There are several types of framebuffer-attachable images:

- The image of a renderbuffer object, which is always two-dimensional.
- A single level of a one-dimensional texture, which is treated as a two-dimensional image with a height of one.
- A single level of a two-dimensional or rectangle texture.
- A single face of a cube map texture level, which is treated as a two-dimensional image.
- A single layer of a one-or two-dimensional array texture or three-dimensional texture, which is treated as a two-dimensional image.
- A single layer-face of a cube map array texture, which is treated as a two-dimensional image.

Additionally, an entire level of a three-dimensional, cube map, cube map array, or one-or two-dimensional array texture can be attached to an attachment point. Such attachments are treated as an array of two-dimensional images, arranged in layers, and the corresponding attachment point is considered to be *layered* (also see section 4.4.7).
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**Renderbuffer Objects**

A renderbuffer is a data storage object containing a single image of a renderable internal format. GL provides the methods described below to allocate and delete a renderbuffer’s image, and to attach a renderbuffer’s image to a framebuffer object.

The namespace for renderbuffer objects is the unsigned integers, with zero reserved for the GL. A renderbuffer object is created by binding a name returned by `GenRenderbuffers` (see below) to `RENDERBUFFER`. The binding is effected by calling

```c
void BindRenderbuffer( enum target, uint renderbuffer );
```

with `target` set to `RENDERBUFFER` and `renderbuffer` set to the renderbuffer object name. If `renderbuffer` is not zero, then the resulting renderbuffer object is a new state vector, initialized with a zero-sized memory buffer, and comprising the state values listed in table 6.27. Any previous binding to `target` is broken.

`BindRenderbuffer` may also be used to bind an existing renderbuffer object. If the bind is successful, no change is made to the state of the newly bound renderbuffer object, and any previous binding to `target` is broken.

While a renderbuffer object is bound, GL operations on the target to which it is bound affect the bound renderbuffer object, and queries of the target to which a renderbuffer object is bound return state from the bound object.

The name zero is reserved. A renderbuffer object cannot be created with the name zero. If `renderbuffer` is zero, then any previous binding to `target` is broken and the `target` binding is restored to the initial state.

In the initial state, the reserved name zero is bound to `RENDERBUFFER`. There is no renderbuffer object corresponding to the name zero, so client attempts to modify or query renderbuffer state for the target `RENDERBUFFER` while zero is bound will generate GL errors, as described in section 6.1.3.

The current `RENDERBUFFER` binding can be determined by calling `GetIntegerv` with the symbolic constant `RENDERBUFFER_BINDING`.

`BindRenderbuffer` fails and an `INVALID_OPERATION` error is generated if `renderbuffer` is not zero or a name returned from a previous call to `GenRenderbuffers`, or if such a name has since been deleted with `DeleteRenderbuffers`.

Renderbuffer objects are deleted by calling

```c
void DeleteRenderbuffers( sizei n, const uint *renderbuffers );
```

where `renderbuffers` contains `n` names of renderbuffer objects to be deleted. After a renderbuffer object is deleted, it has no contents, and its name is again unused. If

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A renderbuffer that is currently bound to \texttt{RENDERBUFFER} is deleted, it is as though \texttt{BindRenderbuffer} had been executed with the \texttt{target} \texttt{RENDERBUFFER} and \texttt{name} of zero. Additionally, special care must be taken when deleting a renderbuffer if the image of the renderbuffer is attached to a framebuffer object (see section 4.4.2). Unused names in \texttt{renderbuffers} are silently ignored, as is the value zero.

The command

\begin{verbatim}
void GenRenderbuffers( sizei n, uint *renderbuffers );
\end{verbatim}

returns \texttt{n} previously unused renderbuffer object names in \texttt{renderbuffers}. These names are marked as used, for the purposes of \texttt{GenRenderbuffers} only, but they acquire renderbuffer state only when they are first bound.

The command

\begin{verbatim}
void RenderbufferStorageMultisample( enum target,
    sizei samples, enum internalformat, sizei width,
    sizei height );
\end{verbatim}

establishes the data storage, format, dimensions, and number of samples of a renderbuffer object’s image. \texttt{target} must be \texttt{RENDERBUFFER}. \texttt{internalformat} must be color-renderable, depth-renderable, or stencil-renderable (as defined in section 4.4.4). \texttt{width} and \texttt{height} are the dimensions in pixels of the renderbuffer. If either \texttt{width} or \texttt{height} is greater than the value of \texttt{MAX_RENDERBUFFER_SIZE}, or if \texttt{samples} is greater than the value of \texttt{MAX_SAMPLES}, then the error \texttt{INVALID_-VALUE} is generated. If \texttt{internalformat} is a signed or unsigned integer format and \texttt{samples} is greater than the value of \texttt{MAX_INTEGER_SAMPLES}, then the error \texttt{INVALID_OPERATION} is generated (see “Required Renderbuffer Formats” below). If the GL is unable to create a data store of the requested size, the error \texttt{OUT_OF_MEMORY} is generated.

Upon success, \texttt{RenderbufferStorageMultisample} deletes any existing data store for the renderbuffer image and the contents of the data store after calling \texttt{RenderbufferStorageMultisample} are undefined. \texttt{RENDERBUFFER_WIDTH} is set to \texttt{width}, \texttt{RENDERBUFFER_HEIGHT} is set to \texttt{height}, and \texttt{RENDERBUFFER_-INTERNAL_FORMAT} is set to \texttt{internalformat}.

If \texttt{samples} is zero, then \texttt{RENDERBUFFER_SAMPLES} is set to zero. Otherwise \texttt{samples} represents a request for a desired minimum number of samples. Since different implementations may support different sample counts for multisampled rendering, the actual number of samples allocated for the renderbuffer image is implementation-dependent. However, the resulting value for \texttt{RENDERBUFFER_-SAMPLES} is guaranteed to be greater than or equal to \texttt{samples} and no more than the next larger sample count supported by the implementation.

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Table 4.10: Correspondence of sized internal formats to base internal formats for formats that can be used only with renderbuffers.

<table>
<thead>
<tr>
<th>Sized Internal Format</th>
<th>Base Internal Format</th>
<th>S bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>STENCIL_INDEX1</td>
<td>STENCIL_INDEX</td>
<td>1</td>
</tr>
<tr>
<td>STENCIL_INDEX4</td>
<td>STENCIL_INDEX</td>
<td>4</td>
</tr>
<tr>
<td>STENCIL_INDEX8</td>
<td>STENCIL_INDEX</td>
<td>8</td>
</tr>
<tr>
<td>STENCIL_INDEX16</td>
<td>STENCIL_INDEX</td>
<td>16</td>
</tr>
</tbody>
</table>

A GL implementation may vary its allocation of internal component resolution based on any RenderbufferStorage parameter (except target), but the allocation and chosen internal format must not be a function of any other state and cannot be changed once they are established.

The command

```c
void RenderbufferStorage( enum target, enum internalformat, sizei width, sizei height );
```

is equivalent to calling RenderbufferStorageMultisample with samples equal to zero.

**Required Renderbuffer Formats**

Implementations are required to support the same internal formats for renderbuffers as the required formats for textures enumerated in section 3.8.3, with the exception of the color formats labelled “texture-only”. Requesting one of these internal formats for a renderbuffer will allocate at least the internal component sizes and exactly the component types shown for that format in tables 3.12-3.13.

Implementations must support creation of renderbuffers in these required formats with up to the value of MAX_SAMPLES multisamples, with the exception that the signed and unsigned integer formats are required only to support creation of renderbuffers with up to the value of MAX_INTEGER_SAMPLES multisamples, which must be at least one.

**Attaching Renderbuffer Images to a Framebuffer**

A renderbuffer can be attached as one of the logical buffers of the currently bound framebuffer object by calling

```c
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```
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```c
void FramebufferRenderbuffer( enum target,
   enum attachment, enum renderbuffertarget,
   uint renderbuffer );
```

`target` must be `DRAW_FRAMEBUFFER`, `READ_FRAMEBUFFER`, or `FRAMEBUFFER`. `FRAMEBUFFER` is equivalent to `DRAW_FRAMEBUFFER`. An `INVALID_OPERATION` error is generated if the value of the corresponding binding is zero. `attachment` should be set to one of the attachment points of the framebuffer listed in table 4.11.

`renderbuffertarget` must be `RENDERBUFFER` and `renderbuffer` should be set to the name of the renderbuffer object to be attached to the framebuffer. `renderbuffer` must be either zero or the name of an existing renderbuffer object of type `renderbuffertarget`, otherwise an `INVALID_OPERATION` error is generated. If `renderbuffer` is zero, then the value of `renderbuffertarget` is ignored.

If `renderbuffer` is not zero and if `FramebufferRenderbuffer` is successful, then the renderbuffer named `renderbuffer` will be used as the logical buffer identified by `attachment` of the framebuffer currently bound to `target`. The value of `FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE` for the specified attachment point is set to `RENDERBUFFER` and the value of `FRAMEBUFFER_ATTACHMENT_OBJECT_NAME` is set to `renderbuffer`. All other state values of the attachment point specified by `attachment` are set to their default values listed in table 6.25. No change is made to the state of the renderbuffer object and any previous attachment to the attachment logical buffer of the framebuffer object bound to framebuffer `target` is broken. If the attachment is not successful, then no change is made to the state of either the renderbuffer object or the framebuffer object.

Calling `FramebufferRenderbuffer` with the `renderbuffer` name zero will detach the image, if any, identified by `attachment`, in the framebuffer currently bound to `target`. All state values of the attachment point specified by `attachment` in the object bound to `target` are set to their default values listed in table 6.25.

Setting `attachment` to the value `DEPTH_STENCIL_ATTACHMENT` is a special case causing both the depth and stencil attachments of the framebuffer object to be set to `renderbuffer`, which should have base internal format `DEPTH_STENCIL`.

If a renderbuffer object is deleted while its image is attached to one or more attachment points in the currently bound framebuffer, then it is as if `FramebufferRenderbuffer` had been called, with a `renderbuffer` of 0, for each attachment point to which this image was attached in the currently bound framebuffer. In other words, this renderbuffer image is first detached from all attachment points in the currently bound framebuffer. Note that the renderbuffer image is specifically not detached from any non-bound framebuffers. Detaching the image from any non-bound framebuffers is the responsibility of the application.
4.4. FRAMEBUFFER OBJECTS

<table>
<thead>
<tr>
<th>Name of attachment</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLOR_ATTACHMENT\ ili (see caption)</td>
</tr>
<tr>
<td>DEPTH_ATTACHMENT</td>
</tr>
<tr>
<td>STENCIL_ATTACHMENT</td>
</tr>
<tr>
<td>DEPTH_STENCIL_ATTACHMENT</td>
</tr>
</tbody>
</table>

Table 4.11: Framebuffer attachment points. \( i \) in COLOR_ATTACHMENT\( i \) may range from zero to the value of MAX_COLOR_ATTACHMENTS - 1.

Attaching Texture Images to a Framebuffer

GL supports copying the rendered contents of the framebuffer into the images of a texture object through the use of the routines CopyTexImage* and CopyTexSubImage*. Additionally, GL supports rendering directly into the images of a texture object.

To render directly into a texture image, a specified level of a texture object can be attached as one of the logical buffers of the currently bound framebuffer object by calling:

```c
void FramebufferTexture( enum target, enum attachment, uint texture, int level);
```

`target` must be DRAW_FRAMEBUFFER, READ_FRAMEBUFFER, or FRAMEBUFFER. FRAMEBUFFER is equivalent to DRAW_FRAMEBUFFER. An INVALID_OPERATION error is generated if the value of the corresponding binding is zero. `attachment` must be one of the attachment points of the framebuffer listed in Table 4.11.

If `texture` is non-zero, the specified mipmap `level` of the texture object named `texture` is attached to the framebuffer attachment point named by `attachment`. An INVALID_VALUE error is generated if `texture` is not the name of a texture object, or if `level` is not a supported texture level number for textures of the type corresponding to `target`. An INVALID_OPERATION error is generated if `texture` is the name of a buffer texture.

If `texture` is the name of a three-dimensional texture, cube map texture, one- or two-dimensional array texture, or two-dimensional multisample array texture, the texture level attached to the framebuffer attachment point is an array of images, and the framebuffer attachment is considered layered.

Additionally, a specified image from a texture object can be attached as one of the logical buffers of the currently bound framebuffer object by calling one of the following routines, depending on the type of the texture:
voidFramebufferTexture1D(enum target, enum attachment, enum textarget, uint texture, int level);
voidFramebufferTexture2D(enum target, enum attachment, enum textarget, uint texture, int level);
voidFramebufferTexture3D(enum target, enum attachment, enum textarget, uint texture, int level, int layer);

In all three routines, target must be DRAW_FRAMEBUFFER, READ_FRAMEBUFFER, or FRAMEBUFFER. FRAMEBUFFER is equivalent to DRAW_FRAMEBUFFER. An INVALID_OPERATION error is generated if the value of the corresponding binding is zero. attachment must be one of the attachment points of the framebuffer listed in table 4.11.

If texture is not zero, then texture must either name an existing texture object with an target of textarget, or texture must name an existing cube map texture and textarget must be one of TEXTURE_CUBE_MAP_POSITIVE_X, TEXTURE_CUBE_MAP_POSITIVE_Y, TEXTURE_CUBE_MAP_POSITIVE_Z, TEXTURE_CUBE_MAP_NEGATIVE_X, TEXTURE_CUBE_MAP_NEGATIVE_Y, or TEXTURE_CUBE_MAP_NEGATIVE_Z. Otherwise, an INVALID_OPERATION error is generated.

level specifies the mipmap level of the texture image to be attached to the framebuffer.

If textarget is TEXTURE_RECTANGLE, TEXTURE_2D_MULTISAMPLE, or TEXTURE_2D_MULTISAMPLE_ARRAY, then level must be zero. If textarget is TEXTURE_3D, then level must be greater than or equal to zero and less than or equal to \( \log_2 \) of the value of MAX_3D_TEXTURE_SIZE. If textarget is one of TEXTURE_CUBE_MAP_POSITIVE_X, TEXTURE_CUBE_MAP_POSITIVE_Y, TEXTURE_CUBE_MAP_POSITIVE_Z, TEXTURE_CUBE_MAP_NEGATIVE_X, TEXTURE_CUBE_MAP_NEGATIVE_Y, or TEXTURE_CUBE_MAP_NEGATIVE_Z, then level must be greater than or equal to zero and less than or equal to \( \log_2 \) of the value of MAX_CUBE_MAP_TEXTURE_SIZE. For all other values of textarget, level must be greater than or equal to zero and no larger than \( \log_2 \) of the value of MAX_TEXTURE_SIZE. Otherwise, an INVALID_VALUE error is generated.

layer specifies the layer of a 2-dimensional image within a 3-dimensional texture. An INVALID_VALUE error is generated if layer is larger than the value of MAX_3D_TEXTURE_SIZE.

ForFramebufferTexture1D, if texture is not zero, then textarget must be TEXTURE_1D.

For framebufferTexture2D, if texture is not zero, then textarget must be one of TEXTURE_2D, TEXTURE_RECTANGLE, TEXTURE_CUBE_MAP_POSITIVE_X, TEXTURE_CUBE_MAP_POSITIVE_Y, TEXTURE_CUBE_MAP_POSITIVE_Z,
4.4. FRAMEBUFFER OBJECTS

TEXTURE_CUBE_MAP_NEGATIVE_X, TEXTURE_CUBE_MAP_NEGATIVE_Y, TEXTURE_CUBE_MAP_NEGATIVE_Z, or TEXTURE_2D_MULTISAMPLE.

For FramebufferTexture3D, if texture is not zero, then textarget must be TEXTURE_3D.

The command

```c
void FramebufferTextureLayer( enum target,
                           enum attachment, uint texture, int level, int layer);
```

operates identically to FramebufferTexture3D, except that it attaches a single layer of a three-dimensional, one-or two-dimensional array, cube map array, or two-dimensional multisample array texture. layer is an integer indicating the layer number, and is treated identically to the layer parameter in FramebufferTexture3D except for cube map array textures, where

\[
layer \mod 6
\]

indicates a face of a cube map slice within the cube map array. The order of the faces is as described for cube map array targets to TexImage3D in section 3.8.3. The error INVALID_VALUE is generated if texture is non-zero and layer is negative. The error INVALID_OPERATION is generated if texture is non-zero and is not the name of a three dimensional, two-dimensional multisample array, one-or two-dimensional array, or cube map array texture. Unlike FramebufferTexture3D, no textarget parameter is accepted.

If texture is non-zero and the command does not result in an error, the framebuffer attachment state corresponding to attachment is updated as in the other FramebufferTexture commands, except that the value of FRAMEBUFFER_-ATTACHMENT_TEXTURE_LAYER is set to layer.

**Effects of Attaching a Texture Image**

The remaining comments in this section apply to all forms of FramebufferTexture*.

If texture is zero, any image or array of images attached to the attachment point named by attachment is detached. Any additional parameters (level, textarget, and/or layer) are ignored when texture is zero. All state values of the attachment point specified by attachment are set to their default values listed in table 6.25.

If texture is not zero, and if FramebufferTexture* is successful, then the specified texture image will be used as the logical buffer identified by attachment of the framebuffer currently bound to target. State values of the specified attachment point are set as follows:
The value of `FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE` is set to `TEXTURE`.

The value of `FRAMEBUFFER_ATTACHMENT_OBJECT_NAME` is set to `texture`.

The value of `FRAMEBUFFER_ATTACHMENT_TEXTURE_LEVEL` is set to `level`.

If `FramebufferTexture2D` is called and `texture` is a cube map texture, then the value of `FRAMEBUFFER_ATTACHMENT_TEXTURE_CUBE_MAP_FACE` is set to `textarget`; otherwise it is set to `TEXTURE_CUBE_MAP_POSITIVE_X`.

If `FramebufferTextureLayer` or `FramebufferTexture3D` is called, then the value of `FRAMEBUFFER_ATTACHMENT_TEXTURE_LAYER` is set to `layer`; otherwise it is set to zero.

If `FramebufferTexture` is called and `texture` is the name of a three-dimensional, cube map, two-dimensional multisample array, or one-or two-dimensional array texture, the value of `FRAMEBUFFER_ATTACHMENT_LAYERED` is set to `TRUE`; otherwise it is set to `FALSE`.

All other state values of the attachment point specified by `attachment` are set to their default values listed in table 6.25. No change is made to the state of the texture object, and any previous attachment to the `attachment` logical buffer of the framebuffer object bound to framebuffer `target` is broken. If the attachment is not successful, then no change is made to the state of either the texture object or the framebuffer object.

Setting `attachment` to the value `DEPTH_STENCIL_ATTACHMENT` is a special case causing both the depth and stencil attachments of the framebuffer object to be set to `texture`. `texture` must have base internal format `DEPTH_STENCIL`, or the depth and stencil framebuffer attachments will be incomplete (see section 4.4.4).

If a texture object is deleted while its image is attached to one or more attachment points in the currently bound framebuffer, then it is as if `FramebufferTexture*` had been called, with a `texture` of zero, for each attachment point to which this image was attached in the currently bound framebuffer. In other words, this texture image is first detached from all attachment points in the currently bound framebuffer. Note that the texture image is specifically not detached from any other framebuffer objects. Detaching the texture image from any other framebuffer objects is the responsibility of the application.

### 4.4.3 Feedback Loops Between Textures and the Framebuffer

A feedback loop may exist when a texture object is used as both the source and destination of a GL operation. When a feedback loop exists, undefined behavior
results. This section describes rendering feedback loops (see section 3.8.11) and texture copying feedback loops (see section 3.8.4) in more detail.

Rendering Feedback Loops

The mechanisms for attaching textures to a framebuffer object do not prevent a one-or two-dimensional texture level, a face of a cube map texture level, or a layer of a two-dimensional array or three-dimensional texture from being attached to the draw framebuffer while the same texture is bound to a texture unit. While this conditions holds, texturing operations accessing that image will produce undefined results, as described at the end of section 3.8.11. Conditions resulting in such undefined behavior are defined in more detail below. Such undefined texturing operations are likely to leave the final results of fragment processing operations undefined, and should be avoided.

Special precautions need to be taken to avoid attaching a texture image to the currently bound framebuffer while the texture object is currently bound and enabled for texturing. Doing so could lead to the creation of a rendering feedback loop between the writing of pixels by GL rendering operations and the simultaneous reading of those same pixels when used as texels in the currently bound texture. In this scenario, the framebuffer will be considered framebuffer complete (see section 4.4.4), but the values of fragments rendered while in this state will be undefined. The values of texture samples may be undefined as well, as described under “Rendering Feedback Loops” in section 3.8.11.

Specifically, the values of rendered fragments are undefined if all of the following conditions are true:

- an image from texture object $T$ is attached to the currently bound draw framebuffer at attachment point $A$
- the texture object $T$ is currently bound to a texture unit $U$, and
- the current programmable vertex and/or fragment processing state makes it possible (see below) to sample from the texture object $T$ bound to texture unit $U$

while either of the following conditions are true:

- the value of $\text{TEXTURE\_MIN\_FILTER}$ for texture object $T$ is $\text{NEAREST}$ or $\text{LINEAR}$, and the value of $\text{FRAMEBUFFER\_ATTACHMENT\_TEXTURE\_LEVEL}$ for attachment point $A$ is equal to the value of $\text{TEXTURE\_BASE\_LEVEL}$ for the texture object $T$
• the value of `TEXTURE_MIN_FILTER` for texture object `T` is one of `NEAREST_MIPMAP_NEAREST`, `NEAREST_MIPMAP_LINEAR`, `LINEAR_MIPMAP_NEAREST`, or `LINEAR_MIPMAP_LINEAR`, and the value of `FRAMEBUFFER_ATTACHMENT_TEXTURE_LEVEL` for attachment point `A` is within the the range specified by the current values of `TEXTURE_BASE_LEVEL` to `q`, inclusive, for the texture object `T`. (`q` is defined in the Mipmapping discussion of section 3.8.11).

For the purpose of this discussion, it is possible to sample from the texture object `T` bound to texture unit `U` if the active fragment or vertex shader contains any instructions that might sample from the texture object `T` bound to `U`, even if those instructions might only be executed conditionally.

Note that if `TEXTURE_BASE_LEVEL` and `TEXTURE_MAX_LEVEL` exclude any levels containing image(s) attached to the currently bound framebuffer, then the above conditions will not be met (i.e., the above rule will not cause the values of rendered fragments to be undefined.)

**Texture Copying Feedback Loops**

Similarly to rendering feedback loops, it is possible for a texture image to be attached to the read framebuffer while the same texture image is the destination of a `CopyTexImage*` operation, as described under “Texture Copying Feedback Loops” in section 3.8.4. While this condition holds, a texture copying feedback loop between the writing of texels by the copying operation and the reading of those same texels when used as pixels in the read framebuffer may exist. In this scenario, the values of texels written by the copying operation will be undefined (in the same fashion that overlapping copies via `BlitFramebuffer` are undefined).

Specifically, the values of copied texels are undefined if all of the following conditions are true:

• an image from texture object `T` is attached to the currently bound read framebuffer at attachment point `A`

• the selected read buffer is attachment point `A`

• `T` is bound to the texture target of a `CopyTexImage*` operation

• the `level` argument of the copying operation selects the same image that is attached to `A`
4.4.4 Framebuffer Completeness

A framebuffer must be framebuffer complete to effectively be used as the draw or read framebuffer of the GL.

The default framebuffer is always complete if it exists; however, if no default framebuffer exists (no window system-provided drawable is associated with the GL context), it is deemed to be incomplete.

A framebuffer object is said to be framebuffer complete if all of its attached images, and all framebuffer parameters required to utilize the framebuffer for rendering and reading, are consistently defined and meet the requirements defined below. The rules of framebuffer completeness are dependent on the properties of the attached images, and on certain implementation-dependent restrictions.

The internal formats of the attached images can affect the completeness of the framebuffer, so it is useful to first define the relationship between the internal format of an image and the attachment points to which it can be attached.

- The following base internal formats from table 3.11 are color-renderable: RED, RG, RGB, and RGBA. The sized internal formats from table 3.12 that have a color-renderable base internal format are also color-renderable. No other formats, including compressed internal formats, are color-renderable.

- An internal format is depth-renderable if it is DEPTH_COMPONENT or one of the formats from table 3.13 whose base internal format is DEPTH_COMPONENT or DEPTH_STENCIL. No other formats are depth-renderable.

- An internal format is stencil-renderable if it is STENCIL_INDEX or DEPTH_STENCIL, if it is one of the STENCIL_INDEX formats from table 4.10, or if it is one of the formats from table 3.13 whose base internal format is DEPTH_STENCIL. No other formats are stencil-renderable.

Framebuffer Attachment Completeness

If the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE for the framebuffer attachment point attachment is not NONE, then it is said that a framebuffer-attachable image, named image, is attached to the framebuffer at the attachment point. image is identified by the state in attachment as described in section 4.4.2.

The framebuffer attachment point attachment is said to be framebuffer attachment complete if the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE for attachment is NONE (i.e., no image is attached), or if all of the following conditions are true:
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- *image* is a component of an existing object with the name specified by the value of FRAMEBUFFER_ATTACHMENT_OBJECT_NAME, and of the type specified by the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE.

- The width and height of *image* are non-zero.

- If the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE is TEXTURE and the value of FRAMEBUFFER_ATTACHMENT_OBJECT_NAME names a three-dimensional texture, then the value of FRAMEBUFFER_ATTACHMENT_TEXTURE_LAYER must be smaller than the depth of the texture.

- If the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE is TEXTURE and the value of FRAMEBUFFER_ATTACHMENT_OBJECT_NAME names a one-or two-dimensional array or cube map array texture, then the value of FRAMEBUFFER_ATTACHMENT_TEXTURE_LAYER must be smaller than the number of layers in the texture.

- If *attachment* is COLOR_ATTACHMENT, then *image* must have a color-renderable internal format.

- If *attachment* is DEPTH_ATTACHMENT, then *image* must have a depth-renderable internal format.

- If *attachment* is STENCIL_ATTACHMENT, then *image* must have a stencil-renderable internal format.

**Whole Framebuffer Completeness**

Each rule below is followed by an error token enclosed in { brackets }. The meaning of these errors is explained below and under “Effects of Framebuffer Completeness on Framebuffer Operations” later in section 4.4.4.

The framebuffer object *target* is said to be *framebuffer complete* if all the following conditions are true:

- *target* is the default framebuffer, and the default framebuffer exists.

  { FRAMEBUFFER_UNDEFINED }

- All framebuffer attachment points are *framebuffer attachment complete*.

  { FRAMEBUFFER_INCOMPLETE_ATTACHMENT }

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- There is at least one image attached to the framebuffer.
  \{ FRAMEBUFFER_INCOMPLETE_MISSING_ATTACHMENT \}

- The value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE must not be NONE for any color attachment point(s) named by DRAW_BUFFERi.
  \{ FRAMEBUFFER_INCOMPLETE_DRAW_BUFFER \}

- If READ_BUFFER is not NONE, then the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE must not be NONE for the color attachment point named by READ_BUFFER.
  \{ FRAMEBUFFER_INCOMPLETE_READ_BUFFER \}

- The combination of internal formats of the attached images does not violate an implementation-dependent set of restrictions.
  \{ FRAMEBUFFER_UNSUPPORTED \}

- The value of RENDERBUFFER_SAMPLES is the same for all attached renderbuffers; the value of TEXTURE_SAMPLES is the same for all attached textures; and, if the attached images are a mix of renderbuffers and textures, the value of RENDERBUFFER_SAMPLES matches the value of TEXTURE_SAMPLES.
  \{ FRAMEBUFFER_INCOMPLETE_MULTISAMPLE \}

- The value of TEXTURE_FIXED_SAMPLE_LOCATIONS is the same for all attached textures; and, if the attached images are a mix of renderbuffers and textures, the value of TEXTURE_FIXED_SAMPLE_LOCATIONS must be TRUE for all attached textures.
  \{ FRAMEBUFFER_INCOMPLETE_MULTISAMPLE \}

- If any framebuffer attachment is layered, all populated attachments must be layered. Additionally, all populated color attachments must be from textures of the same target (three-dimensional, one-or two-dimensional array, cube map, or cube map array textures).
  \{ FRAMEBUFFER_INCOMPLETE_LAYER_TARGETS \}
The token in brackets after each clause of the framebuffer completeness rules specifies the return value of CheckFramebufferStatus (see below) that is generated when that clause is violated. If more than one clause is violated, it is implementation-dependent which value will be returned by CheckFramebufferStatus.

Performing any of the following actions may change whether the framebuffer is considered complete or incomplete:

- Binding to a different framebuffer with BindFramebuffer.
- Attaching an image to the framebuffer with FramebufferTexture* or FramebufferRenderbuffer.
- Detaching an image from the framebuffer with FramebufferTexture* or FramebufferRenderbuffer.
- Changing the internal format of a texture image that is attached to the framebuffer by calling CopyTexImage* or CompressedTexImage*.
- Changing the internal format of a renderbuffer that is attached to the framebuffer by calling RenderbufferStorage.
- Deleting, with DeleteTextures or DeleteRenderbuffers, an object containing an image that is attached to a framebuffer object that is bound to the framebuffer.
- Changing the read buffer or one of the draw buffers.
- Associating a different window system-provided drawable, or no drawable, with the default framebuffer using a window system binding API such as those described in section 1.7.2.

Although the GL defines a wide variety of internal formats for framebuffer-attachable images, such as texture images and renderbuffer images, some implementations may not support rendering to particular combinations of internal formats. If the combination of formats of the images attached to a framebuffer object are not supported by the implementation, then the framebuffer is not complete under the clause labeled FRAMEBUFFER_UNSUPPORTED.

Implementations are required to support certain combinations of framebuffer internal formats as described under “Required Framebuffer Formats” in section 4.4.4.

Because of the implementation-dependent clause of the framebuffer completeness test in particular, and because framebuffer completeness can change when the...
set of attached images is modified, it is strongly advised, though not required, that an application check to see if the framebuffer is complete prior to rendering. The status of the framebuffer object currently bound to target can be queried by calling

```c
enum CheckFramebufferStatus( enum target );
```

target must be DRAW_FRAMEBUFFER, READ_FRAMEBUFFER, or FRAMEBUFFER. FRAMEBUFFER is equivalent to DRAW_FRAMEBUFFER. If CheckFramebufferStatus generates an error, zero is returned.

Otherwise, a value is returned that identifies whether or not the framebuffer bound to target is complete, and if not complete the value identifies one of the rules of framebuffer completeness that is violated. If the framebuffer is complete, then FRAMEBUFFER_COMPLETE is returned.

The values of SAMPLE_BUFFERS and SAMPLES are derived from the attachments of the currently bound framebuffer object. If the current DRAW_FRAMEBUFFER_BINDING is not framebuffer complete, then both SAMPLE_BUFFERS and SAMPLES are undefined. Otherwise, SAMPLES is equal to the value of RENDERBUFFER_SAMPLES for the attached images (which all must have the same value for RENDERBUFFER_SAMPLES). Further, SAMPLE_BUFFERS is one if SAMPLES is non-zero. Otherwise, SAMPLE_BUFFERS is zero.

**Required Framebuffer Formats**

Implementations must support framebuffer objects with up to \( \text{MAX}_\text{COLOR}_\text{-ATTACHMENTS} \) color attachments, a depth attachment, and a stencil attachment. Each color attachment may be in any of the required color formats for textures and renderbuffers described in sections 3.8.3 and 4.4.2. The depth attachment may be in any of the required depth or combined depth+stencil formats described in those sections, and the stencil attachment may be in any of the required combined depth+stencil formats. However, when both depth and stencil attachments are present, implementations are only required to support framebuffer objects where both attachments refer to the same image.

There must be at least one default framebuffer format allowing creation of a default framebuffer supporting front-buffered rendering.

**Effects of Framebuffer Completeness on Framebuffer Operations**

Attempting to render to or read from a framebuffer which is not framebuffer complete will generate an INVALID_FRAMEBUFFER_OPERATION error. This means that rendering commands such as **DrawArrays** or one of the other drawing commands defined in section 2.8.3, as well as commands that read the framebuffer...
such as ReadPixels, CopyTexImage, and CopyTexSubImage, will generate the error INVALID_FRAMEBUFFER_OPERATION if called while the framebuffer is not framebuffer complete. This error is generated regardless of whether fragments are actually read from or written to the framebuffer. For example, it will be generated when a rendering command is called and the framebuffer is incomplete even if RASTERIZER_DISCARD is enabled.

### 4.4.5 Effects of Framebuffer State on Framebuffer Dependent Values

The values of the state variables listed in table 6.53 may change when a change is made to DRAW_FRAMEBUFFER_BINDING, to the state of the currently bound framebuffer object, or to an image attached to the currently bound framebuffer object.

When DRAW_FRAMEBUFFER_BINDING is zero, the values of the state variables listed in table 6.53 are implementation defined.

When DRAW_FRAMEBUFFER_BINDING is non-zero, if the currently bound framebuffer object is not framebuffer complete, then the values of the state variables listed in table 6.53 are undefined.

When DRAW_FRAMEBUFFER_BINDING is non-zero and the currently bound framebuffer object is framebuffer complete, then the values of the state variables listed in table 6.53 are completely determined by DRAW_FRAMEBUFFER_BINDING, the state of the currently bound framebuffer object, and the state of the images attached to the currently bound framebuffer object. The actual sizes of the color, depth, or stencil bit planes can be obtained by querying an attachment point using GetFramebufferAttachmentParameteriv, or querying the object attached to that point. If the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE at a particular attachment point is RENDERBUFFER, the sizes may be determined by calling GetRenderbufferParameteriv as described in section 6.1.3. If the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE at a particular attachment point is TEXTURE, the sizes may be determined by calling GetTexParameter, as described in section 6.1.3.

### 4.4.6 Mapping between Pixel and Element in Attached Image

When DRAW_FRAMEBUFFER_BINDING is non-zero, an operation that writes to the framebuffer modifies the image attached to the selected logical buffer, and an operation that reads from the framebuffer reads from the image attached to the selected logical buffer.

If the attached image is a renderbuffer image, then the window coordinates \((x_w, y_w)\) corresponds to the value in the renderbuffer image at the same coordi-
If the attached image is a texture image, then the window coordinates \((x_w, y_w)\) correspond to the texel \((i, j, k)\) from figure 3.6 as follows:

\[
i = (x_w - b) \\
j = (y_w - b) \\
k = (layer - b)
\]

where \(b\) is the texture image’s border width and \(layer\) is the value of \text{FRAMEBUFFER_ATTACHMENT_TEXTURE_LAYER} for the selected logical buffer. For a two-dimensional texture, \(k\) and \(layer\) are irrelevant; for a one-dimensional texture, \(j\), \(k\), and \(layer\) are irrelevant. \((x_w, y_w)\) corresponds to a border texel if \(x_w\), \(y_w\), or \(layer\) is less than the border width, or if \(x_w\), \(y_w\), or \(layer\) is greater than or equal to the border width plus the width, height, or depth, respectively, of the texture image.

Conversion to Framebuffer-Attachable Image Components

When an enabled color value is written to the framebuffer while the draw framebuffer binding is non-zero, for each draw buffer the \(R, G, B,\) and \(A\) values are converted to internal components as described in table 3.11, according to the table row corresponding to the internal format of the framebuffer-attachable image attached to the selected logical buffer, and the resulting internal components are written to the image attached to logical buffer. The masking operations described in section 4.2.2 are also effective.

Conversion to RGBA Values

When a color value is read or is used as the source of a logical operation or blending while the read framebuffer binding is non-zero, the components of the framebuffer-attachable image that is attached to the logical buffer selected by \text{READ_BUFFER} are first converted to \(R, G, B,\) and \(A\) values according to table 3.20 and the internal format of the attached image.

4.4.7 Layered Framebuffers

A framebuffer is considered to be layered if it is complete and all of its populated attachments are layered. When rendering to a layered framebuffer, each fragment generated by the GL is assigned a layer number. The layer number for a fragment is zero if
4.4. FRAMEBUFFER OBJECTS

<table>
<thead>
<tr>
<th>Layer Number</th>
<th>Cube Map Face</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>TEXTURE_CUBE_MAP_POSITIVE_X</td>
</tr>
<tr>
<td>1</td>
<td>TEXTURE_CUBE_MAP_NEGATIVE_X</td>
</tr>
<tr>
<td>2</td>
<td>TEXTURE_CUBE_MAP_POSITIVE_Y</td>
</tr>
<tr>
<td>3</td>
<td>TEXTURE_CUBE_MAP_NEGATIVE_Y</td>
</tr>
<tr>
<td>4</td>
<td>TEXTURE_CUBE_MAP_POSITIVE_Z</td>
</tr>
<tr>
<td>5</td>
<td>TEXTURE_CUBE_MAP_NEGATIVE_Z</td>
</tr>
</tbody>
</table>

Table 4.12: Layer numbers for cube map texture faces. The layers are numbered in the same sequence as the cube map face token values.

- geometry shaders are disabled, or
- the current geometry shader does not statically assign a value to the built-in output variable gl_Layer.

Otherwise, the layer for each point, line, or triangle emitted by the geometry shader is taken from the gl_Layer output of one of the vertices of the primitive. The vertex used is implementation-dependent. To get defined results, all vertices of each primitive emitted should set the same value for gl_Layer. Since the EndPrimitive built-in function starts a new output primitive, defined results can be achieved if EndPrimitive is called between two vertices emitted with different layer numbers. A layer number written by a geometry shader has no effect if the framebuffer is not layered.

When fragments are written to a layered framebuffer, the fragment’s layer number selects an image from the array of images at each attachment point to use for the stencil test (see section 4.1.4), depth buffer test (see section 4.1.5), and for blending and color buffer writes (see section 4.1.7). If the fragment’s layer number is negative, or greater than the minimum number of layers of any attachment, the effects of the fragment on the framebuffer contents are undefined.

When the Clear or ClearBuffer* commands are used to clear a layered framebuffer attachment, all layers of the attachment are cleared.

When commands such as ReadPixels read from a layered framebuffer, the image at layer zero of the selected attachment is always used to obtain pixel values.

When cube map texture levels are attached to a layered framebuffer, there are six layers, numbered zero through five. Each layer number corresponds to a cube map face, as shown in table 4.12.

When cube map array texture levels are attached to a layered framebuffer, the layer number corresponds to a layer-face. The layer-face can be translated into an
array layer and a cube map face by

\[
array\text{layer} = \left\lfloor \frac{\text{layer}}{6} \right\rfloor
\]

\[
\text{face} = \text{layer} \mod 6
\]

The face number corresponds to the cube map faces as shown in table 4.12.
Chapter 5

Special Functions

This chapter describes additional GL functionality that does not fit easily into any of the preceding chapters. This functionality consists of flushing and finishing (used to synchronize the GL command stream), and hints.

5.1 Timer Queries

Timer queries use query objects to track the amount of time needed to fully complete a set of GL commands, or to determine the current time of the GL.

When BeginQuery and EndQuery are called with a target of TIME_ELAPSED, the GL prepares to start and stop the timer used for timer queries. The timer is started or stopped when the effects from all previous commands on the GL client and server state and the framebuffer have been fully realized. The BeginQuery and EndQuery commands may return before the timer is actually started or stopped. When the timer query timer is finally stopped, the elapsed time (in nanoseconds) is written to the corresponding query object as the query result value, and the query result for that object is marked as available.

If the elapsed time overflows the number of bits, \( n \), available to hold elapsed time, its value becomes undefined. It is recommended, but not required, that implementations handle this overflow case by saturating at \( 2^n - 1 \).

When the command

```c
void QueryCounter(uint id, enum target);
```

is called with target TIMESTAMP, the GL records the current time into the corresponding query object. The time is recorded after all previous commands on the GL client and server state and the framebuffer have been fully realized. When the time is recorded, the query result for that object is marked available. QueryCounter
timer queries can be used within a **BeginQuery / EndQuery** block where the **target** is **TIME_ELAPSED** and it does not affect the result of that query object. The error **INVALID_OPERATION** is generated if **id** is already in use within a **BeginQuery / EndQuery** block.

The current time of the GL may be queried by calling **GetIntegerv** or **GetInteger64v** with the symbolic constant **TIMESTAMP**. This will return the GL time after all previous commands have reached the GL server but have not yet necessarily executed. By using a combination of this synchronous get command and the asynchronous timestamp query object target, applications can measure the latency between when commands reach the GL server and when they are realized in the framebuffer.

### 5.2 Flush and Finish

The command

```c
void Flush(void);
```

indicates that all commands that have previously been sent to the GL must complete in finite time.

The command

```c
void Finish(void);
```

forces all previous GL commands to complete. **Finish** does not return until all effects from previously issued commands on GL client and server state and the framebuffer are fully realized.

### 5.3 Sync Objects and Fences

Sync objects act as a *synchronization primitive* - a representation of events whose completion status can be tested or waited upon. Sync objects may be used for synchronization with operations occurring in the GL state machine or in the graphics pipeline, and for synchronizing between multiple graphics contexts, among other purposes.

Sync objects have a status value with two possible states: **signaled** and **unsignedalated**. Events are associated with a sync object. When a sync object is created, its status is set to unsignedalated. When the associated event occurs, the sync object is signaled (its status is set to signaled). The GL may be asked to wait for a sync object to become signaled.

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5.3. SYNC OBJECTS AND FENCES

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Property Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBJECT_TYPE</td>
<td>SYNC_FENCE</td>
</tr>
<tr>
<td>SYNC_CONDITION</td>
<td>condition</td>
</tr>
<tr>
<td>SYNC_STATUS</td>
<td>UNSIGNALED</td>
</tr>
<tr>
<td>SYNC_FLAGS</td>
<td>flags</td>
</tr>
</tbody>
</table>

Table 5.1: Initial properties of a sync object created with FenceSync.

Initially, only one specific type of sync object is defined: the fence sync object, whose associated event is triggered by a fence command placed in the GL command stream. Fence sync objects are used to wait for partial completion of the GL command stream, as a more flexible form of Finish.

The command

```c
sync FenceSync( enum condition, bitfield flags );
```

creates a new fence sync object, inserts a fence command in the GL command stream and associates it with that sync object, and returns a non-zero name corresponding to the sync object.

When the specified `condition` of the sync object is satisfied by the fence command, the sync object is signaled by the GL, causing any ClientWaitSync or WaitSync commands (see below) blocking on `sync` to unblock. No other state is affected by FenceSync or by execution of the associated fence command.

`condition` must be SYNC_GPU_COMMANDS_COMPLETE. This condition is satisfied by completion of the fence command corresponding to the sync object and all preceding commands in the same command stream. The sync object will not be signaled until all effects from these commands on GL client and server state and the framebuffer are fully realized. Note that completion of the fence command occurs once the state of the corresponding sync object has been changed, but commands waiting on that sync object may not be unblocked until after the fence command completes.

`flags` must be 0.¹

Each sync object contains a number of properties which determine the state of the object and the behavior of any commands associated with it. Each property has a property name and property value. The initial property values for a sync object created by FenceSync are shown in table 5.1.

¹ `flags` is a placeholder for anticipated future extensions of fence sync object capabilities.
5.3. SYNC OBJECTS AND FENCES

Properties of a sync object may be queried with `GetSynciv` (see section 6.1.8). The `SYNC_STATUS` property will be changed to `SIGNALED` when `condition` is satisfied.

If `FenceSync` fails to create a sync object, zero will be returned and a GL error will be generated as described. An `INVALID_ENUM` error is generated if `condition` is not `SYNC_GPU_COMMANDS_COMPLETE`. If `flags` is not zero, an `INVALID_VALUE` error is generated.

A sync object can be deleted by passing its name to the command

```c
void DeleteSync( sync sync );
```

If the fence command corresponding to the specified sync object has completed, or if no `ClientWaitSync` or `WaitSync` commands are blocking on `sync`, the object is deleted immediately. Otherwise, `sync` is flagged for deletion and will be deleted when it is no longer associated with any fence command and is no longer blocking any `ClientWaitSync` or `WaitSync` command. In either case, after returning from `DeleteSync` the `sync` name is invalid and can no longer be used to refer to the sync object.

`DeleteSync` will silently ignore a `sync` value of zero. An `INVALID_VALUE` error is generated if `sync` is neither zero nor the name of a sync object.

### 5.3.1 Waiting for Sync Objects

The command

```c
enum ClientWaitSync( sync sync, bitfield flags, uint64 timeout );
```

causes the GL to block, and will not return until the sync object `sync` is signaled, or until the specified `timeout` period expires. `timeout` is in units of nanoseconds. `timeout` is adjusted to the closest value allowed by the implementation-dependent timeout accuracy, which may be substantially longer than one nanosecond, and may be longer than the requested period.

If `sync` is signaled at the time `ClientWaitSync` is called, then `ClientWaitSync` returns immediately. If `sync` is unsignaled at the time `ClientWaitSync` is called, then `ClientWaitSync` will block and will wait up to `timeout` nanoseconds for `sync` to become signaled. `flags` controls command flushing behavior, and may be `SYNC_FLUSH_COMMANDS_BIT`, as discussed in section 5.3.2.

`ClientWaitSync` returns one of four status values. A return value of `ALREADY_SIGNALED` indicates that `sync` was signaled at the time `ClientWaitSync` was called. `ALREADY_SIGNALED` will always be returned if `sync` was signaled, even if the value of `timeout` is zero. A return value of `TIMEOUT_EXPIRED`...
indicates that the specified timeout period expired before \textit{sync} was signaled. A return value of \texttt{CONDITION_SATISIFIED} indicates that \textit{sync} was signaled before the timeout expired. Finally, if an error occurs, in addition to generating a GL error as specified below, \texttt{ClientWaitSync} immediately returns \texttt{WAIT_FAILED} without blocking.

If the value of \textit{timeout} is zero, then \texttt{ClientWaitSync} does not block, but simply tests the current state of \textit{sync}. \texttt{TIMEOUT_EXPIRED} will be returned in this case if \textit{sync} is not signaled, even though no actual wait was performed.

If \textit{sync} is not the name of a sync object, an \texttt{INVALID_VALUE} error is generated. If \textit{flags} contains any bits other than \texttt{SYNC_FLUSH_COMMANDS_BIT}, an \texttt{INVALID_VALUE} error is generated.

The command

\begin{verbatim}
void WaitSync( sync sync, bitfield flags, 
    uint64 timeout );
\end{verbatim}

is similar to \texttt{ClientWaitSync}, but instead of blocking and not returning to the application until \textit{sync} is signaled, \texttt{WaitSync} returns immediately, instead causing the GL server to block \footnote{The GL server may choose to wait either in the CPU executing server-side code, or in the GPU hardware if it supports this operation.} until \textit{sync} is signaled \footnote{\texttt{WaitSync} allows applications to continue to queue commands from the client in anticipation of the sync being signalled, increasing client-server parallelism.}

\textit{sync} has the same meaning as for \texttt{ClientWaitSync}.

\textit{timeout} must currently be the special value \texttt{TIMEOUT_IGNORED}, and is not used. Instead, \texttt{WaitSync} will always wait no longer than an implementation-dependent timeout. The duration of this timeout in nanoseconds may be queried by calling \texttt{GetInteger64v} with the symbolic constant \texttt{MAX_SERVER_WAIT_TIMEOUT}. There is currently no way to determine whether \texttt{WaitSync} unblocked because the timeout expired or because the sync object being waited on was signaled.

\textit{flags} must be 0.

If an error occurs, \texttt{WaitSync} generates a GL error as specified below, and does not cause the GL server to block.

If \textit{sync} is not the name of a sync object, an \texttt{INVALID_VALUE} error is generated. If \textit{timeout} is not \texttt{TIMEOUT_IGNORED} or \textit{flags} is not zero, an \texttt{INVALID_VALUE} error is generated\footnote{\textit{flags} and \textit{timeout} are placeholders for anticipated future extensions of \textit{sync} object capabilities. They must have these reserved values in order that existing code calling \texttt{WaitSync} operate properly in the presence of such extensions.}.
5.3. SYNC OBJECTS AND FENCES

Multiple Waiters

It is possible for both the GL client to be blocked on a sync object in a ClientWaitSync command, the GL server to be blocked as the result of a previous WaitSync command, and for additional WaitSync commands to be queued in the GL server, all for a single sync object. When such a sync object is signaled in this situation, the client will be unblocked, the server will be unblocked, and all such queued WaitSync commands will continue immediately when they are reached.

See appendix D.2 for more information about blocking on a sync object in multiple GL contexts.

5.3.2 Signalling

A fence sync object enters the signaled state only once the corresponding fence command has completed and signaled the sync object.

If the sync object being blocked upon will not be signaled in finite time (for example, by an associated fence command issued previously, but not yet flushed to the graphics pipeline), then ClientWaitSync may hang forever. To help prevent this behavior, if the SYNC_FLUSH_COMMANDS_BIT bit is set in flags, and sync is unsignaled when ClientWaitSync is called, then the equivalent of Flush will be performed before blocking on sync.

If a sync object is marked for deletion while a client is blocking on that object in a ClientWaitSync command, or a GL server is blocking on that object as a result of a prior WaitSync command, deletion is deferred until the sync object is signaled and all blocked GL clients and servers are unblocked.

Additional constraints on the use of sync objects are discussed in appendix D.

State must be maintained to indicate which sync object names are currently in use. The state require for each sync object in use is an integer for the specific type, an integer for the condition, and a bit indicating whether the object is signaled or unsignaled. The initial values of sync object state are defined as specified by FenceSync.

5The simple flushing behavior defined by SYNC_FLUSH_COMMANDS_BIT will not help when waiting for a fence command issued in another context’s command stream to complete. Applications which block on a fence sync object must take additional steps to assure that the context from which the corresponding fence command was issued has flushed that command to the graphics pipeline.
5.4 HINTS

Certain aspects of GL behavior, when there is room for variation, may be controlled with hints. A hint is specified using

```c
void Hint(enum target, enum hint);
```

target is a symbolic constant indicating the behavior to be controlled, and hint is a symbolic constant indicating what type of behavior is desired. The possible targets are described in table 5.2; for each target, hint must be one of FASTEST, indicating that the most efficient option should be chosen; NICEST, indicating that the highest quality option should be chosen; and DONT_CARE, indicating no preference in the matter.

For the texture compression hint, a hint of FASTEST indicates that texture images should be compressed as quickly as possible, while NICEST indicates that the texture images be compressed with as little image degradation as possible. FASTEST should be used for one-time texture compression, and NICEST should be used if the compression results are to be retrieved by GetCompressedTexImage (section 6.1.4) for reuse.

The interpretation of hints is implementation-dependent. An implementation may ignore them entirely.

The initial value of all hints is DONT_CARE.

<table>
<thead>
<tr>
<th>Target</th>
<th>Hint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINE_SMOOTH_HINT</td>
<td>Line sampling quality</td>
</tr>
<tr>
<td>POLYGON_SMOOTH_HINT</td>
<td>Polygon sampling quality</td>
</tr>
<tr>
<td>TEXTURE_COMPRESSION_HINT</td>
<td>Quality and performance of texture image compression</td>
</tr>
<tr>
<td>FRAGMENT_SHADER_DERIVATIVE_HINT</td>
<td>Derivative accuracy for fragment processing built-in functions dFdx, dFdy and fwidth</td>
</tr>
</tbody>
</table>

Table 5.2: Hint targets and descriptions.
Chapter 6

State and State Requests

The state required to describe the GL machine is enumerated in section 6.2. Most state is set through the calls described in previous chapters, and can be queried using the calls described in section 6.1.

6.1 Querying GL State

6.1.1 Simple Queries

Much of the GL state is completely identified by symbolic constants. The values of these state variables can be obtained using a set of Get commands. There are four commands for obtaining simple state variables:

```c
void GetBooleanv( enum pname, boolean *data );
void GetIntegerv( enum pname, int *data );
void GetInteger64v( enum pname, int64 *data );
void GetFloatv( enum pname, float *data );
void GetDoublev( enum pname, double *data );
```

The commands obtain boolean, integer, 64-bit integer, floating-point, or double-precision state variables. `pname` is a symbolic constant indicating the state variable to return. `data` is a pointer to a scalar or array of the indicated type in which to place the returned data.

Indexed simple state variables are queried with the commands:

```c
void GetBooleaniv( enum target, uint index, boolean *data );
void GetIntegerv( enum target, uint index, int *data );
```
void GetInteger64i_v( enum target, uint index, int64 *data );

target is the name of the indexed state and index is the index of the particular element being queried. data is a pointer to a scalar or array of the indicated type in which to place the returned data. An INVALID_VALUE error is generated if index is outside the valid range for the indexed state target.

Finally,

boolean IsEnabled( enum cap );

can be used to determine if cap is currently enabled (as with Enable) or disabled, and

boolean IsEnabledi( enum target, uint index );

can be used to determine if the indexed state corresponding to target and index is enabled or disabled. An INVALID_VALUE error is generated if index is outside the valid range for the indexed state target.

6.1.2 Data Conversions

If a Get command is issued that returns value types different from the type of the value being obtained, a type conversion is performed. If GetBooleanv is called, a floating-point or integer value converts to FALSE if and only if it is zero (otherwise it converts to TRUE). If any of the other simple queries are called, a boolean value of TRUE or FALSE is interpreted as 1 or 0, respectively. If GetIntegerv or GetInteger64v are called, a floating-point value is rounded to the nearest integer, unless the value is an RGBA color component, a DepthRange value, or a depth buffer clear value. In these cases, the Get command converts the floating-point value to an integer according to the INT entry of table 4.9; a value not in \([-1, 1]\) converts to an undefined value. If GetFloatv is called, a boolean value of TRUE or FALSE is interpreted as 1.0 or 0.0, respectively, an integer is coerced to floating-point, and a double-precision floating-point value is converted to single-precision. Analogous conversions are carried out in the case of GetDoublev. If a value is so large in magnitude that it cannot be represented with the requested type, then the nearest value representable using the requested type is returned.

Unless otherwise indicated, multi-valued state variables return their multiple values in the same order as they are given as arguments to the commands that set them. For instance, the two DepthRange parameters are returned in the order n followed by f.
6.1. QUERYING GL STATE

If fragment color clamping is enabled, querying of the texture border color, blend color, and RGBA clear color will clamp the corresponding state values to $[0, 1]$ before returning them. This behavior provides compatibility with previous versions of the GL that clamped these values when specified.

Most texture state variables are qualified by the value of `ACTIVE_TEXTURE` to determine which server texture state vector is queried. Table 6.14 indicates those state variables which are qualified by `ACTIVE_TEXTURE` during state queries.

Vertex array state variables are qualified by the value of `VERTEX_ARRAY_BINDING` to determine which vertex array object is queried. Tables 6.5 and 6.6 define the set of state stored in a vertex array object.

6.1.3 Enumerated Queries

Other commands exist to obtain state variables that are identified by a category as well as a symbolic constant.

The commands

```c
void GetTexParameter{if}(enum target, enum value, T data);
void GetTexParameterI{ui}(enum target, enum value, T data);
```

place information about texture parameter `value` for the specified `target` into `data`. `value` must be one of the symbolic values in table 3.16.

`target` may be one of `TEXTURE_1D`, `TEXTURE_2D`, `TEXTURE_3D`, `TEXTURE_1D_ARRAY`, `TEXTURE_2D_ARRAY`, `TEXTURE_RECTANGLE`, `TEXTURE_CUBE_MAP`, or `TEXTURE_CUBE_MAP_ARRAY`, indicating the currently bound one-, two-, three-dimensional, one- or two-dimensional array, rectangular, cube map or cube map array texture object.

Querying `value` `TEXTURE_BORDER_COLOR` with `GetTexParameterIiv` or `GetTexParameterIuiv` returns the border color values as signed integers or unsigned integers, respectively; otherwise the values are returned as described in section 6.1.2. If the border color is queried with a type that does not match the original type with which it was specified, the result is undefined.

```c
void GetTexLevelParameter{if}(enum target, int lod, enum value, T data);
```

places information about texture image parameter `value` for level-of-detail `lod` of the specified `target` into `data`. `value` must be one of the symbolic values in table 6.17.
6.1. QUERYING GL STATE

*target* may be one of `TEXTURE_1D`, `TEXTURE_2D`, `TEXTURE_3D`, `TEXTURE_1D_ARRAY`, `TEXTURE_2D_ARRAY`, `TEXTURE_CUBE_MAP_ARRAY`, `TEXTURE_RECTANGLE`, `TEXTURE_CUBE_MAP_POSITIVE_X`, `TEXTURE_CUBE_MAP_NEGATIVE_X`, `TEXTURE_CUBE_MAP_POSITIVE_Y`, `TEXTURE_CUBE_MAP_NEGATIVE_Y`, `TEXTURE_CUBE_MAP_POSITIVE_Z`, `TEXTURE_CUBE_MAP_NEGATIVE_Z`, `TEXTURE_2D_MULTISAMPLE`, `TEXTURE_2D_MULTISAMPLE_ARRAY`, `PROXY_TEXTURE_1D`, `PROXY_TEXTURE_2D`, `PROXY_TEXTURE_3D`, `PROXY_TEXTURE_1D_ARRAY`, `PROXY_TEXTURE_2D_ARRAY`, `PROXY_TEXTURE_CUBE_MAP_ARRAY`, `PROXY_TEXTURE_RECTANGLE`, `PROXY_TEXTURE_CUBE_MAP`, `PROXY_TEXTURE_2D_MULTISAMPLE`, or `PROXY_TEXTURE_2D_MULTISAMPLE_ARRAY`, indicating the one-, two-, or three-dimensional texture, one-or two-dimensional array texture, cube map array texture, rectangular texture, one of the six distinct 2D images making up the cube map texture object, two-dimensional multisample texture, two-dimensional multisample array texture; or the one-, two-, three-dimensional, one-or two-dimensional array, cube map array, rectangular, cube map, two-dimensional multisample, or two-dimensional multisample array proxy state vector.

*target* may also be `TEXTURE_BUFFER`, indicating the texture buffer. In the case *lod* must be zero or an `INVALID_VALUE` error is generated.

Note that `TEXTURE_CUBE_MAP` is not a valid *target* parameter for `GetTexLevelParameter`, because it does not specify a particular cube map face.

*lod* determines which level-of-detail’s state is returned. If *lod* is less than zero or larger than the maximum allowable level-of-detail, then an `INVALID_VALUE` error is generated.

For texture images with uncompressed internal formats, queries of *value* `TEXTURE_RED_TYPE`, `TEXTURE_GREEN_TYPE`, `TEXTURE_BLUE_TYPE`, `TEXTURE_ALPHA_TYPE`, and `TEXTURE_DEPTH_TYPE` return the data type used to store the component. Types `NONE`, `SIGNED_NORMALIZED`, `UNSIGNED_NORMALIZED`, `FLOAT`, `INT`, and `UNSIGNED_INT` respectively indicate missing, signed normalized fixed-point, unsigned normalized fixed-point, floating-point, signed unnormalized integer, and unsigned unnormalized integer components. Queries of *value* `TEXTURE_RED_SIZE`, `TEXTURE_GREEN_SIZE`, `TEXTURE_BLUE_SIZE`, `TEXTURE_ALPHA_SIZE`, `TEXTURE_DEPTH_SIZE`, `TEXTURE_STENCIL_SIZE`, and `TEXTURE_SHARED_SIZE` return the actual resolutions of the stored image array components, not the resolutions specified when the image array was defined.

For texture images with compressed internal formats, the types returned specify how components are interpreted after decompression, while the resolutions returned specify the component resolution of an uncompressed internal format that produces an image of roughly the same quality as the compressed image in ques-

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6.1. QUERYING GL STATE

Since the quality of the implementation’s compression algorithm is likely data-dependent, the returned component sizes should be treated only as rough approximations.

Querying value TEXTURE_COMPRESSED_IMAGE_SIZE returns the size (in ubytes) of the compressed texture image that would be returned by GetCompressedTexImage (section 6.1.4). Querying TEXTURE_COMPRESSED_IMAGE_SIZE is not allowed on texture images with an uncompressed internal format or on proxy targets and will result in an INVALID_OPERATION error if attempted.

Queries of value TEXTURE_WIDTH, TEXTURE_HEIGHT, and TEXTURE_DEPTH return the width, height, and depth as specified when the image array was created. The internal format of the image array is queried as TEXTURE_INTERNAL_FORMAT.

6.1.4 Texture Queries

The command

```c
void GetTexImage( enum tex, int lod, enum format, enum type, void *img );
```

is used to obtain texture images. It is somewhat different from the other Get* commands; tex is a symbolic value indicating which texture (or texture face in the case of a cube map texture target name) is to be obtained. TEXTURE_1D, TEXTURE_2D, TEXTURE_3D, TEXTURE_1D_ARRAY, TEXTURE_2D_ARRAY, TEXTURE_CUBE_MAP_ARRAY, and TEXTURE_RECTANGLE indicate a one-, two-, or three-dimensional, one- or two-dimensional array, cube map array, or rectangular texture respectively. TEXTURE_CUBE_MAP_POSITIVE_X, TEXTURE_CUBE_MAP_NEGATIVE_X, TEXTURE_CUBE_MAP_POSITIVE_Y, TEXTURE_CUBE_MAP_NEGATIVE_Y, TEXTURE_CUBE_MAP_POSITIVE_Z, and TEXTURE_CUBE_MAP_NEGATIVE_Z indicate the respective face of a cube map texture. lod is a level-of-detail number, format is a pixel format from table 3.3, type is a pixel type from table 3.2.

Any of the following mismatches between format and the internal format of the texture image will generate an INVALID_OPERATION error:

- format is a color format (one of the formats in table 3.3 whose target is the color buffer) and the base internal format of the texture image is not a color format.

- format is DEPTH_COMPONENT and the base internal format is not DEPTH_COMPONENT or DEPTH_STENCIL.
6.1. QUERYING GL STATE

- `format` is `DEPTH_STENCIL` and the base internal format is not `DEPTH_STENCIL`.

- `format` is one of the integer formats in table 3.3 and the internal format of the texture image is not integer, or `format` is not one of the integer formats in table 3.3 and the internal format is integer.

**GetTexImage** obtains component groups from a texture image with the indicated level-of-detail. If `format` is a color format then the components are assigned among R, G, B, and A according to table 6.1, starting with the first group in the first row, and continuing by obtaining groups in order from each row and proceeding from the first row to the last, and from the first image to the last for three-dimensional textures. One- and two-dimensional array and cube map array textures are treated as two-, three-, and three-dimensional images, respectively, where the layers are treated as rows or images. If `format` is `DEPTH_COMPONENT`, then each depth component is assigned with the same ordering of rows and images. If `format` is `DEPTH_STENCIL`, then each depth component and each stencil index is assigned with the same ordering of rows and images.

These groups are then packed and placed in client or pixel buffer object memory. If a pixel pack buffer is bound (as indicated by a non-zero value of `PIXEL_PACK_BUFFER_BINDING`), `img` is an offset into the pixel pack buffer; otherwise, `img` is a pointer to client memory. Pixel storage modes that are applicable to **ReadPixels** are applied.

For three-dimensional, two-dimensional array, and cube map array textures, pixel storage operations are applied as if the image were two-dimensional, except that the additional pixel storage state values `PACK_IMAGE_HEIGHT` and `PACK_SKIP_IMAGES` are applied. The correspondence of texels to memory locations is as defined for **TexImage3D** in section 3.8.3.

The row length, number of rows, image depth, and number of images are determined by the size of the texture image (including any borders). Calling **GetTexImage** with `lod` less than zero or larger than the maximum allowable causes the error `INVALID_VALUE`. Calling **GetTexImage** with a `format` of `STENCIL_INDEX` causes the error `INVALID_ENUM`. Calling **GetTexImage** with a non-zero `lod` when `tex` is `TEXTURE_RECTANGLE` causes the error `INVALID_VALUE`. If a pixel pack buffer object is bound and packing the texture image into the buffer’s memory would exceed the size of the buffer, an `INVALID_OPERATION` error results. If a pixel pack buffer object is bound and `img` is not evenly divisible by the number of basic machine units needed to store in memory the GL data type corresponding to `type` (see table 3.2), an `INVALID_OPERATION` error results.

The command
Table 6.1: Texture, table, and filter return values. $R_i$, $G_i$, $B_i$, and $A_i$ are components of the internal format that are assigned to pixel values $R$, $G$, $B$, and $A$. If a requested pixel value is not present in the internal format, the specified constant value is used.

<table>
<thead>
<tr>
<th>Internal Format</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED</td>
<td>$R_i$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>RG</td>
<td>$R_i$</td>
<td>$G_i$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>RGB</td>
<td>$R_i$</td>
<td>$G_i$</td>
<td>$B_i$</td>
<td>1</td>
</tr>
<tr>
<td>RGBA</td>
<td>$R_i$</td>
<td>$G_i$</td>
<td>$B_i$</td>
<td>$A_i$</td>
</tr>
</tbody>
</table>

The command

```c
void GetCompressedTexImage( enum target, int lod, void *img );
```

is used to obtain texture images stored in compressed form. The parameters `target`, `lod`, and `img` are interpreted in the same manner as in `GetTexImage`. When called, `GetCompressedTexImage` writes $n$ ubytes of compressed image data to the pixel pack buffer or client memory pointed to by `img`, where $n$ is the value of `TEXTURE_COMPRESSED_IMAGE_SIZE` for the texture. The compressed image data is formatted according to the definition of the texture’s internal format. All pixel storage modes are ignored when returning a compressed texture image.

Calling `GetCompressedTexImage` with an `lod` value less than zero or greater than the maximum allowable causes an `INVALID_VALUE` error. Calling `GetCompressedTexImage` with a texture image stored with an uncompressed internal format causes an `INVALID_OPERATION` error. If a pixel pack buffer object is bound and `img + n` is greater than the size of the buffer, an `INVALID_OPERATION` error results.

The command

```c
boolean IsTexture( uint texture );
```

returns `TRUE` if `texture` is the name of a texture object. If `texture` is zero, or is a non-zero value that is not the name of a texture object, or if an error condition occurs, `IsTexture` returns `FALSE`. A name returned by `GenTextures`, but not yet bound, is not the name of a texture object.

### 6.1.5 Sampler Queries

The command
6.1. QUERYING GL STATE

boolean IsSampler(uint sampler);

may be called to determine whether sampler is the name of a sampler object. IsSampler will return TRUE if sampler is the name of a sampler object previously returned from a call to GenSamplers and FALSE otherwise. Zero is not the name of a sampler object.

The current values of the parameters of a sampler object may be queried by calling

void GetSamplerParameter{if|}v(uint sampler, enum pname, T *params);
void GetSamplerParameterI{i|ui}v(uint sampler, enum pname, T *params);

sampler is the name of the sampler object from which to retrieve parameters. pname is the name of the parameter to be queried. params is the address of an array into which the current value of the parameter will be placed. GetSamplerParameter* accepts the same values for pname as SamplerParameter* (see section 3.8.2). An INVALID_VALUE error is generated if sampler is not the name of a sampler object previously returned from a call to GenSamplers. An INVALID_ENUM error is generated if pname is not the name of a parameter accepted by GetSamplerParameter*.

Querying TEXTURE_BORDER_COLOR with GetSamplerParameterIiv or GetSamplerParameterIuiv returns the border color values as signed integers or unsigned integers, respectively; otherwise the values are returned as described in section 6.1.2. If the border color is queried with a type that does not match the original type with which it was specified, the result is undefined.

6.1.6 String Queries

String queries return pointers to UTF-8 encoded, NULL-terminated static strings describing properties of the current GL context 1. The command

ubyte *GetString( enum name );

accepts name values of RENDERER, VENDOR, VERSION, and SHADING_LANGUAGE_VERSION. The format of the RENDERER and VENDOR strings is implementation-dependent. The VERSION and SHADING_LANGUAGE_VERSION strings are laid out as follows:

1Applications making copies of these static strings should never use a fixed-length buffer, because the strings may grow unpredictably between releases, resulting in buffer overflow when copying.
6.1. QUERYING GL STATE

<table>
<thead>
<tr>
<th>Value</th>
<th>OpenGL Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTEXT_CORE_PROFILE_BIT</td>
<td>Core</td>
</tr>
<tr>
<td>CONTEXT_COMPATIBILITY_PROFILE_BIT</td>
<td>Compatibility</td>
</tr>
</tbody>
</table>

Table 6.2: Context profile bits returned by the CONTEXT_PROFILE_MASK query.

The version number is either of the form major_number:minor_number or major_number:minor_number:release_number, where the numbers all have one or more digits. The minor_number for SHADING_LANGUAGE_VERSION is always two digits, matching the OpenGL Shading Language Specification release number. For example, this query might return the string "4.00" while the corresponding VERSION query returns "4.0". The release_number and vendor specific information are optional. However, if present, then they pertain to the server and their format and contents are implementation-dependent.

GetString returns the version number (in the VERSION string) that can be supported by the current GL context. Thus, if the client and server support different versions a compatible version is returned.

The version, profile, and additional properties of the context may also be queried by calling GetIntegerv with values MAJOR_VERSION and MINOR_VERSION, which respectively return the same values as major_number and minor_number in the VERSION string; with value CONTEXT_PROFILE_MASK, which returns a mask containing one of the bits in table 6.2, corresponding to the API profile implemented by the context (see appendix E.1); or with value CONTEXT_FLAGS, which returns a set of flags defining additional properties of a context. If CONTEXT_FLAG_FORWARD_COMPATIBLE_BIT is set in CONTEXT_FLAGS, then the context is a forward-compatible context as defined in appendix E, and the deprecated features described in that appendix are not supported; otherwise the context is a full context, and all features described in the specification are supported.

Indexed strings are queried with the command

```
ubyte *GetStringi(enum name, uint index);
```

name is the name of the indexed state and index is the index of the particular element being queried. name may only be EXTENSIONS, indicating that the extension name corresponding to the indexth supported extension should be returned. index may range from zero to the value of NUM_EXTENSIONS minus one. There is no defined relationship between any particular extension name and the index values;
6.1. QUERYING GL STATE

An extension name may correspond to a different index in different GL contexts and/or implementations.

An INVALID_VALUE error is generated if index is outside the valid range for the indexed state name.

6.1.7 Asynchronous Queries

The command

```c
boolean IsQuery(uint id);
```

returns TRUE if id is the name of a query object. If id is zero, or if id is a non-zero value that is not the name of a query object, IsQuery returns FALSE.

Information about an indexed query target can be queried with the commands

```c
void GetQueryIndexediv(enum target, uint index, enum pname, int *params);
void GetQueryiv(enum target, enum pname, int *params);
```

target identifies the query target, and must be one of SAMPLES_PASSED or ANY_SAMPLES_PASSED for occlusion queries, TIME_ELAPSED or TIMESTAMP for timer queries, or PRIMITIVES_GENERATED or TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN for primitive queries. index is the index of the query target, and must be between zero and a target-specific maximum. If index is outside of this range, the error INVALID_VALUE is generated. Calling GetQueryiv is equivalent to calling GetQueryIndexediv with index set to zero.

If pname is CURRENT_QUERY, the name of the currently active query for the specified index of target, or zero if no query is active for that index of target, will be placed in params.

If pname is QUERY_COUNTER_BITS, index is ignored and the implementation-dependent number of bits used to hold the query result for target will be placed in params. The number of query counter bits may be zero, in which case the counter contains no useful information.

For primitive queries (PRIMITIVES_GENERATED and TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN) if the number of bits is non-zero, the minimum number of bits allowed is 32.

For occlusion queries with target ANY_SAMPLES_PASSED, if the number of bits is non-zero, the minimum number of bits is 1. For occlusion queries with target SAMPLES_PASSED, if the number of bits is non-zero, the minimum number of bits allowed is a function of the implementation’s maximum viewport dimensions (MAX_VIEWPORT_DIMS). The counter must be able to represent at least two.
overdraws for every pixel in the viewport. The formula to compute the allowable minimum value (where \(n\) is the minimum number of bits) is

\[n = \min\{32, \lceil \log_2(\text{maxViewportWidth} \times \text{maxViewportHeight} \times 2) \rceil\}.

For timer queries (\texttt{target TIME_ELAPSED} and \texttt{TIMESTAMP}), if the number of bits is non-zero, the minimum number of bits allowed is 30. This will allow at least 1 second of timing.

The state of a query object can be queried with the commands

\begin{verbatim}
void GetQueryObjectiv( uint id, enum pname, int *params );
void GetQueryObjectuiv( uint id, enum pname, uint *params );
void GetQueryObjecti64v( uint id, enum pname, int64 *params );
void GetQueryObjectui64v( uint id, enum pname, uint64 *params );
\end{verbatim}

If \(id\) is not the name of a query object, or if the query object named by \(id\) is currently active, then an \texttt{INVALID_OPERATION} error is generated. \texttt{pname} must be \texttt{QUERY_RESULT} or \texttt{QUERY_RESULT_AVAILABLE}.

If \texttt{pname} is \texttt{QUERY_RESULT}, then the query object’s result value is returned as a single integer in \texttt{params}. If the value is so large in magnitude that it cannot be represented with the requested type, then the nearest value representable using the requested type is returned. If the number of query counter bits for \texttt{target} is zero, then the result is returned as a single integer with the value zero.

There may be an indeterminate delay before the above query returns. If \texttt{pname} is \texttt{QUERY_RESULT_AVAILABLE}, \texttt{FALSE} is returned if such a delay would be required; otherwise \texttt{TRUE} is returned. It must always be true that if any query object returns a result available of \texttt{TRUE}, all queries of the same type issued prior to that query must also return \texttt{TRUE}.

Querying the state for any given query object forces that occlusion query to complete within a finite amount of time.

If multiple queries are issued using the same object name prior to calling \texttt{GetQueryObject*}, the result and availability information returned will always be from the last query issued. The results from any queries before the last one will be lost if they are not retrieved before starting a new query on the same \texttt{target} and \texttt{id}.
6.1.8 Sync Object Queries

Properties of sync objects may be queried using the command

```c
void GetSynciv( sync sync, enum pname, sizei bufSize,
                sizei *length, int *values );
```

The value or values being queried are returned in the parameters `length` and `values`.

On success, `GetSynciv` replaces up to `bufSize` integers in `values` with the corresponding property values of the object being queried. The actual number of integers replaced is returned in `*length`. If `length` is `NULL`, no length is returned.

If `pname` is `OBJECT_TYPE`, a single value representing the specific type of the sync object is placed in `values`. The only type supported is `SYNC_FENCE`.

If `pname` is `SYNC_STATUS`, a single value representing the status of the sync object (`SIGNALED` or `UNSIGNALED`) is placed in `values`. If an error occurs, nothing will be written to `values` or `length`.

The command

```c
boolean IsSync( sync sync );
```

returns `TRUE` if `sync` is the name of a sync object. If `sync` is not the name of a sync object, or if an error condition occurs, `IsSync` returns `FALSE` (note that zero is not the name of a sync object).

Sync object names immediately become invalid after calling `DeleteSync`, as discussed in sections 5.3 and D.2, but the underlying sync object will not be deleted until it is no longer associated with any fence command and no longer blocking any *WaitSync command.

6.1.9 Buffer Object Queries

The command

```c
boolean IsBuffer( uint buffer );
```

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returns TRUE if buffer is the name of an buffer object. If buffer is zero, or if buffer is a non-zero value that is not the name of an buffer object, IsBuffer returns FALSE.

The commands

```c
void GetBufferParameteriv( enum target, enum pname, int *data );
void GetBufferParameteri64v( enum target, enum pname, int64 *data );
```

return information about a bound buffer object. target must be one of the targets listed in table 2.8, and pname must be one of the buffer object parameters in table 2.9, other than BUFFER_MAP_POINTER. The value of the specified parameter of the buffer object bound to target is returned in data.

The command

```c
void GetBufferSubData( enum target, intptr offset, sizeptr size, void *data );
```

queries the data contents of a buffer object. target must be one of the targets listed in table 2.8. offset and size indicate the range of data in the buffer object that is to be queried, in terms of basic machine units. data specifies a region of client memory, size basic machine units in length, into which the data is to be retrieved.

An error is generated if GetBufferSubData is executed for a buffer object that is currently mapped.

While the data store of a buffer object is mapped, the pointer to the data store can be queried by calling

```c
void GetBufferPointerv( enum target, enum pname, void **params );
```

with target set to one of the targets listed in table 2.8 and pname set to BUFFER_-MAP_POINTER. The single buffer map pointer is returned in params. GetBufferPointerv returns the NULL pointer value if the buffer’s data store is not currently mapped, or if the requesting client did not map the buffer object’s data store, and the implementation is unable to support mappings on multiple clients.

To query which buffer objects are bound to the array of uniform buffer binding points and will be used as the storage for active uniform blocks, call GetIntegeri_v with param set to UNIFORM_BUFFER_BINDING. index must be in the range zero to the value of MAX_UNIFORM_BUFFER_BINDINGS - 1. The name of the buffer object bound to index is returned in values. If no buffer object is bound for index, zero is returned in values.
6.1. QUERYING GL STATE

To query the starting offset or size of the range of each buffer object binding used for uniform buffers, call `GetInteger64iv` with `param` set to `UNIFORM_BUFFER_START` or `UNIFORM_BUFFER_SIZE` respectively. `index` must be in the range zero to the value of `MAX_UNIFORM_BUFFER_BINDINGS` - 1. If the parameter (starting offset or size) was not specified when the buffer object was bound, zero is returned. If no buffer object is bound to `index`, -1 is returned.

To query which buffer objects are bound to the array of transform feedback binding points and will be used when transform feedback is active, call `GetIntegerv` with `param` set to `TRANSFORM_FEEDBACK_BUFFER_BINDING`. `index` must be in the range zero to the value of `MAX_TRANSFORM_FEEDBACK_BUFFERS` minus one. The name of the buffer object bound to `index` is returned in `values`. If no buffer object is bound for `index`, zero is returned in `values`. The error `INVALID_VALUE` is generated if `index` is greater than or equal to the value of `MAX_TRANSFORM_FEEDBACK_BUFFERS`.

To query the starting offset or size of the range of each buffer object binding used for transform feedback, call `GetInteger64iv` with `param` set to `TRANSFORM_FEEDBACK_BUFFER_START` or `TRANSFORM_FEEDBACK_BUFFER_SIZE` respectively. `index` must be in the range 0 to the value of `MAX_TRANSFORM_FEEDBACK_BUFFERS` minus one. If the parameter (starting offset or size) was not specified when the buffer object was bound, zero is returned. If no buffer object is bound to `index`, -1 is returned. The error `INVALID_VALUE` is generated if `index` is greater than or equal to the value of `MAX_TRANSFORM_FEEDBACK_BUFFERS`.

6.1.10 Vertex Array Object Queries

The command

```c
boolean IsVertexArray(uint array);
```

returns `TRUE` if `array` is the name of a vertex array object. If `array` is zero, or a non-zero value that is not the name of a vertex array object, `IsVertexArray` returns `FALSE`. No error is generated if `array` is not a valid vertex array object name.

6.1.11 Transform Feedback Queries

The command

```c
boolean IsTransformFeedback(uint id);
```

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returns\n\nTRUE if \textit{id} is the name of a transform feedback object. If \textit{id} is zero, or a non-zero value that is not the name of a transform feedback object, \texttt{IsTransformFeedback} return FALSE. No error is generated if \textit{id} is not a valid transform feedback object name.

### 6.1.12 Shader and Program Queries

State stored in shader or program objects can be queried by commands that accept shader or program object names. These commands will generate the error \texttt{INVALID\_VALUE} if the provided name is not the name of either a shader or program object, and \texttt{INVALID\_OPERATION} if the provided name identifies an object of the other type. If an error is generated, variables used to hold return values are not modified.

The command

\begin{verbatim}
boolean IsShader( uint shader );
\end{verbatim}

returns TRUE if \textit{shader} is the name of a shader object. If \textit{shader} is zero, or a non-zero value that is not the name of a shader object, \texttt{IsShader} returns FALSE. No error is generated if \textit{shader} is not a valid shader object name.

The command

\begin{verbatim}
void GetShaderiv( uint shader, enum pname, int *params );
\end{verbatim}

returns properties of the shader object named \textit{shader} in \texttt{params}. The parameter value to return is specified by \textit{pname}.

If \textit{pname} is \texttt{SHADER\_TYPE}, \texttt{VERTEX\_SHADER}, \texttt{TESS\_CONTROL\_SHADER}, \texttt{TESS\_EVALUATION\_SHADER}, \texttt{GEOMETRY\_SHADER}, or \texttt{FRAGMENT\_SHADER} is returned if \textit{shader} is a vertex, tessellation control, tessellation evaluation, geometry, or fragment shader object respectively. If \textit{pname} is \texttt{DELETE\_STATUS}, TRUE is returned if the shader has been flagged for deletion and FALSE is returned otherwise. If \textit{pname} is \texttt{COMPIL\_STATUS}, TRUE is returned if the shader was last compiled successfully, and FALSE is returned otherwise. If \textit{pname} is \texttt{INFO\_LOG\_LENGTH}, the length of the info log, including a null terminator, is returned. If there is no info log, zero is returned. If \textit{pname} is \texttt{SHADER\_SOURCE\_LENGTH}, the length of the concatenation of the source strings making up the shader source, including a null terminator, is returned. If no source has been defined, zero is returned.

The command

\begin{verbatim}
boolean IsProgram( uint program );
\end{verbatim}
returns **true** if *program* is the name of a program object. If *program* is zero, or a non-zero value that is not the name of a program object, **IsProgram** returns **false**. No error is generated if *program* is not a valid program object name.

The command

```c
void GetProgramiv( uint program, enum pname, int *params );
```

returns properties of the program object named *program* in *params*. The parameter value to return is specified by *pname*.

- If *pname* is **DELETE_STATUS**, **true** is returned if the program has been flagged for deletion, and **false** is returned otherwise.
- If *pname* is **LINK_STATUS**, **true** is returned if the program was last compiled successfully, and **false** is returned otherwise.
- If *pname* is **VALIDATE_STATUS**, **true** is returned if the last call to **ValidateProgram** with *program* was successful, and **false** is returned otherwise.
- If *pname* is **INFO_LOG_LENGTH**, the length of the info log, including a null terminator, is returned. If there is no info log, zero is returned.
- If *pname* is **ATTACHED_SHADERS**, the number of objects attached is returned.
- If *pname* is **ACTIVE_ATTRIBUTES**, the number of active attributes in *program* is returned. If no active attributes exist, zero is returned.
- If *pname* is **ACTIVE_ATTRIBUTE_MAX_LENGTH**, the length of the longest active attribute name, including a null terminator, is returned. If no active attributes exist, zero is returned.
- If *pname* is **ACTIVE_UNIFORMS**, the number of active uniforms is returned. If no active uniforms exist, zero is returned.
- If *pname* is **ACTIVE_UNIFORM_MAX_LENGTH**, the length of the longest active uniform name, including a null terminator, is returned. If no active uniforms exist, zero is returned.
- If *pname* is **TRANSFORM_FEEDBACK_BUFFER_MODE**, the buffer mode used when transform feedback is active is returned. It can be one of **SEPARATE_ATTRIBS** or **INTERLEAVED_ATTRIBS**.
- If *pname* is **TRANSFORM_FEEDBACK_VARYINGS**, the number of varying variables to capture in transform feedback mode for the program is returned.
- If *pname* is **TRANSFORM_FEEDBACK_VARYING_MAX_LENGTH**, the length of the longest varying name specified to be used for transform feedback, including a null terminator, is returned. If no varyings are used for transform feedback, zero is returned.
- If *pname* is **ACTIVE_UNIFORM_BLOCKS**, the number of uniform blocks for *program* containing active uniforms is returned.
If \textit{pname} is \texttt{ACTIVE_UNIFORM_BLOCK_MAX_NAME_LENGTH}, the length of the longest active uniform block name, including the null terminator, is returned.

If \textit{pname} is \texttt{GEOMETRY_VERTICES_OUT}, the maximum number of vertices the geometry shader will output is returned.

If \textit{pname} is \texttt{GEOMETRY_INPUT_TYPE}, the geometry shader input type, which must be one of \texttt{POINTS}, \texttt{LINES}, \texttt{LINES_ADJACENCY}, \texttt{TRIANGLES} or \texttt{TRIANGLES_ADJACENCY}, is returned.

If \textit{pname} is \texttt{GEOMETRY_OUTPUT_TYPE}, the geometry shader output type, which must be one of \texttt{POINTS}, \texttt{LINE_STRIP} or \texttt{TRIANGLE_STRIP}, is returned.

If \textit{pname} is \texttt{GEOMETRY_SHADER_INVOCATIONS}, the number of geometry shader invocations per primitive will be returned.

If \textit{GEOMETRY_VERTICES_OUT}, \texttt{GEOMETRY_INPUT_TYPE}, \texttt{GEOMETRY_OUTPUT_TYPE}, or \texttt{GEOMETRY_SHADER_INVOCATIONS} are queried for a program which has not been linked successfully, or which does not contain objects to form a geometry shader, then an \texttt{INVALID_OPERATION} error is generated.

If \textit{pname} is \texttt{TESS_CONTROL_OUTPUT_VERTICES}, the number of vertices in the tessellation control shader output patch is returned. If \texttt{TESS_CONTROL_OUTPUT_VERTICES} is queried for a program which has not been linked successfully, or which does not contain objects to form a tessellation control shader, then an \texttt{INVALID_OPERATION} error is generated.

If \textit{pname} is \texttt{TESS_GEN_MODE}, \texttt{QUADS}, \texttt{TRIANGLES}, or \texttt{ISOLINES} is returned, depending on the primitive mode declaration in the tessellation evaluation shader. If \textit{pname} is \texttt{TESS_GEN_SPACING}, \texttt{EQUAL}, \texttt{FRACTIONAL_EVEN}, or \texttt{FRACTIONAL_ODD} is returned, depending on the spacing declaration in the tessellation evaluation shader. If \textit{pname} is \texttt{TESS_GEN_VERTEX_ORDER}, \texttt{CCW} or \texttt{CW} is returned, depending on the vertex order declaration in the tessellation evaluation shader. If \textit{pname} is \texttt{TESS_GEN_POINT_MODE}, \texttt{TRUE} is returned if point mode is enabled in a tessellation evaluation shader declaration; \texttt{FALSE} is returned otherwise. If any of the \textit{pname} values in this paragraph are queried for a program which has not been linked successfully, or which does not contain objects to form a tessellation evaluation shader, then an \texttt{INVALID_OPERATION} error is generated.

The command

\begin{verbatim}
void GetAttachedShaders( uint program, sizei maxCount, 
sizei *count, uint *shaders );
\end{verbatim}

returns the names of shader objects attached to \textit{program} in \textit{shaders}. The actual number of shader names written into \textit{shaders} is returned in \textit{count}. If no shaders are attached, \textit{count} is set to zero. If \textit{count} is \texttt{NULL} then it is ignored. The maximum number of shader names that may be written into \textit{shaders} is specified by \textit{maxCount}.
The number of objects attached to program is given by can be queried by calling `GetProgramiv` with `ATTACHED_SHADERS`.

A string that contains information about the last compilation attempt on a shader object or last link or validation attempt on a program object, called the info log, can be obtained with the commands

```c
void GetShaderInfoLog( uint shader, sizei bufSize, sizei *length, char *infoLog );
void GetProgramInfoLog( uint program, sizei bufSize, sizei *length, char *infoLog );
```

These commands return the info log string in `infoLog`. This string will be null-terminated. The actual number of characters written into `infoLog`, excluding the null terminator, is returned in `length`. If `length` is `NULL`, then no length is returned. The maximum number of characters that may be written into `infoLog`, including the null terminator, is specified by `bufSize`. The number of characters in the info log can be queried with `GetShaderiv` or `GetProgramiv` with `INFO_LOG_LENGTH`. If `shader` is a shader object, the returned info log will either be an empty string or it will contain information about the last compilation attempt for that object. If `program` is a program object, the returned info log will either be an empty string or it will contain information about the last link attempt or last validation attempt for that object.

The info log is typically only useful during application development and an application should not expect different GL implementations to produce identical info logs.

The command

```c
void GetShaderSource( uint shader, sizei bufSize, sizei *length, char *source );
```

returns in `source` the string making up the source code for the shader object `shader`. The string `source` will be null-terminated. The actual number of characters written into `source`, excluding the null terminator, is returned in `length`. If `length` is `NULL`, no length is returned. The maximum number of characters that may be written into `source`, including the null terminator, is specified by `bufSize`. The string `source` is a concatenation of the strings passed to the GL using `ShaderSource`. The length of this concatenation is given by `SHADER_SOURCE_LENGTH`, which can be queried with `GetShaderiv`.

The commands

```c
void GetVertexAttribdv( uint index, enum pname, double *params );
```
6.1. QUERYING GL STATE

void GetVertexAttribfv(uint index, enum pname, float *params);
void GetVertexAttribiv(uint index, enum pname, int *params);
void GetVertexAttribIiv(uint index, enum pname, int *params);
void GetVertexAttribIuiv(uint index, enum pname, uint *params);

obtain the vertex attribute state named by *pname for the generic vertex attribute numbered *index and places the information in the array *params. *pname must be one of VERTEX_ATTRIB_ARRAY_BUFFER_BINDING, VERTEX_ATTRIB_ -ARRAYEnabled, VERTEX_ATTRIB_ARRAY_SIZE, VERTEX_ATTRIB_ -ARRAY_STRIDE, VERTEX_ATTRIB_ARRAY_TYPE, VERTEX_ATTRIB_ -ARRAY_NORMALIZED, VERTEX_ATTRIB_ARRAY_INTEGER, VERTEX_ATTRIB_ -ARRAY_DIVISOR, or CURRENT_VERTEX_ATTRIB. Note that all the queries except CURRENT_VERTEX_ATTRIB return values stored in the currently bound vertex array object (the value of VERTEX_ARRAY_BINDING). If the zero object is bound, these values are client state. The error INVALID_VALUE is generated if *index is greater than or equal to MAX_VERTEX_ATTRIBS.

All but CURRENT_VERTEX_ATTRIB return information about generic vertex attribute arrays. The enable state of a generic vertex attribute array is set by the command EnableVertexAttribArray and cleared by DisableVertexAttribArray. The size, stride, type, normalized flag, and unconverted integer flag are set by the commands VertexAttribPointer and VertexAttribIPointer. The normalized flag is always set to FALSE by VertexAttribIPointer. The unconverted integer flag is always set to FALSE by VertexAttribPointer and TRUE by VertexAttribIPointer.

The query CURRENT_VERTEX_ATTRIB returns the current value for the generic attribute *index. GetVertexAttribdv and GetVertexAttribfv read and return the current attribute values as floating-point values; GetVertexAttribiv reads them as floating-point values and converts them to integer values; GetVertexAttribIiv reads and returns them as integers; GetVertexAttribIuiv reads and returns them as unsigned integers. The results of the query are undefined if the current attribute values are read using one data type but were specified using a different one.

The command

void GetVertexAttribPointerv(uint index, enum pname, void **pointer);

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obtains the pointer named \textit{pname} for the vertex attribute numbered \textit{index} and places the information in the array \textit{pointer}. \textit{pname} must be \texttt{VERTEX_ATTRIB_ARRAY_\_POINTER}. The value returned is queried from the currently bound vertex array object. If the zero object is bound, the value is queried from client state. An \texttt{INVALID\_VALUE} error is generated if \textit{index} is greater than or equal to the value of \texttt{MAX\_VERTEX\_ATTRIBS}.

The commands

\begin{verbatim}
void GetUniformfv( uint program, int location,
          float *params );
void GetUniformdv( uint program, int location,
          double *params );
void GetUniformiv( uint program, int location,
          int *params );
void GetUniformuiv( uint program, int location,
          uint *params );
\end{verbatim}

return the value or values of the uniform at location \textit{location} of the default uniform block for program object \textit{program} in the array \textit{params}. The type of the uniform at \textit{location} determines the number of values returned. The error \texttt{INVALID\_OPERATION} is generated if \textit{program} has not been linked successfully, or if \textit{location} is not a valid location for \textit{program}. In order to query the values of an array of uniforms, a \texttt{GetUniform*} command needs to be issued for each array element. If the uniform queried is a matrix, the values of the matrix are returned in column major order. If an error occurred, \textit{params} will not be modified.

The command

\begin{verbatim}
void GetUniformSubroutineuiv( enum shadertype,
          int location, uint *params );
\end{verbatim}

returns the value of the subroutine uniform at location \textit{location} for shader stage \textit{shadertype} of the current program. If \textit{location} is greater than or equal to the value of \texttt{ACTIVE\_SUBROUTINE\_UNIFORM\_LOCATIONS} for the shader currently in use at shader stage \textit{shadertype}, the error \texttt{INVALID\_VALUE} is generated. If no program is active, the error \texttt{INVALID\_OPERATION} is generated.

The command

\begin{verbatim}
void GetProgramStageiv( uint program, enum shadertype,
          enum pname, int *values );
\end{verbatim}
returns properties of the program object *program* specific to the programmable stage corresponding to *shadertype* in *values*. The parameter value to return is specified by *pname*. If *pname* is `ACTIVE_SUBROUTINE_UNIFORMS`, the number of active subroutine variables in the stage is returned. If *pname* is `ACTIVE_SUBROUTINE_UNIFORM_LOCATIONS`, the number of active subroutine variable locations in the stage is returned. If *pname* is `ACTIVE_SUBROUTINES`, the number of active subroutines in the stage is returned. If *pname* is `ACTIVE_SUBROUTINE_UNIFORM_MAX_LENGTH` or `ACTIVE_SUBROUTINE_MAX_LENGTH`, the length of the longest subroutine uniform or subroutine name, respectively, for the stage is returned. The returned name length includes space for a null terminator. If there is no shader of type *shadertype* in *program*, the values returned will be consistent with a shader with no subroutines or subroutine uniforms.

### 6.1.13 Framebuffer Object Queries

The command

```c
boolean IsFramebuffer( uint framebuffer );
```

returns `TRUE` if *framebuffer* is the name of an framebuffer object. If *framebuffer* is zero, or if *framebuffer* is a non-zero value that is not the name of an framebuffer object, `IsFramebuffer` return `FALSE`.

The command

```c
void GetFramebufferAttachmentParameteriv( enum target, enum attachment, enum pname, int *params );
```

returns information about attachments of a bound framebuffer object. *target* must be `DRAW_FRAMEBUFFER`, `READ_FRAMEBUFFER`, or `FRAMEBUFFER`. `FRAMEBUFFER` is equivalent to `DRAW_FRAMEBUFFER`.

If the default framebuffer is bound to *target*, then *attachment* must be one of `FRONT_LEFT`, `FRONT_RIGHT`, `BACK_LEFT`, or `BACK_RIGHT`, identifying a color buffer; `DEPTH`, identifying the depth buffer; or `STENCIL`, identifying the stencil buffer.

If a framebuffer object is bound to *target*, then *attachment* must be one of the attachment points of the framebuffer listed in table 4.11.

If *attachment* is `DEPTH_STENCIL_ATTACHMENT`, and different objects are bound to the depth and stencil attachment points of *target*, the query will fail and generate an `INVALID_OPERATION` error. If the same object is bound to both attachment points, information about that object will be returned.
Upon successful return from `GetFramebufferAttachmentParameteriv`, if `pname` is `FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE`, then `param` will contain one of `NONE`, `FRAMEBUFFER_DEFAULT`, `TEXTURE`, or `RENDERBUFFER`, identifying the type of object which contains the attached image. Other values accepted for `pname` depend on the type of object, as described below.

If the value of `FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE` is `NONE`, no framebuffer is bound to `target`. In this case querying `pname` `FRAMEBUFFER_ATTACHMENT_OBJECT_NAME` will return zero, and all other queries will generate an `INVALID_OPERATION` error.

If the value of `FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE` is not `NONE`, these queries apply to all other framebuffer types:

- If `pname` is `FRAMEBUFFER_ATTACHMENT_RED_SIZE`, `FRAMEBUFFER_ATTACHMENT_GREEN_SIZE`, `FRAMEBUFFER_ATTACHMENT_BLUE_SIZE`, `FRAMEBUFFER_ATTACHMENT_ALPHA_SIZE`, `FRAMEBUFFER_ATTACHMENT_DEPTH_SIZE`, or `FRAMEBUFFER_ATTACHMENT_STENCIL_SIZE`, then `param` will contain the number of bits in the corresponding red, green, blue, alpha, depth, or stencil component of the specified attachment. Zero is returned if the requested component is not present in `attachment`.

- If `pname` is `FRAMEBUFFER_ATTACHMENT_COMPONENT_TYPE`, `param` will contain the format of components of the specified attachment, one of `FLOAT`, `INT`, `UNSIGNED_INT`, `SIGNED_NORMALIZED`, or `UNSIGNED_NORMALIZED` for floating-point, signed integer, unsigned integer, signed normalized fixed-point, or unsigned normalized fixed-point components respectively. Only color buffers may have integer components.

- If `pname` is `FRAMEBUFFER_ATTACHMENT_COLOR_ENCODING`, `param` will contain the encoding of components of the specified attachment, one of `LINEAR` or `SRGB` for linear or sRGB-encoded components, respectively. Only color buffer components may be sRGB-encoded; such components are treated as described in sections 4.1.7 and 4.1.8. For the default framebuffer, color encoding is determined by the implementation. For framebuffer objects, components are sRGB-encoded if the internal format of a color attachment is one of the color-renderable SRGB formats described in section 3.8.17.

If the value of `FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE` is `RENDERBUFFER`, then
6.1. QUERYING GL STATE

• If *pname* is FRAMEBUFFER_ATTACHMENT_OBJECT_NAME, *params* will contain the name of the renderbuffer object which contains the attached image.

If the value of FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE is TEXTURE, then

• If *pname* is FRAMEBUFFER_ATTACHMENT_OBJECT_NAME, then *params* will contain the name of the texture object which contains the attached image.

• If *pname* is FRAMEBUFFER_ATTACHMENT_TEXTURE_LEVEL, then *params* will contain the mipmap level of the texture object which contains the attached image.

• If *pname* is FRAMEBUFFER_ATTACHMENT_TEXTURE_CUBE_MAP_FACE and the texture object named FRAMEBUFFER_ATTACHMENT_OBJECT_NAME is a cube map texture, then *params* will contain the cube map face of the cube-map texture object which contains the attached image. Otherwise *params* will contain the value zero.

• If *pname* is FRAMEBUFFER_ATTACHMENT_TEXTURE_LAYER and the texture object named FRAMEBUFFER_ATTACHMENT_OBJECT_NAME is a layer of a three-dimensional texture or a one-or two-dimensional array texture, then *params* will contain the number of the texture layer which contains the attached image. Otherwise *params* will contain the value zero.

• If *pname* is FRAMEBUFFER_ATTACHMENT_LAYERED, then *params* will contain TRUE if an entire level of a three-dimensional texture, cube map texture, or one-or two-dimensional array texture is attached. Otherwise, *params* will contain FALSE.

Any combinations of framebuffer type and *pname* not described above will generate an INVALID_ENUM error.

6.1.14 Renderbuffer Object Queries

The command

```c
boolean IsRenderbuffer( uint renderbuffer );
```

returns TRUE if *renderbuffer* is the name of a renderbuffer object. If *renderbuffer* is zero, or if *renderbuffer* is a non-zero value that is not the name of a renderbuffer object, *IsRenderbuffer* return FALSE.

The command
void GetRenderbufferParameteriv(enum target, enum pname, int* params);

returns information about a bound renderbuffer object. target must be RENDERBUFFER and pname must be one of the symbolic values in table 6.27. If the renderbuffer currently bound to target is zero, then an INVALID_OPERATION error is generated.

Upon successful return from GetRenderbufferParameteriv, if pname is RENDERBUFFER_WIDTH, RENDERBUFFER_HEIGHT, RENDERBUFFER_INTERNAL_FORMAT, or RENDERBUFFER_SAMPLES, then params will contain the width in pixels, height in pixels, internal format, or number of samples, respectively, of the image of the renderbuffer currently bound to target.

If pname is RENDERBUFFER_RED_SIZE, RENDERBUFFER_GREEN_SIZE, RENDERBUFFER_BLUE_SIZE, RENDERBUFFER_ALPHA_SIZE, RENDERBUFFER_DEPTH_SIZE, or RENDERBUFFER_STENCIL_SIZE, then params will contain the actual resolutions (not the resolutions specified when the image array was defined) for the red, green, blue, alpha depth, or stencil components, respectively, of the image of the renderbuffer currently bound to target.

Otherwise, an INVALID_ENUM error is generated.

In the tables that follow, a type is indicated for each variable. Table 6.3 explains these types. The type actually identifies all state associated with the indicated description; in certain cases only a portion of this state is returned. This is the case with textures, where only the selected texture or texture parameter is returned.

The $M$ and $m$ entries for initial minmax table values represent the maximum and minimum possible representable values, respectively.

### 6.2 State Tables

The tables on the following pages indicate which state variables are obtained with what commands. State variables that can be obtained using any of GetBooleanv, GetIntegerv, GetFloatv, or GetDoublev are listed with just one of these commands – the one that is most appropriate given the type of the data to be returned. These state variables cannot be obtained using IsEnabled. However, state variables for which IsEnabled is listed as the query command can also be obtained using GetBooleanv, GetIntegerv, GetFloatv, and GetDoublev. State variables for which any other command is listed as the query command can be obtained by using that command or any of its typed variants, although information may be lost when not using the listed command. Unless otherwise specified, when floating-
6.2. STATE TABLES

<table>
<thead>
<tr>
<th>Type code</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>Boolean</td>
</tr>
<tr>
<td>BMU</td>
<td>Basic machine units</td>
</tr>
<tr>
<td>$C$</td>
<td>Color (floating-point R, G, B, and A values)</td>
</tr>
<tr>
<td>$Z$</td>
<td>Integer</td>
</tr>
<tr>
<td>$Z^+$</td>
<td>Non-negative integer or enumerated token value</td>
</tr>
<tr>
<td>$Z_{k}$, $Z_{k^*}$</td>
<td>$k$-valued integer ($k^*$ indicates $k$ is minimum)</td>
</tr>
<tr>
<td>$R$</td>
<td>Floating-point number</td>
</tr>
<tr>
<td>$R^+$</td>
<td>Non-negative floating-point number</td>
</tr>
<tr>
<td>$R^{[a,b]}$</td>
<td>Floating-point number in the range $[a, b]$</td>
</tr>
<tr>
<td>$R^k$</td>
<td>$k$-tuple of floating-point numbers</td>
</tr>
<tr>
<td>$S$</td>
<td>NULL-terminated string</td>
</tr>
<tr>
<td>$I$</td>
<td>Image</td>
</tr>
<tr>
<td>$Y$</td>
<td>Pointer (data type unspecified)</td>
</tr>
<tr>
<td>$n \times type$</td>
<td>$n$ copies of type $type$ ($n^*$ indicates $n$ is minimum)</td>
</tr>
</tbody>
</table>

Table 6.3: State Variable Types

Point state is returned as integer values or integer state is returned as floating-point values it is converted in the fashion described in section 6.1.2.
### Table 6.4. Current Values and Associated Data

<table>
<thead>
<tr>
<th>Get Command Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+</td>
<td>GetIntegerv</td>
<td>3</td>
<td>Number of vertices in input patch</td>
<td>2.6.1</td>
</tr>
<tr>
<td></td>
<td>GetFloatv</td>
<td>(1.0, 1.0, 1.0, 1.0)</td>
<td>Default outer tess. level w/o control shader</td>
<td>2.12.2</td>
</tr>
<tr>
<td></td>
<td>GetFloatv</td>
<td>2 × R</td>
<td>Default inner tess. level w/o control shader</td>
<td>2.12.2</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Get Command</th>
<th>Initial Value</th>
<th>Command</th>
<th>Description</th>
<th>See</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetVertexAttribiv</td>
<td>FALSE</td>
<td></td>
<td>Vertex attrib array enable</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertex attrib array size</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertex attrib array stride</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertex attrib array type</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertex attrib array nor-</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>malized</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Instance divisor</td>
<td>2.8.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pointer</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 6.5. Vertex Array Object State (cont.)
<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Description</th>
<th>Initial Value</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEMENT ARRAY BUFFER BINDING</td>
<td>Z+</td>
<td>GetIntegerv</td>
<td>Element array binding</td>
<td>0</td>
<td>2.9.7</td>
</tr>
<tr>
<td>VERTEX ARRAY BUFFER BINDING</td>
<td>16 × Z+</td>
<td>GetVertexAttribiv</td>
<td>Attribute array binding</td>
<td>0</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 6.6. Vertex Array Object State (cont.)
### 6.2. STATE TABLES

<table>
<thead>
<tr>
<th>Get Command</th>
<th>Type</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetIntegerv</td>
<td>ARRAY BUFFER BINDING</td>
<td>0</td>
<td>Current buffer binding</td>
<td>2.9</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>BUFFER BINDING</td>
<td>0</td>
<td>Indirect command buffer binding</td>
<td>2.9.8</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>VERTEX ARRAY OBJECT BINDING</td>
<td>0</td>
<td>Current vertex array object binding</td>
<td>2.10</td>
</tr>
<tr>
<td>IsEnabled</td>
<td>PRIMITIVE RESTART</td>
<td>FALSE</td>
<td>Primitive restart enable</td>
<td>2.8</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>PRIMITIVE RESTART INDEX</td>
<td>0</td>
<td>Primitive restart index</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 6.7. Vertex Array Data (not in Vertex Array objects)
### Table 6.8. Buffer Object State

<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER SIZE</td>
<td>GetBufferParameteriv</td>
<td>Buffer data size</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer usage pattern</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFERACCESSP</td>
<td>GetBufferParameteriv</td>
<td>Buffer access flag</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer usage pattern</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer access flag</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer usage pattern</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer access flag</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer usage pattern</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER ACCESS</td>
<td>GetBufferParameteriv</td>
<td>Buffer access flag</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER MAP</td>
<td>GetBufferParameteriv</td>
<td>Start of mapped buffer range</td>
</tr>
<tr>
<td>$n \times Z^+$</td>
<td>BUFFER MAP</td>
<td>GetBufferParameteriv</td>
<td>Size of mapped buffer range</td>
</tr>
</tbody>
</table>

---

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<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIEWPORT</td>
<td>$4 \times Z$</td>
<td>GetIntegerv</td>
<td>see 2.14.1</td>
<td>Viewport origin &amp; extent</td>
<td>2.14.1</td>
</tr>
<tr>
<td>DEPTH,RANGE</td>
<td>$2 \times R^+$</td>
<td>GetFloatv</td>
<td>0,1</td>
<td>Depth range near &amp; far</td>
<td>2.14.1</td>
</tr>
<tr>
<td>CLIP,DISTANCE;i</td>
<td>$6 + B$</td>
<td>IsEnabled</td>
<td>FALSE</td>
<td>$i$th user clipping plane enabled</td>
<td>2.20</td>
</tr>
<tr>
<td>DEPTH,CLAMP</td>
<td>$B$</td>
<td>IsEnabled</td>
<td>FALSE</td>
<td>Depth clamping enabled</td>
<td>2.20</td>
</tr>
<tr>
<td>TRANSFORM,FEEDBACK,BINDING</td>
<td>$Z^+$</td>
<td>GetIntegerv</td>
<td>0</td>
<td>Object bound for transform feedback operations</td>
<td>2.17</td>
</tr>
</tbody>
</table>
### Table 6.10. Coloring

<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAMP, READ, COLOR</td>
<td>$Z_3$</td>
<td>GetIntegerv</td>
<td>FIXED_ONLY</td>
<td>Read color clamping</td>
<td>4.3.1</td>
</tr>
<tr>
<td>PROVOKING, VERTEX</td>
<td>$Z_2$</td>
<td>GetIntegerv</td>
<td>LAST_VERTEX</td>
<td>Provoking vertex convention</td>
<td>2.19</td>
</tr>
</tbody>
</table>
### Table 6.11. Rasterization

<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>POINT_SIZE</td>
<td>$R^+$</td>
<td>GetFloatv</td>
<td>1.0</td>
<td>Point size</td>
<td>3.4</td>
</tr>
<tr>
<td>POINT_FADE_THRESHOLD_SIZE</td>
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<td>GetFloatv</td>
<td>1.0</td>
<td>Threshold for alpha attenuation</td>
<td>3.4</td>
</tr>
<tr>
<td>POINT_SPRITE_COORD_ORIGIN</td>
<td>$Z_2$</td>
<td>GetIntegerv</td>
<td>UPPER_LEFT</td>
<td>Origin orientation for point sprites</td>
<td>3.4</td>
</tr>
<tr>
<td>LINE_WIDTH</td>
<td>$R^+$</td>
<td>GetFloatv</td>
<td>1.0</td>
<td>Line width</td>
<td>3.5</td>
</tr>
<tr>
<td>LINE_SMOOTH</td>
<td>$B$</td>
<td>IsEnabled</td>
<td>FALSE</td>
<td>Line antialiasing on</td>
<td>3.5</td>
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### Table 6.12. Rasterization (cont.)

<table>
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<th>Sec.</th>
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<td>CULL_FACE</td>
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<td>FALSE</td>
<td>Polygon culling enabled</td>
<td>3.6.1</td>
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<tr>
<td>CULL_FACING_MODE</td>
<td>Z_3</td>
<td>GetIntegerv</td>
<td>BACK</td>
<td>Cull front-/back-facing polygons</td>
<td>3.6.1</td>
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<tr>
<td>FRONT_FACE</td>
<td>Z_2</td>
<td>GetIntegerv</td>
<td>CCW</td>
<td>Polygon frontface CW/CCW indicator</td>
<td>3.6.1</td>
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<td>POLYGON_SMOOTH</td>
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<td>POLYGON_OFFSET_FACTOR</td>
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<td>Polygon offset factor</td>
<td>3.6.4</td>
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<td>POLYGON_OFFSET_UNITS</td>
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<td>GetFloatv</td>
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<td>Polygon offset units</td>
<td>3.6.4</td>
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<td>POLYGON_OFFSET_POINT</td>
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<td>Polygon offset enable for POINT mode rasterization</td>
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<td>POLYGON_OFFSET_LINE</td>
<td>B</td>
<td>IsEnabled</td>
<td>FALSE</td>
<td>Polygon offset enable for LINE mode rasterization</td>
<td>3.6.4</td>
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<td>Get Command</td>
<td>Initial Value</td>
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<td>--------------------------------------</td>
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<td>MULTISAMPLE</td>
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<td>Multisample rasterization</td>
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<td>SAMPLE_ALPHA_TO_COVERAGE</td>
<td>B</td>
<td>IsEnabled</td>
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<td>Modify coverage from alpha</td>
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<tr>
<td>SAMPLE_ALPHA_TO_ONE</td>
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<td>Set alpha to maximum</td>
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<td>SAMPLE_COVERAGE</td>
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<td>Mask to modify coverage</td>
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<td>SAMPLE_COVERAGE_VALUE</td>
<td>R^+</td>
<td>GetFloatv</td>
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<td>Coverage mask value</td>
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<td>SAMPLE_COVERAGE_INVERT</td>
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<td>GetBooleanv</td>
<td>FALSE</td>
<td>Invert coverage mask value</td>
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<td>SAMPLE_SHADING</td>
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<td>GetFloatv</td>
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<td>Fraction of multisamples to use for</td>
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<td>sample shading</td>
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<td>SAMPLE_MASK</td>
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<tr>
<td>SAMPLE_MASK_VALUE</td>
<td>n × Z^+</td>
<td>GetIntegeri_v</td>
<td>n × 1's</td>
<td>Sample mask words</td>
<td>4.1.3</td>
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Table 6.13. Multisampling
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<th>Description</th>
<th>Sec.</th>
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<tr>
<td>TEXTURE_BINDING_1D</td>
<td>$80 \times 3 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_1D</code></td>
<td>3.8.1</td>
</tr>
<tr>
<td>TEXTURE_BINDING_1D_ARRAY</td>
<td>$80 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_1D_ARRAY</code></td>
<td>3.8.1</td>
</tr>
<tr>
<td>TEXTURE_BINDING_2D_ARRAY</td>
<td>$80 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_2D_ARRAY</code></td>
<td>3.8.1</td>
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<tr>
<td>TEXTURE_BINDING_CUBE_MAP_ARRAY</td>
<td>$80 \times 3 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_CUBE_MAP_ARRAY</code></td>
<td>3.8.1</td>
</tr>
<tr>
<td>TEXTURE_BINDING_RECTANGLE</td>
<td>$80 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_RECTANGLE</code></td>
<td>3.8.1</td>
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<tr>
<td>TEXTURE_BINDING_BUFFER</td>
<td>$80 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
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<td>3.8.1</td>
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<tr>
<td>TEXTURE_BINDING_CUBE_MAP</td>
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<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_CUBE_MAP</code></td>
<td>3.8.1</td>
</tr>
<tr>
<td>TEXTURE_BINDING_2D_MULTISAMPLE</td>
<td>$80 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_2D_MULTISAMPLE</code></td>
<td>3.8.15</td>
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<td>$80 \times Z^+$</td>
<td><code>GetIntegerv</code></td>
<td>0</td>
<td>Texture object bound to <code>TEXTURE_BINDING_2D_MULTISAMPLE_ARRAY</code></td>
<td>3.8.15</td>
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<tr>
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<td>Initial Value</td>
<td>Command</td>
<td>Description</td>
<td>Sec.</td>
</tr>
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<td>----------------------</td>
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<td>----------------------------------</td>
<td>------------------------------------------------------------------</td>
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<td>SAMPLER-BINDING</td>
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<td>GetTexImage</td>
<td>Sampler object bound to active texture unit</td>
<td>3.8.2</td>
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<tr>
<td>TEXTURE-1D</td>
<td>( n \times I )</td>
<td></td>
<td>GetTexImage</td>
<td>1D texture array/image at l.o.d. ( i )</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE-2D-ARRAY</td>
<td>( n \times I )</td>
<td></td>
<td>GetTexImage</td>
<td>2D texture array/image at row ( i )</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE-RECTANGLE</td>
<td>( n \times I )</td>
<td></td>
<td>GetTexImage</td>
<td>Rectangular texture image at l.o.d. ( i )</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE-CUBE-MAP-POSITIVE-X</td>
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<td></td>
<td>GetTexImage</td>
<td>+x face cube map texture image at l.o.d. ( i )</td>
<td>3.8.3</td>
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<tr>
<td>TEXTURE-CUBE-MAP-NEGATIVE-X</td>
<td></td>
<td></td>
<td>GetTexImage</td>
<td>−x face cube map texture image at l.o.d. ( i )</td>
<td>3.8.3</td>
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<tr>
<td>TEXTURE-CUBE-MAP-POSITIVE-Y</td>
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<td></td>
<td>GetTexImage</td>
<td>+y face cube map texture image at l.o.d. ( i )</td>
<td>3.8.3</td>
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<tr>
<td>TEXTURE-CUBE-MAP-NEGATIVE-Y</td>
<td></td>
<td></td>
<td>GetTexImage</td>
<td>−y face cube map texture image at l.o.d. ( i )</td>
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<tr>
<td>TEXTURE-CUBE-MAP-POSITIVE-Z</td>
<td></td>
<td></td>
<td>GetTexImage</td>
<td>+z face cube map texture image at l.o.d. ( i )</td>
<td>3.8.3</td>
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<tr>
<td>TEXTURE-CUBE-MAP-NEGATIVE-Z</td>
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<td></td>
<td>GetTexImage</td>
<td>−z face cube map texture image at l.o.d. ( i )</td>
<td>3.8.3</td>
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Table 6.15. Textures (state per texture unit and binding point) (cont.)
<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
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<tbody>
<tr>
<td>TEXTURE_SWIZZLE_R</td>
<td>Z_6</td>
<td>GetTexParameter</td>
<td>RED</td>
<td>Red component swizzle</td>
<td>3.8.8</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_G</td>
<td>Z_6</td>
<td>GetTexParameter</td>
<td>GREEN</td>
<td>Green component swizzle</td>
<td>3.8.8</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_B</td>
<td>Z_6</td>
<td>GetTexParameter</td>
<td>BLUE</td>
<td>Blue component swizzle</td>
<td>3.8.8</td>
</tr>
<tr>
<td>TEXTURE_SWIZZLE_A</td>
<td>Z_6</td>
<td>GetTexParameter</td>
<td>ALPHA</td>
<td>Alpha component swizzle</td>
<td>3.8.8</td>
</tr>
<tr>
<td>TEXTURE_BORDER_COLOR</td>
<td>n x C</td>
<td>GetTexParameter</td>
<td>0,0,0,0</td>
<td>Border color</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_MIN_FILTER</td>
<td>n x Z_6</td>
<td>GetTexParameter</td>
<td>see sec. 3.8.15</td>
<td>Minification function</td>
<td>3.8.11</td>
</tr>
<tr>
<td>TEXTURE_MAG_FILTER</td>
<td>n x Z_2</td>
<td>GetTexParameter</td>
<td>LINEAR</td>
<td>Magnification function</td>
<td>3.8.12</td>
</tr>
<tr>
<td>TEXCOORD_0_WRAP_S</td>
<td>n x Z_4</td>
<td>GetTexParameter</td>
<td>see sec. 3.8.15</td>
<td>Texcoord s wrap mode</td>
<td>3.8.11</td>
</tr>
<tr>
<td>TEXCOORD_1_WRAP_T</td>
<td>n x Z_4</td>
<td>GetTexParameter</td>
<td>see sec. 3.8.15</td>
<td>Texcoord t wrap mode (2D, 3D, cube map textures only)</td>
<td>3.8.11</td>
</tr>
<tr>
<td>TEXCOORD_2_WRAP_R</td>
<td>n x Z_4</td>
<td>GetTexParameter</td>
<td>see sec. 3.8.15</td>
<td>Texcoord r wrap mode (3D textures only)</td>
<td>3.8.11</td>
</tr>
<tr>
<td>TEXTURE_MIN_LOD</td>
<td>n x R</td>
<td>GetTexParameterfv</td>
<td>-1000</td>
<td>Minimum level of detail</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_MAX_LOD</td>
<td>n x R</td>
<td>GetTexParameterfv</td>
<td>1000</td>
<td>Maximum level of detail</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_BASE_LEVEL</td>
<td>n x Z^+</td>
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<td>Base texture array</td>
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<tr>
<td>TEXTURE_MAX_LEVEL</td>
<td>n x Z^+</td>
<td>GetTexParameterfv</td>
<td>1000</td>
<td>Max. texture array level</td>
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<td>TEXTURE_LOD_BIAS</td>
<td>n x R</td>
<td>GetTexParameterfv</td>
<td>0.0</td>
<td>Texture level of detail bias (bias_{texobj})</td>
<td>3.8.11</td>
</tr>
<tr>
<td>TEXTURE_COMPARE_MODE</td>
<td>n x Z_2</td>
<td>GetTexParameteriv</td>
<td>NONE</td>
<td>Comparison mode</td>
<td>3.8.16</td>
</tr>
<tr>
<td>TEXTURE_COMPARE_FUNC</td>
<td>n x Z_8</td>
<td>GetTexParameteriv</td>
<td>LEQUAL</td>
<td>Comparison function</td>
<td>3.8.16</td>
</tr>
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<td>Type</td>
<td>Get Command</td>
<td>Initial Value</td>
<td>Description</td>
<td>Sec.</td>
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<td>------------------------------------------</td>
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</tr>
<tr>
<td>TEXTURE_WIDTH</td>
<td>( n \times Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Specified width</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_HEIGHT</td>
<td>( n \times Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Specified height (2D/3D)</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_DEPTH</td>
<td>( n \times Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Specified depth (3D)</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_SAMPLES</td>
<td>( Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Number of samples per texel</td>
<td>3.8.6</td>
</tr>
<tr>
<td>TEXTURE_FIXED_SAMPLE_LOCATIONS</td>
<td>( B )</td>
<td>GetTexLevelParameter</td>
<td>TRUE</td>
<td>Whether the image uses a fixed sample pattern</td>
<td>3.8.6</td>
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<tr>
<td>TEXTURE_INTERNAL_FORMAT</td>
<td>( n \times Z_{68^+} )</td>
<td>GetTexLevelParameter</td>
<td>RGBA or R8</td>
<td>Internal format (see section 3.8.15)</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_X_SIZE</td>
<td>( n \times 6 \times Z^+ )</td>
<td>GetTexLevelParameter</td>
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<td>Component resolution (( x ) is RED, GREEN, BLUE, ALPHA, DEPTH, or STENCIL)</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_SHARED_SIZE</td>
<td>( n \times Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Shared exponent field resolution</td>
<td>3.8</td>
</tr>
<tr>
<td>TEXTURE_X_TYPE</td>
<td>( n \times Z_5 )</td>
<td>GetTexLevelParameter</td>
<td>NONE</td>
<td>Component type (( x ) is RED, GREEN, BLUE, ALPHA, or DEPTH)</td>
<td>6.1.3</td>
</tr>
<tr>
<td>TEXTURE_COMPRESSED</td>
<td>( n \times B )</td>
<td>GetTexLevelParameter</td>
<td>FALSE</td>
<td>True if image has a compressed internal format</td>
<td>3.8.5</td>
</tr>
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<td>TEXTURE_COMPRESSED_IMAGE_SIZE</td>
<td>( n \times Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Size (in ubytes) of compressed image</td>
<td>3.8.5</td>
</tr>
<tr>
<td>TEXTURE_BUFFER_DATA_STORE_BINDING</td>
<td>( n \times Z^+ )</td>
<td>GetTexLevelParameter</td>
<td>0</td>
<td>Buffer object bound as the data store for the active image unit's buffer texture</td>
<td>3.8.1</td>
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Table 6.17. Textures (state per texture image)
### Table 6.18. Textures (state per sampler object)

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<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
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<tbody>
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<td>GetSamplerParameter</td>
<td>$n \times Z_4$</td>
<td>$0/0/0$</td>
<td>Border color</td>
<td>3.8</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_2$</td>
<td>see sec. 3.8.15</td>
<td>Minification function</td>
<td>3.8.11</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_2$</td>
<td>L1/3/4</td>
<td>Magnification function</td>
<td>3.8.12</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_4$</td>
<td>see sec. 3.8.15</td>
<td>Texcoord $s$ wrap mode</td>
<td>3.8.11</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_4$</td>
<td>see sec. 3.8.15</td>
<td>Texcoord $t$ wrap mode</td>
<td>3.8.11</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_2$</td>
<td>see sec. 3.8.15</td>
<td>(2D, 3D, cube map textures only)</td>
<td>3.8.11</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times R$</td>
<td>$-1000$</td>
<td>Minimum level of detail (3D textures only)</td>
<td>3.8</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times R$</td>
<td>$1000$</td>
<td>Maximum level of detail (bias $bias_{bias_texture}$)</td>
<td>3.8</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_4$</td>
<td>$0.0$</td>
<td>Texture level of detail bias</td>
<td>3.8.11</td>
</tr>
<tr>
<td>GetSamplerParameter</td>
<td>$n \times Z_4$</td>
<td>LEQUAL</td>
<td>Comparison mode</td>
<td>3.8.16</td>
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<th>Get Command</th>
<th>Description</th>
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<td>TEXTURE0</td>
<td>TEXTURE0</td>
<td>GetIntegery</td>
<td>Active texture unit selector</td>
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Table 6.19. Texture Environment and Generation
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### Table 6.21. Pixel Operations (cont.)

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<td>C</td>
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### 6.2. STATE TABLES

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Table 6.22. Framebuffer Control

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Table 6.23. Framebuffer (state per target binding point)

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<tr>
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Type: Z+
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<td>Draw buffer selected for color output $i$</td>
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<td>Read source buffer</td>
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Table 6.24. Framebuffer (state per framebuffer object)
### Table 6.25. Framebuffer (state per attachment point)

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<td>Name of object attached to framebuffer attachment point</td>
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<td>Layer of texture image attached, if object attached is 3D texture</td>
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Table 6.26. Renderbuffer (state per target and binding point)
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<td>INFO-LOG-LENGTH</td>
<td>Z</td>
<td>0</td>
<td>GetShaderiv</td>
<td>Info log for shader objects</td>
<td>6.11.12</td>
</tr>
<tr>
<td>SHADER-SOURCE-LENGTH</td>
<td>Z</td>
<td>0</td>
<td>GetShaderSource</td>
<td>Source code for a shader</td>
<td>2.11.1</td>
</tr>
</tbody>
</table>

Table 6.29. Shader Object State
### Table 6.30. Program Object State

<table>
<thead>
<tr>
<th>Command</th>
<th>Type</th>
<th>Get value</th>
<th>Description</th>
<th>Initial Value</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.11.2</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td>2.11.2</td>
</tr>
<tr>
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<td></td>
<td>6.11.2</td>
</tr>
<tr>
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<td>6.11.2</td>
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<td>6.11.2</td>
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<td>6.11.2</td>
</tr>
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<td>2.11.4</td>
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<td>2.11.4</td>
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<tr>
<td></td>
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<td></td>
<td></td>
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<td>2.11.4</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.11.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.11.3</td>
</tr>
</tbody>
</table>

**CURRENT_PROGRAM**

- **DeleteStatus**
  - Get value: `FALSE`
  - Command: `GetIntegeriv`
  - Type: `Z`+
  - Initial Value: `0`
  - Description: Name of current program object

- **LinkStatus**
  - Get value: `FALSE`
  - Command: `GetProgramiv`
  - Type: `B`
  - Initial Value: `0`
  - Description: Program object deleted

- **ValidateStatus**
  - Get value: `FALSE`
  - Command: `GetProgramiv`
  - Type: `B`
  - Initial Value: `0`
  - Description: Last validate attempt succeeded

**DELETE STATUS**

- **AttachedShaders**
  - Get value: empty
  - Command: `GetAttachedShaders`
  - Type: `Z`+
  - Initial Value: `0` $\times Z$+
  - Description: Number of attached shader objects

- **ProgramInfoLog**
  - Get value: empty
  - Command: `GetProgramInfoLog`
  - Type: `S`
  - Initial Value: `0` $\times S$
  - Description: Info log for program object

**LINK STATUS**

- **ActiveLocation**
  - Get value: empty
  - Command: `GetActiveUniform`
  - Type: `$N$` $\times$ `char`
  - Initial Value: `0` $\times$ `char`
  - Description: Size of active uniform

- **ActiveUniform**
  - Get value: empty
  - Command: `GetActiveUniform`
  - Type: `Z`+
  - Initial Value: `0` $\times Z$+
  - Description: Name of active uniform

**VALIDATE STATUS**

- **ActiveUniformLength**
  - Get value: `512` $\times R$
  - Command: `GetActiveUniformLength`
  - Type: `ACTIVE_ATTRIBUTES_LENGTH`
  - Initial Value: `0`
  - Description: Maximum active uniform name length

- **ActiveUniforms**
  - Get value: empty
  - Command: `GetActiveUniforms`
  - Type: `ACTIVE_ATTRIBUTES`
  - Initial Value: `0` $\times Z$+
  - Description: Number of active attributes
<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>$0 \times \mathbb{Z}$</td>
<td>GetAttribLocation</td>
<td>–</td>
<td>Location of active generic attribute</td>
<td>2.11.3</td>
</tr>
<tr>
<td>-</td>
<td>$0 \times \mathbb{Z}^+$</td>
<td>GetActiveAttrib</td>
<td>–</td>
<td>Size of active attribute</td>
<td>2.11.3</td>
</tr>
<tr>
<td>-</td>
<td>$0 \times \mathbb{Z}^+$</td>
<td>GetActiveAttrib</td>
<td>–</td>
<td>Type of active attribute</td>
<td>2.11.3</td>
</tr>
<tr>
<td>-</td>
<td>$0 \times \text{char}$</td>
<td>GetActiveAttrib</td>
<td>empty</td>
<td>Name of active attribute</td>
<td>2.11.3</td>
</tr>
<tr>
<td>\text{ACTIVE.Attribute_MAX_LENGTH}</td>
<td>$\mathbb{Z}^+$</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Maximum active attribute name length</td>
<td>6.1.12</td>
</tr>
<tr>
<td>\text{GEOMETRY.VER- TICES.OUT}</td>
<td>$\mathbb{Z}^+$</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Maximum number of output vertices</td>
<td>2.13.4</td>
</tr>
<tr>
<td>\text{GEOMETRY(INPUT_TYPE)}</td>
<td>$\mathbb{Z}_5$</td>
<td>GetProgramiv</td>
<td>TRIANGLES</td>
<td>Primitive input type</td>
<td>2.13.1</td>
</tr>
<tr>
<td>\text{GEOMETRY.OUTPUT_TYPE}</td>
<td>$\mathbb{Z}_3$</td>
<td>GetProgramiv</td>
<td>TRIANGLE_STRIP</td>
<td>Primitive output type</td>
<td>2.13.2</td>
</tr>
<tr>
<td>\text{GEOMETRY_SHADER_INVOCATIONS}</td>
<td>$\mathbb{Z}^+$</td>
<td>GetProgramiv</td>
<td>1</td>
<td>No. of times a geom. shader should be executed for each input primitive</td>
<td>2.13.4</td>
</tr>
<tr>
<td>\text{TRANSFORM_FEEDBACK_BUFFER_MODE}</td>
<td>$\mathbb{Z}_2$</td>
<td>GetProgramiv</td>
<td>INTERLEAVED_ATTRIBS</td>
<td>Transform feedback mode for the program</td>
<td>6.1.12</td>
</tr>
<tr>
<td>\text{TRANSFORM_FEEDBACK_VARYING_INPUTS}</td>
<td>$\mathbb{Z}^+$</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Number of varyings to stream to buffer object(s)</td>
<td>6.1.12</td>
</tr>
<tr>
<td>\text{TRANSFORM_FEEDBACK_VARYING_MAX_LENGTH}</td>
<td>$\mathbb{Z}^+$</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Maximum transform feedback varying name length</td>
<td>6.1.12</td>
</tr>
<tr>
<td>-</td>
<td>$\mathbb{Z}^+$</td>
<td>GetTransformFeedbackVarying</td>
<td>–</td>
<td>Size of each transform feedback varying variable</td>
<td>2.11.7</td>
</tr>
<tr>
<td>-</td>
<td>$\mathbb{Z}^+$</td>
<td>GetTransformFeedbackVarying</td>
<td>–</td>
<td>Type of each transform feedback varying variable</td>
<td>2.11.7</td>
</tr>
<tr>
<td>-</td>
<td>$0^+ \times \text{char}$</td>
<td>GetTransformFeedbackVarying</td>
<td>–</td>
<td>Name of each transform feedback varying variable</td>
<td>2.11.7</td>
</tr>
</tbody>
</table>

Table 6.31. Program Object State (cont.)
<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIFORM_BUFFER_BINDING</td>
<td>Z⁰</td>
<td>GetIntegerv</td>
<td>0</td>
<td>Uniform buffer object bound to the context for buffer object manipulation</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_BUFFER_BINDING</td>
<td>n × Z⁰</td>
<td>GetIntegerv</td>
<td>0</td>
<td>Uniform buffer object bound to the specified context binding point</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_BUFFER_START</td>
<td>n × Z⁰</td>
<td>GetInteger64i_v</td>
<td>0</td>
<td>Start of bound uniform buffer region</td>
<td>6.1.9</td>
</tr>
<tr>
<td>UNIFORM_BUFFER_SIZE</td>
<td>n × Z⁰</td>
<td>GetInteger64i_v</td>
<td>0</td>
<td>Size of bound uniform buffer region</td>
<td>6.1.9</td>
</tr>
<tr>
<td>ACTIVE_UNIFORM_BLOCKS</td>
<td>Z⁰</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Number of active uniform blocks in a program</td>
<td>2.11.4</td>
</tr>
<tr>
<td>ACTIVE_UNIFORM_BLOCK_MAX_NAME_LENGTH</td>
<td>Z⁰</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Length of longest active uniform block name</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_TYPE</td>
<td>0 * Z₂⁷</td>
<td>GetActiveUniformsv</td>
<td>-</td>
<td>Type of active uniform</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_SIZE</td>
<td>0 * Z⁰</td>
<td>GetActiveUniformsv</td>
<td>-</td>
<td>Size of active uniform</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_NAME_LENGTH</td>
<td>0 * Z⁰</td>
<td>GetActiveUniformsv</td>
<td>-</td>
<td>Uniform name length</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_BLOCK_INDEX</td>
<td>0 * Z</td>
<td>GetActiveUniformsv</td>
<td>-</td>
<td>Uniform block index</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM_OFFSET</td>
<td>0 * Z</td>
<td>GetActiveUniformsv</td>
<td>-</td>
<td>Uniform buffer offset</td>
<td>2.11.4</td>
</tr>
<tr>
<td>Get value</td>
<td>Type</td>
<td>Get Command</td>
<td>Initial Value</td>
<td>Description</td>
<td>Sec.</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------</td>
<td>-------------------</td>
<td>---------------</td>
<td>------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>UNIFORM ARRAY, STRIDE</td>
<td>0 × Z</td>
<td>GetActiveUniformsiv</td>
<td>-</td>
<td>Uniform buffer array stride</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM MATRIX, STRIDE</td>
<td>0 × Z</td>
<td>GetActiveUniformsiv</td>
<td>-</td>
<td>Uniform buffer intra-matrix stride</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM IS, ROW, MAJOR</td>
<td>0 × Z+</td>
<td>GetActiveUniformsiv</td>
<td>-</td>
<td>Whether uniform is a row-major matrix</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, BINDING</td>
<td>Z+</td>
<td>GetActiveUniformBlockiv</td>
<td>0</td>
<td>Uniform buffer binding points associated with the specified uniform block</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, DATA, SIZE</td>
<td>Z+</td>
<td>GetActiveUniformBlockiv</td>
<td>-</td>
<td>Size of the storage needed to hold this uniform block’s data</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, ACTIVE, UNIFORMS</td>
<td>Z+</td>
<td>GetActiveUniformBlockiv</td>
<td>-</td>
<td>Count of active uniforms in the specified uniform block</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, ACTIVE, UNIFORM INDICES</td>
<td>n × Z+</td>
<td>GetActiveUniformBlockiv</td>
<td>-</td>
<td>Array of active uniform indices of the specified uniform block</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, REFERENCED, BY VERTEX, SHADER</td>
<td>B</td>
<td>GetActiveUniformBlockiv</td>
<td>0</td>
<td>True if uniform block is actively referenced by the vertex stage</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, REFERENCED, BY TESS, CONTROL, SHADER</td>
<td>B</td>
<td>GetActiveUniformBlockiv</td>
<td>0</td>
<td>True if uniform block is actively referenced by tess. control stage</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, REFERENCED, BY TESS, EVALUATION, SHADER</td>
<td>B</td>
<td>GetActiveUniformBlockiv</td>
<td>0</td>
<td>True if uniform block is actively referenced by tess evaluation stage</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, REFERENCED, BY GEOMETRY, SHADER</td>
<td>B</td>
<td>GetActiveUniformBlockiv</td>
<td>0</td>
<td>True if uniform block is actively referenced by the geometry stage</td>
<td>2.11.4</td>
</tr>
<tr>
<td>UNIFORM BLOCK, REFERENCED, BY FRAGMENT, SHADER</td>
<td>B</td>
<td>GetActiveUniformBlockiv</td>
<td>0</td>
<td>True if uniform block is actively referenced by the fragment stage</td>
<td>2.11.4</td>
</tr>
</tbody>
</table>
Table 6.34. Program Object State (cont.)

<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESS,CONTROL,OUTPUT,VERTICES</td>
<td>$Z^+$</td>
<td>GetProgramiv</td>
<td>0</td>
<td>Output patch size for tess. control shader</td>
<td>2.12.1</td>
</tr>
<tr>
<td>TESS,GEN,MODE</td>
<td>$Z^+$</td>
<td>GetProgramiv</td>
<td>QUADS</td>
<td>Base primitive type for tess. prim. generator</td>
<td>2.12.2</td>
</tr>
<tr>
<td>TESS,GEN,SPACING</td>
<td>$Z^+$</td>
<td>GetProgramiv</td>
<td>EQUAL</td>
<td>Spacing of tess. prim. generator edge subdivision</td>
<td>2.12.2</td>
</tr>
<tr>
<td>TESS,GEN,VERTEX,ORDER</td>
<td>$Z^+$</td>
<td>GetProgramiv</td>
<td>CCW</td>
<td>Order of vertices in primitives generated by tess. prim generator</td>
<td>2.12.2</td>
</tr>
<tr>
<td>TESS,GEN,POINT,MODE</td>
<td>$Z^+$</td>
<td>GetProgramiv</td>
<td>FALSE</td>
<td>Tess. prim. generator emits points?</td>
<td>2.12.2</td>
</tr>
</tbody>
</table>
### 6.2. STATE TABLES

Table 6.35. Program Object State (cont.)

<table>
<thead>
<tr>
<th>Get Command</th>
<th>Type</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×Z+</td>
<td>Number of subroutine uniform locations in the shader</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetProgramStageiv</td>
<td>Z+</td>
<td>5×Z+</td>
<td>Number of subroutine variables in the shader</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetProgramStageiv</td>
<td>Z+</td>
<td>5×Z+</td>
<td>Number of subroutine functions in the shader</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetProgramStageiv</td>
<td>Z+</td>
<td>5×Z+</td>
<td>Maximum number of compatible subroutine names</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetProgramStageiv</td>
<td>Z+</td>
<td>5×Z+</td>
<td>Maximum length of uniform name length</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetProgramStageiv</td>
<td>Z+</td>
<td>5×Z+</td>
<td>Number of subroutines compatible with a subroutine uniform</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×0×Z+</td>
<td>List of subroutines compatible with a subroutine uniform</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×0×Z+</td>
<td>Number of elements in a subroutine uniform array</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×0×Z+</td>
<td>Length of uniform name in a subroutine uniform name</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×0×Z+</td>
<td>Length of subroutine name string</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×0×Z+</td>
<td>Subroutine name string</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetActiveSubroutineUniformiv</td>
<td>Z+</td>
<td>5×0×Z+</td>
<td>Subroutine name string</td>
<td>2.11.5</td>
</tr>
</tbody>
</table>

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### Table 6.36. Vertex and Geometry Shader State

<table>
<thead>
<tr>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GetVertexAttrib</strong></td>
<td>0.0, 0.0, 0.0, 1.0</td>
<td>Current generic vertex attribute values</td>
</tr>
<tr>
<td><strong>IsEnabled</strong></td>
<td>FALSE</td>
<td>Point size mode</td>
</tr>
</tbody>
</table>

- **Type**: $16 \times R^4$
- **Value**: CURRENT_VERTEX_ATTRIB
- **Value**: PROGRAM_VERTEX_ATTRIB
### Table 6.37. Query Object State

<table>
<thead>
<tr>
<th>Get Command</th>
<th>Type</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetQueryObjectiv</td>
<td>Z</td>
<td>FALSE</td>
<td>Query object result</td>
<td>6.1.7</td>
</tr>
<tr>
<td>GetQueryObjectiv</td>
<td>B</td>
<td>FALSE</td>
<td>Is the query object result available?</td>
<td>6.1.7</td>
</tr>
</tbody>
</table>

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### Table 6.38. Transform Feedback State

<table>
<thead>
<tr>
<th>Initial Value</th>
<th>Get Command</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>GetInteger</td>
<td>$Z^+$</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>GetIntegeri</td>
<td>$n \times Z^+$</td>
<td>Buffer object bound to generic bind point for transform feedback</td>
</tr>
<tr>
<td>0</td>
<td>GetIntegeri64</td>
<td>$n \times Z^+$</td>
<td>Buffer object bound to each transform feedback attribute stream</td>
</tr>
<tr>
<td>0</td>
<td>GetInteger64i</td>
<td>0</td>
<td>Start offset of binding range for each transform feedback attrib. stream</td>
</tr>
<tr>
<td>0</td>
<td>GetInteger64i</td>
<td>0</td>
<td>Size of binding range for each transform feedback attrib. stream</td>
</tr>
</tbody>
</table>

---

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### Table 6.39. Sync (state per sync object)

<table>
<thead>
<tr>
<th>Get value</th>
<th>Type</th>
<th>Get Command</th>
<th>Initial Value</th>
<th>Description</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBJECT_TYPE</td>
<td>$Z_1$</td>
<td>GetSynciv</td>
<td>SYNC_FENCE</td>
<td>Type of sync object</td>
<td>5.3</td>
</tr>
<tr>
<td>SYNC_STATUS</td>
<td>$Z_2$</td>
<td>GetSynciv</td>
<td>UNSIGNED</td>
<td>Sync object status</td>
<td>5.3</td>
</tr>
<tr>
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<td>SYNC_GPU_COMMANDS_COMPLETE</td>
<td>Sync object condition</td>
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</tr>
<tr>
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<td>$Z$</td>
<td>GetSynciv</td>
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<td>Sync object flags</td>
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<td>GetIntegerv</td>
<td>DONT_CARE</td>
<td>Line smooth hint</td>
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<td>POLYGON_SMOOTH_HINT</td>
<td>Z₃</td>
<td>GetIntegerv</td>
<td>DONT_CARE</td>
<td>Polygon smooth hint</td>
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<tr>
<td>TEXTURE_COMPRESSION_HINT</td>
<td>Z₃</td>
<td>GetIntegerv</td>
<td>DONT_CARE</td>
<td>Texture compression quality hint</td>
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<tr>
<td>FRAGMENT_SHADER_DERIVATIVE_HINT</td>
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<td>GetIntegerv</td>
<td>DONT_CARE</td>
<td>Fragment shader derivative accuracy hint</td>
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### Table 6.41. Implementation Dependent Values

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<th>Get Value</th>
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<td>MAX_CLAMP_DISTANCE</td>
<td>Z+</td>
<td>Maximum number of用户 clipping planes</td>
<td>GetIntegerv</td>
<td>8</td>
<td>MAX.Clamp.value</td>
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<tr>
<td>SUBPIXEL_BITS</td>
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<td>Number of bits of subpixel precision in screen</td>
<td>GetIntegerv</td>
<td>4</td>
<td>256</td>
</tr>
<tr>
<td>MAX_3D_TEXTURE_SIZE</td>
<td>Z+</td>
<td>Maximum 3D texture image dimension</td>
<td>GetIntegerv</td>
<td>3</td>
<td>3.8.3</td>
</tr>
<tr>
<td>MAX_ARRAY_TEXTURE_IMAGE_SIZE</td>
<td>Z+</td>
<td>Maximum number of layers for texture arrays</td>
<td>GetIntegerv</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>MAX_TEXTURE_LOD_BIAS</td>
<td>R+</td>
<td>Maximum absolute texture level of detail bias</td>
<td>GetFloatv</td>
<td>2.0</td>
<td>MAX_TEXTURE_LOD_BIAS</td>
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<tr>
<td>MAX_CUBE_MAP_TEXTURE_SIZE</td>
<td>Z+</td>
<td>Maximum cube map texture image dimension</td>
<td>GetIntegerv</td>
<td>1024</td>
<td>1024</td>
</tr>
<tr>
<td>MAX_RENDERBUFFER_SIZE</td>
<td>Z+</td>
<td>Maximum width and height of renderbuffers</td>
<td>GetIntegerv</td>
<td>1024</td>
<td>MAX_RENDERBUFFER_SIZE</td>
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<tr>
<td>Get value</td>
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<td>Get Command</td>
<td>Minimum Value</td>
<td>Description</td>
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<td>------------</td>
<td>-------------</td>
<td>---------------</td>
<td>-------------------------------</td>
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</tr>
<tr>
<td>MAX. VIEWPORT.DIMS</td>
<td>$2 \times Z^+$</td>
<td>GetIntegerv</td>
<td>see 2.14.1</td>
<td>Maximum viewport dimensions</td>
<td>2.14.1</td>
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<td>POINT.SIZE.RANGE</td>
<td>$2 \times R^+$</td>
<td>GetFloatv</td>
<td>1,1</td>
<td>Range (lo to hi) of point sprite sizes</td>
<td>3.4</td>
</tr>
<tr>
<td>POINT_SIZE_GRANULARITY</td>
<td>$R^+$</td>
<td>GetFloatv</td>
<td>–</td>
<td>Point sprite size granularity</td>
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### 6.2. STATE TABLES

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<th>Description</th>
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<td>GetFloatv</td>
<td>Range (lo to hi) of aliased line widths</td>
<td>3.5</td>
</tr>
<tr>
<td>GetFloatv</td>
<td>Range (lo to hi) of antialiased line widths</td>
<td>3.5</td>
</tr>
<tr>
<td>GetFloatv</td>
<td>Antialiased line width granularity</td>
<td>3.5</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>Recommended max. number of DrawRangeElements indices</td>
<td>2.8</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>Recommended max. number of DrawRangeElements vertices</td>
<td>2.8</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>Number of compressed texture formats</td>
<td>3.8.5</td>
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<tr>
<td>GetIntegerv</td>
<td>No. of addressable levels for buffer textures</td>
<td>3.8.7</td>
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<tr>
<td>GetIntegerv</td>
<td>Max. width &amp; height of rectangular textures</td>
<td>3.8.3</td>
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</tr>
<tr>
<td>SMOOTH_LINE_WIDTH_RANGE</td>
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<td>1.1</td>
</tr>
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<td>MAX_ELEMENTS_INDICES</td>
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<td>-</td>
</tr>
<tr>
<td>SMOOTH_LINE_WIDTH_GRANULARITY</td>
<td>$Z^+$</td>
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</tr>
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<td>MAX_ELEMENTS_VERTICES</td>
<td>$4 \times Z^+$</td>
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<td>MAX_COMPRESSED_TEXTURE_FORMATS</td>
<td>$Z^+$</td>
<td>-</td>
</tr>
<tr>
<td>NUM_TEXTUREBUFFERS</td>
<td>$Z^+$</td>
<td>-</td>
</tr>
<tr>
<td>MAX_RECTANGLE_TEXTURE_SIZE</td>
<td>$Z^+$</td>
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<td>MAX_TEXTURE_COORD_SIZE</td>
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Table 6.43. Implementation Dependent Values (cont.)

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### Table 6.44. Implementation Dependent Version and Extension Support

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<thead>
<tr>
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<th>Minimum Value</th>
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<td>×S</td>
<td>–</td>
<td>Supported individual extension names</td>
<td>6.1.5</td>
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<td>GetIntegerv</td>
<td>Z+</td>
<td>–</td>
<td>Number of individual extension names</td>
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<tr>
<td>GetIntegerv</td>
<td>≥3</td>
<td>–</td>
<td>Major version number supported</td>
<td>6.1.5</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>Z+</td>
<td>–</td>
<td>Minor version number supported</td>
<td>6.1.5</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>Z≥</td>
<td>–</td>
<td>Context full/forward-compatible flag</td>
<td>6.1.5</td>
</tr>
<tr>
<td>GetString</td>
<td>S</td>
<td>–</td>
<td>Renderer string</td>
<td>6.1.5</td>
</tr>
<tr>
<td>GetString</td>
<td>S</td>
<td>–</td>
<td>Shading Language version supported</td>
<td>6.1.5</td>
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<td>–</td>
<td>Vendor string</td>
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<td>S</td>
<td>–</td>
<td>OpenGL version supported</td>
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<td>Type</td>
<td>Get Command</td>
<td>Minimum Value</td>
<td>Description</td>
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<td>-------------</td>
<td>---------------</td>
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</tr>
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<td>GetIntegerv</td>
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<td>Number of active vertex attributes</td>
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<tr>
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<td>Z⁺</td>
<td>GetIntegerv</td>
<td>1024</td>
<td>Number of components for vertex shader uniform variables</td>
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<tr>
<td>MAX_VERTEX_UNIFORM_BLOCKS</td>
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<td>GetIntegerv</td>
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<td>Max number of vertex uniform buffers per program</td>
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<td>Description</td>
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<td>-------------</td>
<td>---------------</td>
<td>-------------------------------------------------------------------------------</td>
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<tr>
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<td>GetIntegerv</td>
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<td>No. of supported uniform blocks for TCS</td>
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<td>Get Command</td>
<td>Minimum Value</td>
<td>Description</td>
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<td>-----------------------------------------------</td>
<td>------</td>
<td>---------------</td>
<td>---------------</td>
<td>------------------------------------------------------------------------------</td>
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<td>Max number of geometry uniform buffers per program</td>
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<td>GetIntegerv</td>
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<td>GetIntegerv</td>
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<td>Maximum number of vertices that any geometry shader can can emit</td>
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<td>MAX_GEOMETRY_TOTAL_OUTPUT_COMPONENTS</td>
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<td>GetIntegerv</td>
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<td>Maximum number of total components (all vertices) of active varyings that a geometry shader can emit</td>
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<td>GetIntegerv</td>
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<td>Max supported geom. shader invocation count</td>
</tr>
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<td>MAX_VERTEX_STREAMS</td>
<td>Z+</td>
<td>GetInteger</td>
<td>4</td>
<td>Total number of vertex streams</td>
</tr>
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Table 6.47. Implementation Dependent Geometry Shader Limits
### 6.2. STATE TABLES

<table>
<thead>
<tr>
<th>Get Command</th>
<th>Get value</th>
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<th>Sec.</th>
<th>Type</th>
<th>Description</th>
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<td>1024</td>
<td>GetIntegerv</td>
<td>3.9.1</td>
<td>Z+</td>
<td>Number of components for frag. shader uniform variables</td>
</tr>
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<td>GetIntegerv</td>
<td>12</td>
<td>12</td>
<td>GetIntegerv</td>
<td>2.11.4</td>
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<td>Max number of fragment uniform buffers per program</td>
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<td>128</td>
<td>128</td>
<td>GetIntegerv</td>
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<td>Z+</td>
<td>Max number of components of inputs read by a fragment shader</td>
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<td>16</td>
<td>GetIntegerv</td>
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<td>-8</td>
<td>GetIntegerv</td>
<td>2.11.8</td>
<td>Z</td>
<td>Minimum texel offset allowed in lookup</td>
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<td>7</td>
<td>7</td>
<td>GetIntegerv</td>
<td>2.11.8</td>
<td>Z+</td>
<td>Max. texel offset allowed in lookup</td>
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<td>-8</td>
<td>-8</td>
<td>GetIntegerv</td>
<td>3.8.11</td>
<td>Z+</td>
<td>Min. texel offset for textureGather</td>
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<tr>
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<td>7</td>
<td>GetIntegerv</td>
<td>3.8.11</td>
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<td>Max. texel offset for textureGather</td>
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Table 6.48. Implementation Dependent Fragment Processing Limits
### 6.2. State Tables

Table 6.49. Implementation Dependent Aggregate Shader Limits

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<th>Description</th>
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<th>Sec.</th>
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<tr>
<td>GetIntegerv</td>
<td>MAX_UNIFORM_BUFFER_BINDINGS</td>
<td>Max number of uniform buffer binding points on the context</td>
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<tr>
<td>GetIntegerv</td>
<td>MAX_UNIFORM_BUFFER_BLOCK_SIZE</td>
<td>Max size in basic machine units of a uniform block</td>
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<tr>
<td>GetIntegerv</td>
<td>UNIFORM_BUFFER_OFFSET_ALIGNMENT</td>
<td>Minimum required alignment for uniform buffer sizes and offsets</td>
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<td>2.11.4</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>MAX_UNIFORM_BUFFER_OFFSET_ALIGNMENT</td>
<td>Max number of uniform buffers per program</td>
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<td>2.11.4</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>MAX_UNIFORM_BUFFER_OFFSET_ALIGNMENT</td>
<td>Number of components for varying variables</td>
<td>60</td>
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</tr>
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<td>GetIntegerv</td>
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<td>Total number of texture units accessible by the GL</td>
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<td>2.11.8</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>MAX_UNIFORM_BUFFER_OFFSET_ALIGNMENT</td>
<td>Maximum number of subroutines per shader</td>
<td>256</td>
<td>2.11.5</td>
</tr>
<tr>
<td>GetIntegerv</td>
<td>MAX_UNIFORM_BUFFER_OFFSET_ALIGNMENT</td>
<td>Maximum number of subroutine uniform locations per stage</td>
<td>1024</td>
<td>2.11.5</td>
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### Table 6.50. Implementation Dependent Aggregate Shader Limits (cont.)

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<th>Type</th>
<th>Command</th>
<th>Minimum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetInteger</td>
<td>Z+</td>
<td>GetInteger</td>
<td>( \text{MAX}<em>\text{stage}</em>\text{UNIFORM_BLOCKS} \times \text{MAX}<em>{\text{UNIFORM_BLOCK_SIZE}} / 4 + \text{MAX}</em>\text{stage}_\text{UNIFORM_COMPONENTS} )</td>
</tr>
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<td>Type</td>
<td>Get Command</td>
<td>Minimum Value</td>
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</tr>
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<td>$Z^+$</td>
<td>GetIntegerv</td>
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</tr>
<tr>
<td>MAX_COLOR, TEXTURE, SAMPLES</td>
<td>$Z^+$</td>
<td>GetIntegerv</td>
<td>1</td>
</tr>
<tr>
<td>MAX_DEPTH, TEXTURE, SAMPLES</td>
<td>$Z^+$</td>
<td>GetIntegerv</td>
<td>1</td>
</tr>
<tr>
<td>MAX_INTEGER, SAMPLES</td>
<td>$Z^+$</td>
<td>GetIntegerv</td>
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</tr>
<tr>
<td>QUERY, COUNTER_BITS</td>
<td>$3 \times Z^+$</td>
<td>GetQueryiv</td>
<td>see 6.1.7</td>
</tr>
<tr>
<td>MAX_SERVER, WAIT_TIMEOUT</td>
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<td>------</td>
<td>-------------</td>
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Appendix A

Invariance

The OpenGL specification is not pixel exact. It therefore does not guarantee an exact match between images produced by different GL implementations. However, the specification does specify exact matches, in some cases, for images produced by the same implementation. The purpose of this appendix is to identify and provide justification for those cases that require exact matches.

A.1 Repeatability

The obvious and most fundamental case is repeated issuance of a series of GL commands. For any given GL and framebuffer state vector, and for any GL command, the resulting GL and framebuffer state must be identical whenever the command is executed on that initial GL and framebuffer state.

One purpose of repeatability is avoidance of visual artifacts when a double-buffered scene is redrawn. If rendering is not repeatable, swapping between two buffers rendered with the same command sequence may result in visible changes in the image. Such false motion is distracting to the viewer. Another reason for repeatability is testability.

Repeatability, while important, is a weak requirement. Given only repeatability as a requirement, two scenes rendered with one (small) polygon changed in position might differ at every pixel. Such a difference, while within the law of repeatability, is certainly not within its spirit. Additional invariance rules are desirable to ensure useful operation.
A.2 Multi-pass Algorithms

Invariance is necessary for a whole set of useful multi-pass algorithms. Such algorithms render multiple times, each time with a different GL mode vector, to eventually produce a result in the framebuffer. Examples of these algorithms include:

- “Erasing” a primitive from the framebuffer by redrawing it, either in a different color or using the XOR logical operation.
- Using stencil operations to compute capping planes.

On the other hand, invariance rules can greatly increase the complexity of high-performance implementations of the GL. Even the weak repeatability requirement significantly constrains a parallel implementation of the GL. Because GL implementations are required to implement ALL GL capabilities, not just a convenient subset, those that utilize hardware acceleration are expected to alternate between hardware and software modules based on the current GL mode vector. A strong invariance requirement forces the behavior of the hardware and software modules to be identical, something that may be very difficult to achieve (for example, if the hardware does floating-point operations with different precision than the software).

What is desired is a compromise that results in many compliant, high-performance implementations, and in many software vendors choosing to port to OpenGL.

A.3 Invariance Rules

For a given instantiation of an OpenGL rendering context:

**Rule 1** For any given GL and framebuffer state vector, and for any given GL command, the resulting GL and framebuffer state must be identical each time the command is executed on that initial GL and framebuffer state.

**Rule 2** Changes to the following state values have no side effects (the use of any other state value is not affected by the change):

**Required:**

- Framebuffer contents (all bitplanes)
- The color buffers enabled for writing
- Scissor parameters (other than enable)
A.4. TESSELLATION INVARIANCE

- Writemasks (color, depth, stencil)
- Clear values (color, depth, stencil)

**Strongly suggested:**

- Stencil parameters (other than enable)
- Depth test parameters (other than enable)
- Blend parameters (other than enable)
- Logical operation parameters (other than enable)
- Pixel storage state
- Polygon offset parameters (other than enables, and except as they affect the depth values of fragments)

**Corollary 1** Fragment generation is invariant with respect to the state values marked with • in Rule 2.

**Rule 3** The arithmetic of each per-fragment operation is invariant except with respect to parameters that directly control it.

**Corollary 2** Images rendered into different color buffers sharing the same framebuffer, either simultaneously or separately using the same command sequence, are pixel identical.

**Rule 4** The same vertex or fragment shader will produce the same result when run multiple times with the same input. The wording ‘the same shader’ means a program object that is populated with the same source strings, which are compiled and then linked, possibly multiple times, and which program object is then executed using the same GL state vector.

**Rule 5** All fragment shaders that either conditionally or unconditionally assign gl_FragCoord.z to gl_FragDepth are depth-invariant with respect to each other, for those fragments where the assignment to gl_FragDepth actually is done.

### A.4 Tessellation Invariance

When using a program containing tessellation evaluation shaders, the fixed-function tessellation primitive generator consumes the input patch specified by an application and emits a new set of primitives. The following invariance rules are
intended to provide repeatability guarantees. Additionally, they are intended to allow an application with a carefully crafted tessellation evaluation shader to ensure that the sets of triangles generated for two adjacent patches have identical vertices along shared patch edges, avoiding “cracks” caused by minor differences in the positions of vertices along shared edges.

**Rule 1** When processing two patches with identical outer and inner tessellation levels, the tessellation primitive generator will emit an identical set of point, line, or triangle primitives as long as the active program used to process the patch primitives has tessellation evaluation shaders specifying the same tessellation mode, spacing, vertex order, and point mode input layout qualifiers. Two sets of primitives are considered identical if and only if they contain the same number and type of primitives and the generated tessellation coordinates for the vertex numbered \( m \) of the primitive numbered \( n \) are identical for all values of \( m \) and \( n \).

**Rule 2** The set of vertices generated along the outer edge of the subdivided primitive in triangle and quad tessellation, and the tessellation coordinates of each, depends only on the corresponding outer tessellation level and the spacing input layout qualifier in the tessellation evaluation shader of the active program.

**Rule 3** The set of vertices generated when subdividing any outer primitive edge is always symmetric. For triangle tessellation, if the subdivision generates a vertex with tessellation coordinates of the form \((0, x, 1 - x)\), \((x, 0, 1 - x)\), or \((x, 1 - x, 0)\), it will also generate a vertex with coordinates of exactly \((0, 1 - x, x)\), \((1 - x, 0, x)\), or \((1 - x, x, 0)\), respectively. For quad tessellation, if the subdivision generates a vertex with coordinates of \((x, 0)\) or \((0, x)\), it will also generate a vertex with coordinates of exactly \((1 - x, 0)\) or \((0, 1 - x)\), respectively. For isoline tessellation, if it generates vertices at \((0, x)\) and \((1, x)\) where \(x\) is not zero, it will also generate vertices at exactly \((0, 1 - x)\) and \((1, 1 - x)\), respectively.

**Rule 4** The set of vertices generated when subdividing outer edges in triangular and quad tessellation must be independent of the specific edge subdivided, given identical outer tessellation levels and spacing. For example, if vertices at \((x, 1 - x, 0)\) and \((1 - x, x, 0)\) are generated when subdividing the \(w = 0\) edge in triangular tessellation, vertices must be generated at \((x, 0, 1 - x)\) and \((1 - x, 0, x)\) when subdividing an otherwise identical \(v = 0\) edge. For quad tessellation, if vertices at \((x, 0)\) and \((1 - x, 0)\) are generated when subdividing the \(v = 0\) edge, vertices must be generated at \((0, x)\) and \((0, 1 - x)\) when subdividing an otherwise identical \(u = 0\) edge.
Rule 5  When processing two patches that are identical in all respects enumerated in rule 1 except for vertex order, the set of triangles generated for triangle and quad tessellation must be identical except for vertex and triangle order. For each triangle $n_1$ produced by processing the first patch, there must be a triangle $n_2$ produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in $n_1$.

Rule 6  When processing two patches that are identical in all respects enumerated in rule 1 other than matching outer tessellation levels and/or vertex order, the set of interior triangles generated for triangle and quad tessellation must be identical in all respects except for vertex and triangle order. For each interior triangle $n_1$ produced by processing the first patch, there must be a triangle $n_2$ produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in $n_1$. A triangle produced by the tessellator is considered an interior triangle if none of its vertices lie on an outer edge of the subdivided primitive.

Rule 7  For quad and triangle tessellation, the set of triangles connecting an inner and outer edge depends only on the inner and outer tessellation levels corresponding to that edge and the spacing input layout qualifier.

Rule 8  The value of all defined components of $\text{gl}_\text{TessCoord}$ will be in the range $[0, 1]$. Additionally, for any defined component $x$ of $\text{gl}_\text{TessCoord}$, the results of computing $1.0 - x$ in a tessellation evaluation shader will be exact. Some floating-point values in the range $[0, 1]$ may fail to satisfy this property, but such values may never be used as tessellation coordinate components.

A.5  What All This Means

Hardware accelerated GL implementations are expected to default to software operation when some GL state vectors are encountered. Even the weak repeatability requirement means, for example, that OpenGL implementations cannot apply hysteresis to this swap, but must instead guarantee that a given mode vector implies that a subsequent command always is executed in either the hardware or the software machine.

The stronger invariance rules constrain when the switch from hardware to software rendering can occur, given that the software and hardware renderers are not pixel identical. For example, the switch can be made when blending is enabled or disabled, but it should not be made when a change is made to the blending parameters.
Because floating point values may be represented using different formats in different renderers (hardware and software), many OpenGL state values may change subtly when renderers are swapped. This is the type of state value change that Rule 1 seeks to avoid.
Appendix B

Corollaries

The following observations are derived from the body and the other appendixes of the specification. Absence of an observation from this list in no way impugns its veracity.

1. The error semantics of upward compatible OpenGL revisions may change, and features deprecated in a previous revision may be removed. Otherwise, only additions can be made to upward compatible revisions.

2. GL query commands are not required to satisfy the semantics of the **Flush** or the **Finish** commands. All that is required is that the queried state be consistent with complete execution of all previously executed GL commands.

3. Application specified point size and line width must be returned as specified when queried. Implementation-dependent clamping affects the values only while they are in use.

4. The mask specified as the third argument to **StencilFunc** affects the operands of the stencil comparison function, but has no direct effect on the update of the stencil buffer. The mask specified by **StencilMask** has no effect on the stencil comparison function; it limits the effect of the update of the stencil buffer.

5. There is no atomicity requirement for OpenGL rendering commands, even at the fragment level.

6. Because rasterization of non-antialiased polygons is point sampled, polygons that have no area generate no fragments when they are rasterized in **FILL** mode, and the fragments generated by the rasterization of “narrow” polygons may not form a continuous array.
7. OpenGL does not force left- or right-handedness on any of its coordinate systems.

8. (No pixel dropouts or duplicates.) Let two polygons share an identical edge. That is, there exist vertices A and B of an edge of one polygon, and vertices C and D of an edge of the other polygon; the positions of vertex A and C are identical; and the positions of vertex B and D are identical. Vertex positions are identical if the `gl_Position` values output by the vertex (or if active, geometry) shader are identical. Then, when the fragments produced by rasterization of both polygons are taken together, each fragment intersecting the interior of the shared edge is produced exactly once.

9. Dithering algorithms may be different for different components. In particular, alpha may be dithered differently from red, green, or blue, and an implementation may choose to not dither alpha at all.
Appendix C

Compressed Texture Image Formats

C.1 RGTC Compressed Texture Image Formats

Compressed texture images stored using the RGTC compressed image encodings are represented as a collection of $4 \times 4$ texel blocks, where each block contains 64 or 128 bits of texel data. The image is encoded as a normal 2D raster image in which each $4 \times 4$ block is treated as a single pixel. If an RGTC image has a width or height that is not a multiple of four, the data corresponding to texels outside the image are irrelevant and undefined.

When an RGTC image with a width of $w$, height of $h$, and block size of $\text{block-size}$ (8 or 16 bytes) is decoded, the corresponding image size (in bytes) is:

$$\lceil \frac{w}{4} \rceil \times \lceil \frac{h}{4} \rceil \times \text{blocksize}.$$  

When decoding an RGTC image, the block containing the texel at offset $(x, y)$ begins at an offset (in bytes) relative to the base of the image of:

$$\text{blocksize} \times \left( \left\lceil \frac{w}{4} \right\rceil \times \left\lceil \frac{y}{4} \right\rceil + \left\lfloor \frac{x}{4} \right\rfloor \right).$$

The data corresponding to a specific texel $(x, y)$ are extracted from a $4 \times 4$ texel block using a relative $(x, y)$ value of

$$(x \mod 4, y \mod 4).$$

There are four distinct RGTC image formats:
C.1. RGTC COMPRESSED TEXTURE IMAGE FORMATS

C.1.1 Format COMPRESSED_RED_RGTC1

Each 4 \times 4 block of texels consists of 64 bits of unsigned red image data.

Each red image data block is encoded as a sequence of 8 bytes, called (in order of increasing address):

\[ red_0, red_1, bits_0, bits_1, bits_2, bits_3, bits_4, bits_5 \]

The 6 \( bits \) bytes of the block are decoded into a 48-bit bit vector:

\[ bits = bits_0 + 256 \times (bits_1 + 256 \times (bits_2 + 256 \times (bits_3 + 256 \times (bits_4 + 256 \times bits_5)))) \]

\( red_0 \) and \( red_1 \) are 8-bit unsigned integers that are unpacked to red values \( RED_0 \) and \( RED_1 \).

\( bits \) is a 48-bit unsigned integer, from which a three-bit control code is extracted for a texel at location \((x, y)\) in the block using:

\[ code(x, y) = bits \left[ 3 \times (4 \times y + x) + 2 \ldots 3 \times (4 \times y + x) + 0 \right] \]

where bit 47 is the most significant and bit 0 is the least significant bit.

The red value \( R \) for a texel at location \((x, y)\) in the block is given by:

\[
R = \begin{cases} 
RED_0, & red_0 > red_1, code(x, y) = 0 \\
RED_1, & red_0 > red_1, code(x, y) = 1 \\
\frac{6RED_0 + RED_1}{7}, & red_0 > red_1, code(x, y) = 2 \\
\frac{5RED_0 + 2RED_1}{7}, & red_0 > red_1, code(x, y) = 3 \\
\frac{4RED_0 + 3RED_1}{7}, & red_0 > red_1, code(x, y) = 4 \\
\frac{3RED_0 + 4RED_1}{7}, & red_0 > red_1, code(x, y) = 5 \\
\frac{2RED_0 + 5RED_1}{7}, & red_0 > red_1, code(x, y) = 6 \\
\frac{RED_0 + 6RED_1}{7}, & red_0 > red_1, code(x, y) = 7 \\
RED_0, & red_0 \leq red_1, code(x, y) = 0 \\
RED_1, & red_0 \leq red_1, code(x, y) = 1 \\
\frac{4RED_0 + RED_1}{5}, & red_0 \leq red_1, code(x, y) = 2 \\
\frac{3RED_0 + 2RED_1}{5}, & red_0 \leq red_1, code(x, y) = 3 \\
\frac{2RED_0 + 3RED_1}{5}, & red_0 \leq red_1, code(x, y) = 4 \\
\frac{RED_0 + 4RED_1}{5}, & red_0 \leq red_1, code(x, y) = 5 \\
RED_{min}, & red_0 \leq red_1, code(x, y) = 6 \\
RED_{max}, & red_0 \leq red_1, code(x, y) = 7 
\end{cases}
\]
C.1. RGTC COMPRESSED TEXTURE IMAGE FORMATS

\( \text{RED}_{\text{min}} \) and \( \text{RED}_{\text{max}} \) are 0.0 and 1.0 respectively.

Since the decoded texel has a red format, the resulting RGBA value for the texel is \((R, 0, 0, 1)\).

C.1.2 Format COMPRESSED_SIGNED_RED_RGTC1

Each \(4 \times 4\) block of texels consists of 64 bits of signed red image data. The red values of a texel are extracted in the same way as COMPRESSED_RED_RGTC1 except \(\text{red}_0, \text{red}_1, \text{RED}_0, \text{RED}_1, \text{RED}_{\text{min}},\) and \(\text{RED}_{\text{max}}\) are signed values defined as follows:

\(\text{red}_0\) and \(\text{red}_1\) are 8-bit signed (twos complement) integers.

\[
\begin{align*}
\text{RED}_0 &= \begin{cases}
\frac{\text{red}_0}{127}, & \text{red}_0 > -128 \\
-1.0, & \text{red}_0 = -128
\end{cases} \\
\text{RED}_1 &= \begin{cases}
\frac{\text{red}_1}{127}, & \text{red}_1 > -128 \\
-1.0, & \text{red}_1 = -128
\end{cases}
\end{align*}
\]

\(\text{RED}_{\text{min}} = -1.0\)

\(\text{RED}_{\text{max}} = 1.0\)

CAVEAT for signed \(\text{red}_0\) and \(\text{red}_1\) values: the expressions \(\text{red}_0 > \text{red}_1\) and \(\text{red}_0 \leq \text{red}_1\) above are considered undefined (read: may vary by implementation) when \(\text{red}_0 = -127\) and \(\text{red}_1 = -128\). This is because if \(\text{red}_0\) were remapped to -127 prior to the comparison to reduce the latency of a hardware decompressor, the expressions would reverse their logic. Encoders for the signed red-green formats should avoid encoding blocks where \(\text{red}_0 = -127\) and \(\text{red}_1 = -128\).

C.1.3 Format COMPRESSED_RG_RGTC2

Each \(4 \times 4\) block of texels consists of 64 bits of compressed unsigned red image data followed by 64 bits of compressed unsigned green image data.

The first 64 bits of compressed red are decoded exactly like COMPRESSED_RED_RGTC1 above.

The second 64 bits of compressed green are decoded exactly like COMPRESSED_RED_RGTC1 above except the decoded value \(R\) for this second block is considered the resulting green value \(G\).

Since the decoded texel has a red-green format, the resulting RGBA value for the texel is \((R, G, 0, 1)\).
C.1.4 Format COMPRESSED_SIGNED_RG_RGTC2

Each $4 \times 4$ block of texels consists of 64 bits of compressed signed red image data followed by 64 bits of compressed signed green image data.

The first 64 bits of compressed red are decoded exactly like COMPRESSED_SIGNED_RED_RGTC1 above.

The second 64 bits of compressed green are decoded exactly like COMPRESSED_SIGNED_RED_RGTC1 above except the decoded value $R$ for this second block is considered the resulting green value $G$.

Since this image has a red-green format, the resulting RGBA value is $(R, G, 0, 1)$.  

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Appendix D

Shared Objects and Multiple Contexts

This appendix describes special considerations for objects shared between multiple OpenGL context, including deletion behavior and how changes to shared objects are propagated between contexts.

Objects that can be shared between contexts include pixel and vertex buffer objects, program and shader objects, renderbuffer objects, sync objects, and texture objects (except for the texture objects named zero).

Framebuffer, query, and vertex array objects are not shared.

Implementations may allow sharing between contexts implementing different OpenGL versions or different profiles of the same OpenGL version (see appendix E). However, implementation-dependent behavior may result when aspects and/or behaviors of such shared objects do not apply to, and/or are not described by more than one version or profile.

D.1 Object Deletion Behavior

D.1.1 Automatic Unbinding of Deleted Objects

When a buffer, texture, or renderbuffer object is deleted, it is unbound from any bind points it is bound to in the current context, as described for DeleteBuffers, DeleteTextures, and DeleteRenderbuffers. Bind points in other contexts are not affected.
D.2. SYNC OBJECTS AND MULTIPLE CONTEXTS

D.1.2 Deleted Object and Object Name Lifetimes

When a buffer, texture, renderbuffer, query, transform feedback, or sync object is deleted, its name immediately becomes invalid (e.g. is marked unused), but the underlying object will not be deleted until it is no longer in use. A buffer, texture, or renderbuffer object is in use while it is attached to any container object or bound to a context bind point in any context. A sync object is in use while there is a corresponding fence command which has not yet completed and signaled the sync object, or while there are any GL clients and/or servers blocked on the sync object as a result of ClientWaitSync or WaitSync commands. Query and transform feedback objects are in use so long as they are active, as described in sections 2.15 and 2.17.1, respectively.

When a shader object or program object is deleted, it is flagged for deletion, but its name remains valid until the underlying object can be deleted because it is no longer in use. A shader object is in use while it is attached to any program object. A program object is in use while it is the current program in any context.

Caution should be taken when deleting an object attached to a container object (such as a buffer object attached to a vertex array object, or a renderbuffer or texture attached to a framebuffer object), or a shared object bound in multiple contexts. Following its deletion, the object’s name may be returned by Gen* commands, even though the underlying object state and data may still be referred to by container objects, or in use by contexts other than the one in which the object was deleted. Such a container or other context may continue using the object, and may still contain state identifying its name as being currently bound, until such time as the container object is deleted, the attachment point of the container object is changed to refer to another object, or another attempt to bind or attach the name is made in that context. Since the name is marked unused, binding the name will create a new object with the same name, and attaching the name will generate an error. The underlying storage backing a deleted object will not be reclaimed by the GL until all references to the object from container object attachment points or context binding points are removed.

D.2 Sync Objects and Multiple Contexts

When multiple GL clients and/or servers are blocked on a single sync object and that sync object is signalled, all such blocks are released. The order in which blocks are released is implementation-dependent.
D.3 Propagating Changes to Objects

GL objects contain two types of information, *data* and *state*. Collectively these are referred to below as the contents of an object. For the purposes of propagating changes to object contents as described below, data and state are treated consistently.

*Data* is information the GL implementation does not have to inspect, and does not have an operational effect. Currently, data consists of:

- Pixels in the framebuffer.
- The contents of textures and renderbuffers.
- The contents of buffer objects.

*State* determines the configuration of the rendering pipeline and the driver does have to inspect. In hardware-accelerated GL implementations, state typically lives in GPU registers, while data typically lives in GPU memory.

When the contents of an object $T$ are changed, such changes are not always immediately visible, and do not always immediately affect GL operations involving that object. Changes to an object may occur via any of the following means:

- State-setting commands, such as *TexParameter*.
- Data-setting commands, such as *TexSubImage* or *BufferSubData*.
- Data-setting through rendering to attached renderbuffers or transform feedback operations.
- Commands that affect both state and data, such as *TexImage* and *BufferData*.
- Changes to mapped buffer data followed by a command such as *UnmapBuffer* or *FlushMappedBufferRange*.

D.3.1 Determining Completion of Changes to an object

The contents of an object $T$ are considered to have been changed once a command such as described in section D.3 has completed. Completion of a command $^1$ may

---

$^1$The GL already specifies that a single context processes commands in the order they are received. This means that a change to an object in a context at time $t$ must be completed by the time a command issued in the same context at time $t + 1$ uses the result of that change.
be determined either by calling \texttt{Finish}, or by calling \texttt{FenceSync} and executing a \texttt{WaitSync} command on the associated sync object. The second method does not require a round trip to the GL server and may be more efficient, particularly when changes to $T$ in one context must be known to have completed before executing commands dependent on those changes in another context.

\section*{D.3.2 Definitions}

In the remainder of this section, the following terminology is used:

- An object $T$ is \textit{directly attached} to the current context if it has been bound to one of the context binding points. Examples include but are not limited to bound textures, bound framebuffer, bound vertex arrays, and current programs.

- $T$ is \textit{indirectly attached} to the current context if it is attached to another object $C$, referred to as a \textit{container object}, and $C$ is itself directly or indirectly attached. Examples include but are not limited to renderbuffers or textures attached to framebuffers; buffers attached to vertex arrays; and shaders attached to programs.

- An object $T$ which is directly attached to the current context may be \textit{re-attached} by re-binding $T$ at the same bind point. An object $T$ which is indirectly attached to the current context may be re-attached by re-attaching the container object $C$ to which $T$ is attached.

\textit{Corollary:} re-binding $C$ to the current context re-attaches $C$ and its hierarchy of contained objects.

\section*{D.3.3 Rules}

The following rules must be obeyed by all GL implementations:

\textbf{Rule 1} \textit{If the contents of an object $T$ are changed in the current context while $T$ is directly or indirectly attached, then all operations on $T$ will use the new contents in the current context.}

Note: The intent of this rule is to address state changes in a single context only. The multi-context case is handled by the other rules.

Note: “Updates” via rendering or transform feedback are treated consistently with update via GL commands. Once \texttt{EndTransformFeedback} has been issued, any command in the same context that uses the results of the transform feedback operation will see the results. If a feedback loop is setup between rendering and transform feedback (see above), results will be undefined.
Rule 2 While a container object $C$ is bound, any changes made to its contents of $C$’s attachments in the current context are guaranteed to be seen. To guarantee seeing changes made in another context to objects attached to $C$, such changes must be completed in that other context (see section D.3.1) prior to $C$ being bound. Changes made in another context but not determined to have completed as described in section D.3.1, or after $C$ is bound in the current context, are not guaranteed to be seen.

Rule 3 State Changes to the contents of shared objects are not automatically propagated between contexts. If the contents of a shared object $T$ are changed in a context other than the current context, and $T$ is already directly or indirectly attached to the current context, any operations on the current context involving $T$ via those attachments are not guaranteed to use its new contents.

Rule 4 If the contents of an object $T$ are changed in a context other than the current context, $T$ must be attached or re-attached to at least one binding point in the current context in order to guarantee that the new contents of $T$ are visible in the current context.

   Note: “Attached or re-attached” means either attaching an object to a binding point it wasn’t already attached to, or attaching an object again to a binding point it was already attached.

   Note: This rule also applies to the pointer to the data store of an object. The pointer itself is state, while the content of the data store are data, not state. To guarantee that another context sees data updates to an object, you should attach or re-attach the object in that context, since the pointer to the data store could have changed.

   Note: To be sure that a data update resulting from a transform-feedback operation in another context is visible in the current context, the app needs to make sure that the command `EndTransformFeedback` has completed (see section D.3.1).

Example: If a texture image is bound to multiple texture bind points and the texture is changed in another context, re-binding the texture at any one of the texture bind points is sufficient to cause the changes to be visible at all texture bind points.
Appendix E

Profiles and the Deprecation Model

OpenGL 3.0 introduces a deprecation model in which certain features may be marked as deprecated. Deprecated features are expected to be completely removed from a future version of OpenGL. Deprecated features are summarized in section E.2.

To aid developers in writing applications which will run on such future versions, it is possible to create an OpenGL 3.0 context which does not support deprecated features. Such a context is called a forward compatible context, while a context supporting all OpenGL 3.0 features is called a full context. Forward compatible contexts cannot restore deprecated functionality through extensions, but they may support additional, non-deprecated functionality through extensions.

Profiles define subsets of OpenGL functionality targeted to specific application domains. OpenGL 3.2 defines two profiles (see below), and future versions may introduce additional profiles addressing embedded systems or other domains. OpenGL 3.2 implementations are not required to support all defined profiles, but must support the core profile described below.

To enable application control of deprecation and profiles, new context creation APIs have been defined as extensions to GLX and WGL. These APIs allow specifying a particular version, profile, and full or forward compatible status, and will either create a context compatible with the request, or fail (if, for example, requesting an OpenGL version or profile not supported by the implementation).

Only the ARB may define OpenGL profiles and deprecated features.
E.1 Core and Compatibility Profiles

OpenGL 3.2 is the first version of OpenGL to define multiple profiles. The **core profile** builds on OpenGL 3.1 by adding features described in section H.1. The **compatibility profile** builds on the combination of OpenGL 3.1 with the special GL_ARB_compatibility extension defined together with OpenGL 3.1, adding the same new features and in some cases extending their definition to interact with existing features of OpenGL 3.1 only found in GL_ARB_compatibility.

It is not possible to implement both core and compatibility profiles in a single GL context, since the core profile mandates functional restrictions not present in the compatibility profile. Refer to the WGL_ARB_create_context_profile and GLX_ARB_create_context_profile extensions (see appendix K.3.68) for information on creating a context implementing a specific profile.

E.2 Deprecated and Removed Features

OpenGL 3.0 defined a set of **deprecated features**. OpenGL 3.1 removed most of the deprecated features and moved them into the optional GL_ARB_compatibility extension. The OpenGL 3.2 core profile removes the same features as OpenGL 3.1, while the optional compatibility profile supports all those features.

Deprecated and removed features are summarized below in two groups: features which are marked deprecated by the core profile, but have not yet been removed, and features actually removed from the core profile of the current version of OpenGL (no features have been removed from or deprecated in the compatibility profile).

Functions which have been removed will generate an **INVALID_OPERATION** error if called in the core profile or in a forward-compatible context. Functions which are partially removed (e.g. no longer accept some parameter values) will generate the errors appropriate for any other unrecognized value of that parameter when a removed parameter value is passed in the core profile or a forward-compatible context. Functions which are deprecated but have not yet been removed from the core profile continue to operate normally except in a forward-compatible context, where they are also removed.

E.2.1 Deprecated But Still Supported Features

The following features are deprecated, but still present in the core profile. They may be removed from a future version of OpenGL, and are removed in a forward-compatible context implementing the core profile.
E.2. DEPRECATED AND REMOVED FEATURES

- Wide lines - **LineWidth** values greater than 1.0 will generate an **INVALID_VALUE** error.

- Global component limit query - the implementation-dependent values **MAX_VARYING_COMPONENTS** and **MAX_VARYING_FLOATS**.

E.2.2 Removed Features

- Application-generated object names - the names of all object types, such as buffer, query, and texture objects, must be generated using the corresponding **Gen*** commands. Trying to bind an object name not returned by a **Gen*** command will result in an **INVALID_OPERATION** error. This behavior is already the case for framebuffer, renderbuffer, and vertex array objects. Object types which have default objects (objects named zero), such as vertex array, framebuffer, and texture objects, may also bind the default object, even though it is not returned by **Gen***.

- Color index mode - No color index visuals are supplied by the window system-binding APIs such as GLX and WGL, so the default framebuffer is always in RGBA mode. All language and state related to color index mode vertex, rasterization, and fragment processing behavior is removed. **COLOR_INDEX** formats are also deprecated.

- OpenGL Shading Language versions 1.10 and 1.20. These versions of the shading language depend on many API features that have also been deprecated.

- **Begin / End** primitive specification - **Begin**, **End**, and **EdgeFlag*; Color*, **FogCoord*; Index*, **Normal3*, **SecondaryColor3*; **TexCoord*; **Vertex**; and all associated state. Vertex arrays and array drawing commands must be used to draw primitives. However, **VertexAttrib* and the current vertex attribute state are retained in order to provide default attribute values for disabled attribute arrays.

- Edge flags and fixed-function vertex processing - **ColorPointer, EdgeFlagPointer, FogCoordPointer, IndexPointer, NormalPointer, SecondaryColorPointer, TexCoordPointer, VertexPointer, EnableClientState, DisableClientState, and InterleavedArrays, ClientActiveTexture; Frustum, LoadIdentity, LoadMatrix, LoadTransposeMatrix, MatrixMode, MultMatrix, MultTransposeMatrix, Ortho, PopMatrix, PushMatrix, Rotate, Scale, and Translate; Enable/Disable targets **RESCALE_NORMAL**
and \texttt{NORMALIZE}; \texttt{TexGen}\textsuperscript{*} and \texttt{Enable/Disable} targets \texttt{TEXTUREGEN}_*; \texttt{Material}\textsuperscript{*}, \texttt{Light}\textsuperscript{*}, \texttt{LightModel}\textsuperscript{*}, and \texttt{ColorMaterial}, \texttt{ShadeModel}, and \texttt{Enable/Disable} targets \texttt{LIGHTING}, \texttt{VERTEX_PROGRAM_TWO-SIDE}, \texttt{LIGHTi}, and \texttt{COLOR_MATERIAL}; \texttt{ClipPlane}; and all associated fixed-function vertex array, multitexture, matrix and matrix stack, normal and texture coordinate, lighting, and clipping state. A vertex shader must be defined in order to draw primitives.

Language referring to edge flags in the current specification is modified as though all edge flags are \texttt{TRUE}.

Note that the \texttt{FrontFace} and \texttt{ClampColor} commands are \textbf{not} deprecated, as they still affect other non-deprecated functionality; however, the \texttt{ClampColor targets} \texttt{CLAMP_VERTEX_COLOR} and \texttt{CLAMP_FRAGMENT_COLOR} are deprecated.

- Client vertex and index arrays - all vertex array attribute and element array index pointers must refer to buffer objects. The default vertex array object (the name zero) is also deprecated. Calling \texttt{VertexAttribPointer} when no buffer object or no vertex array object is bound will generate a \texttt{INVALID_OPERATION} error, as will calling any array drawing command when no vertex array object is bound.

- Rectangles - \texttt{Rect}\textsuperscript{*}.

- Current raster position - \texttt{RasterPos}\textsuperscript{*} and \texttt{WindowPos}\textsuperscript{*}, and all associated state.

- Two-sided color selection - \texttt{Enable} target \texttt{VERTEX_PROGRAM_TWO-SIDE}; OpenGL Shading Language built-ins \texttt{gl_BackColor} and \texttt{gl_BackSecondaryColor}; and all associated state.

- Non-sprite points - \texttt{Enable/Disable} targets \texttt{POINT_SMOOTH} and \texttt{POINT_SPRITE}, and all associated state. Point rasterization is always performed as though \texttt{POINT_SPRITE} were enabled.

- Wide lines and line stipple - \texttt{LineWidth} is not deprecated, but values greater than 1.0 will generate an \texttt{INVALID_VALUE} error; \texttt{LineStipple} and \texttt{Enable/Disable} target \texttt{LINE_STIPPLE}, and all associated state.

- Quadrilateral and polygon primitives - vertex array drawing modes \texttt{POLYGON}, \texttt{QUADS}, and \texttt{QUAD_STRIP}, related descriptions of rasterization of non-triangle polygons, and all associated state.
E.2. DEPRECATED AND REMOVED FEATURES

• Separate polygon draw mode - **PolygonMode** face values of **FRONT** and **BACK**; polygons are always drawn in the same mode, no matter which face is being rasterized.

• Polygon Stipple - **PolygonStipple** and Enable/Disable target **POLYGON_-STIPPLE**, and all associated state.

• Pixel transfer modes and operations - all pixel transfer modes, including pixel maps, shift and bias, color table lookup, color matrix, and convolution commands and state, and all associated state and commands defining that state.

• Pixel drawing - **DrawPixels** and **PixelZoom**. However, the language describing pixel rectangles in section 3.7 is retained as it is required for **TexImage** and **ReadPixels**.

• Bitmaps - **Bitmap** and the **BITMAP** external format.

• Legacy OpenGL 1.0 pixel formats - the values 1, 2, 3, and 4 are no longer accepted as internal formats by **TexImage** or any other command taking an internal format argument. The initial internal format of a texel array is **RGBA** instead of **1**. **TEXTURE_COMPONENTS** is deprecated; always use **TEXTURE_INTERNAL_FORMAT**.

• Legacy pixel formats - all **ALPHA**, **LUMINANCE**, **LUMINANCE_ALPHA**, and **INTENSITY** external and internal formats, including compressed, floating-point, and integer variants; all references to luminance and intensity formats elsewhere in the specification, including conversion to and from those formats; and all associated state. including state describing the allocation or format of luminance and intensity texture or framebuffer components.

• Depth texture mode - **DEPTH_TEXTURE_MODE**. Section 3.8.16 is to be changed so that \( r \) is returned to texture samplers directly, and the OpenGL Shading Language 1.30 Specification is to be changed so that \((r, r, r, 1)\) is always returned from depth texture samplers in this case.

• Texture wrap mode **CLAMP** - **CLAMP** is no longer accepted as a value of texture parameters **TEXTURE_WRAP_S**, **TEXTURE_WRAP_T**, or **TEXTURE_WRAP_R**.

• Texture borders - the **border** value to **TexImage** must always be zero, or an **INVALID_VALUE** error is generated (section 3.8.3); all language in section 3.8 referring to nonzero border widths during texture image specification and texture sampling; and all associated state.
E.2. DEPRECATED AND REMOVED FEATURES

- Automatic mipmap generation - TexParameter* target GENERATE_-MIPMAP, and all associated state.

- Fixed-function fragment processing - AreTexturesResident, PrioritizeTextures, and TexParameter target TEXTURE_PRIORITY; TexEnv target TEXTURE_ENV, and all associated parameters; TexEnv target TEXTURE_-FILTER_CONTROL, and parameter name TEXTURE_LOD_BIAS; Enable targets of all dimensionalities (TEXTURE_1D, TEXTURE_2D, TEXTURE_3D, TEXTURE_1D_ARRAY, TEXTURE_2D_ARRAY, and TEXTURE_CUBE_MAP); Enable target COLOR_SUM; Enable target FOG, Fog, and all associated parameters; the implementation-dependent values MAX_TEXTURE_UNITS and MAX_TEXTURE_COORDS; and all associated state.

- Alpha test - AlphaFunc and Enable/Disable target ALPHA_TEST, and all associated state.

- Accumulation buffers - ClearAccum, and ACCUM_BUFFER_BIT is not valid as a bit in the argument to Clear (section 4.2.3); Accum; the ACCUM_*-BITS framebuffer state describing the size of accumulation buffer components; and all associated state.

  Window system-binding APIs such as GLX and WGL may choose to either not expose window configs containing accumulation buffers, or to ignore accumulation buffers when the default framebuffer bound to a GL context contains them.

- Pixel copying - CopyPixels (the comments also applying to CopyTexImage will be moved to section 3.8.4).

- Auxiliary color buffers, including AUXi targets of the default framebuffer.

- Context framebuffer size queries - RED_BITS, GREEN_BITS, BLUE_BITS, ALPHA_BITS, DEPTH_BITS, and STENCIL_BITS.

- Evaluators - Map*, EvalCoord*, MapGrid*, EvalMesh*, EvalPoint*, and all evaluator map enables, and all associated state.

- Selection and feedback modes - RenderMode, InitNames, PopName, PushName, LoadName, and SelectBuffer; FeedbackBuffer and PassThrough; and all associated state.

- Display lists - NewList, EndList, CallList, CallLists, ListBase, GenLists, IsList, and DeleteLists; all references to display lists and behavior when
E.2. DEPRECATED AND REMOVED FEATURES

compiling commands into display lists elsewhere in the specification; and all associated state.

- **Hints** - the PERSPECTIVE_CORRECTION_HINT, POINT_SMOOTH_HINT, FOG_HINT, and GENERATE_MIPMAP_HINT targets to Hint (section 5.4).

- **Attribute stacks** - PushAttrib, PushClientAttrib, PopAttrib, PopClientAttrib, the MAX_ATTRIB_STACK_DEPTH, MAX_CLIENT_ATTRIB_STACK_DEPTH, ATTRIB_STACK_DEPTH, and CLIENT_ATTRIB_STACK_DEPTH state, the client and server attribute stacks, and the values ALL_ATTRIB_BITS and CLIENT_ALL_ATTRIB_BITS.

- **Unified extension string** - EXTENSIONS target to GetString.

- **Token names and queries** - all token names and queries not otherwise mentioned above for deprecated state, as well as all query entry points where all valid targets of that query are deprecated state (chapter 6 and the state tables)
Appendix F

Version 3.0 and Before

OpenGL version 3.0, released on August 11, 2008, is the eighth revision since the original version 1.0. When using a full 3.0 context, OpenGL 3.0 is upward compatible with earlier versions, meaning that any program that runs with a 2.1 or earlier GL implementation will also run unchanged with a 3.0 GL implementation. OpenGL 3.0 context creation is done using a window system binding API, and on most platforms a new command, defined by extensions introduced along with OpenGL 3.0, must be called to create a 3.0 context. Calling the older context creation commands will return an OpenGL 2.1 context. When using a forward compatible context, many OpenGL 2.1 features are not supported.

Following are brief descriptions of changes and additions to OpenGL 3.0. Descriptions of changes and additions in earlier versions of OpenGL (versions 1.1, 1.2, 1.2.1, 1.3, 1.4, 1.5, 2.0, and 2.1) are omitted in this specification, but may be found in the OpenGL 3.0 Specification, available on the World Wide Web at URL http://www.opengl.org/registry/

F.1 New Features

New features in OpenGL 3.0, including the extension or extensions if any on which they were based, include:

- API support for the new texture lookup, texture format, and integer and unsigned integer capabilities of the OpenGL Shading Language 1.30 specification (GL_EXT_gpu_shader4).

- Conditional rendering (GL_NV_conditional_render).
F.2. DEPRECAITION MODEL

- Fine control over mapping buffer subranges into client space and flushing modified data (GL_APPLE_flush_buffer_range).

- Floating-point color and depth internal formats for textures and renderbuffers (GL_ARB_color_buffer_float, GL_NV_depth_buffer_float, GL_ARB_texture_float, GL_EXT_packed_float, and GL_EXT_texture_shared_exponent).

- Framebuffer objects (GL_EXT_framebuffer_object).

- Half-float (16-bit) vertex array and pixel data formats (GL_NV_half_float and GL_ARB_half_float_pixel).

- Multisample stretch blit functionality (GL_EXT_framebuffer_multisample and GL_EXT_framebuffer_blit).

- Non-normalized integer color internal formats for textures and renderbuffers (GL_EXT_texture_integer).

- One- and two-dimensional layered texture targets (GL_EXT_texture_array).

- Packed depth/stencil internal formats for combined depth+stencil textures and renderbuffers (GL_EXT_packed_depth_stencil).

- Per-color-attachment blend enables and color writemasks (GL_EXT_draw_buffers2).

- RGTC specific internal compressed formats (GL_EXT_texture_compression_rgtc).

- Single- and double-channel (R and RG) internal formats for textures and renderbuffers.

- Transform feedback (GL_EXT_transform_feedback).

- Vertex array objects (GL_APPLE_vertex_array_object).

- sRGB framebuffer mode (GL_EXT_framebuffer_sRGB)

F.2 Deprecation Model

OpenGL 3.0 introduces a deprecation model in which certain features may be marked as deprecated. The deprecation model is described in detail in appendix E, together with a summary of features deprecated in OpenGL 3.0.
F.3  CHANGED TOKENS

<table>
<thead>
<tr>
<th>New Token Name</th>
<th>Old Token Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPARE_REF_TO_TEXTURE</td>
<td>COMPARE_R_TO_TEXTURE</td>
</tr>
<tr>
<td>MAX_VARYING_COMPONENTS</td>
<td>MAX_VARYING_FLOATS</td>
</tr>
<tr>
<td>MAX_CLIP_DISTANCES</td>
<td>MAX_CLIP_PLANES</td>
</tr>
<tr>
<td>CLIP_DISTANCE[i]</td>
<td>CLIP_PLANE[i]</td>
</tr>
</tbody>
</table>

Table F.1: New token names and the old names they replace.

F.3 Changed Tokens

New token names are introduced to be used in place of old, inconsistent names. However, the old token names continue to be supported, for backwards compatibility with code written for previous versions of OpenGL. The new names, and the old names they replace, are shown in table F.1.

F.4 Change Log

Minor corrections to the OpenGL 3.0 Specification were made after its initial release.

Changes in the draft of September 23, 2008:

- Changed `ClearBuffer*` in section 4.2.3 to use `DEPTH` and `STENCIL` buffer names. Changed `GetFramebufferAttachmentParameteriv` in section 6.1.13 to accept only `DEPTH` and `STENCIL` to identify default framebuffer depth and stencil buffers, and only `DEPTH_ATTACHMENT` and `STENCIL_ATTACHMENT` to identify framebuffer object depth and stencil buffers (bug 3744).

Changes in the draft of September 18, 2008:

- Added missing close-brace to `ArrayElement` pseudocode in section 2.8 (bug 3897).

- Noted in section 2.15 that `BeginQuery` will generate an `INVALID_OPERATION` error when called with an existing query object name whose type does not match the specified `target` (bug 3712).

- Add description of `gl_ClipDistance` to shader outputs in section 2.11.8 and note that only one of `gl_ClipVertex` and `gl_ClipDistance` should be written by a shader (bug 3898).
• Changed `ClearBuffer*` in section 4.2.3 to indirect through the draw buffer state by specifying the buffer type and draw buffer number, rather than the attachment name; also changed to accept `DEPTH_BUFFER / DEPTH_ATTACHMENT` and `STENCIL_BUFFER / STENCIL_ATTACHMENT` interchangeably, to reduce inconsistency between clearing the default framebuffer and framebuffer objects. Likewise changed `GetFramebufferAttachmentParameteriv` in section 6.1.13 to accept `DEPTH_BUFFER / DEPTH_ATTACHMENT` and `STENCIL_BUFFER / STENCIL_ATTACHMENT` interchangeably (bug 3744).

• Add proper type suffix to query commands in tables 6.5 and 6.36 (Mark Kilgard).

• Update deprecation list in section E.2 to itemize deprecated state for two-sided color selection and include per-texture-unit LOD bias (bug 3735).

Changes in the draft of August 28, 2008:

• Sections 2.9, 2.9.3; tables 2.9, 2.10, and 6.8 - move buffer map/unmap calls into their own subsection and rewrite `MapBuffer` in terms of `MapBufferRange`. Add buffer state `BUFFER_ACCESS_FLAGS`, `BUFFER_MAP_OFFSET`, `BUFFER_MAP_LENGTH`. Make `MapBuffer` and `MapBufferRange` errors consistent (bug 3601).

• Section 2.10 - Extend `INVALID_OPERATION` error to any array pointer-setting command called to specify a client array while a vertex array object is bound, not just `VertexAttrib*Pointer` (bug 3696).

• Sections 2.14.1, 4.1.2, 4.2.1, and 4.3.3 - define initial state when a context is bound with no default framebuffer - null viewport and scissor region, draw buffer = read buffer = `NONE`, max viewport dims = max(display size - if any, max renderbuffer size). Viewport/scissor language added to the GLX and WGL create context extension specs as well (bug 2941).

• Section 2.17 - define “word-aligned” to be a multiple of 4 (e.g. 32 bits) (bug 3624).

• Section 6.1.9 - Moved `GetBufferParameteriv` query from section 6.1.3 and changed formal argument specifying the parameter name from `value` to `pname` (side effect of bug 3697).

• Section 6.1.13 - Moved `GetFramebufferAttachmentParameteriv` query from section 6.1.3. Querying framebuffer attachment parameters other than object
F.5 CREDITS AND ACKNOWLEDGEMENTS

type and name when no attachment is present is an INVALID_ENUM error. Querying texture parameters (level, cube map face, or layer) for a renderbuffer attachment is also an INVALID_ENUM error (note that this was allowed in previous versions of the extension but the return values were not specified; it should clearly be an error as are other parameters that don’t exist for the type of attachment present). Also reorganized the description of this command quite a bit to improve readability and remove redundancy and internal inconsistencies (bug 3697).

- Section 6.1.14 - Moved GetRenderbufferParameteriv query from section 6.1.3 (side effect of bug 3697).
- Appendix D.1 - add language to clarify that attachments to an object affect its reference count, and that object storage doesn’t go away until there are no references remaining (bug 3725).
- Appendix E.2 - remove TEXTURE_BORDER_COLOR and CLAMP_TO_BORDER mode from the deprecated feature list; they were put in by accident (bug 3750).
- Appendix F - Cite GL_EXT_texture_array instead of GL_EXT-geometry_shader4 as the source of 1D/2D array texture functionality. Fix a typo. Add change log relative to initial 3.0 spec release.

F.5 Credits and Acknowledgements

OpenGL 3.0 is the result of the contributions of many people and companies. Members of the Khronos OpenGL ARB Working Group during the development of OpenGL 3.0, including the company that they represented at the time of their contributions, follow. Some major contributions made by individuals are listed together with their name, including specific functionality developed in the form of new ARB extensions together with OpenGL 3.0. In addition, many people participated in developing earlier vendor and EXT extensions on which the OpenGL 3.0 functionality is based in part; those individuals are listed in the respective extension specifications in the OpenGL Extension Registry.

Aaftab Munshi, Apple
Alain Bouchard, Matrox
Alexis Mather, AMD (Chair, ARB Marketing TSG)
Andreas Wolf, AMD
Avi Shapira, Graphic Remedy
Barthold Lichtenbelt, NVIDIA (Chair, Khronos OpenGL ARB Working Group)
Benjamin Lipchak, AMD
Benji Bowman, Imagination Technologies
Bill Licea-Kane, AMD (Chair, ARB Shading Language TSG)
Bob Beretta, Apple
Brent Insko, Intel
Brian Paul, Tungsten Graphics
Bruce Merry, ARM (Detailed specification review)
Cass Everitt, NVIDIA
Chris Dodd, NVIDIA
Daniel Horowitz, NVIDIA
Daniel Koch, TransGaming (Framebuffer objects, half float vertex formats, and instanced rendering)
Daniel Omachi, Apple
Dave Shreiner, ARM
Eric Boumaour, AMD
Eskil Steenberg, Obsession
Evan Hart, NVIDIA
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The ARB gratefully acknowledges administrative support by the members of Gold Standard Group, including Andrew Riegel, Elizabeth Riegel, Glenn Fredericks, and Michelle Clark, and technical support from James Riordon, webmaster of Khronos.org and OpenGL.org.
Appendix G

Version 3.1

OpenGL version 3.1, released on March 24, 2009, is the ninth revision since the original version 1.0.

Unlike earlier versions of OpenGL, OpenGL 3.1 is not upward compatible with earlier versions. The commands and interfaces identified as deprecated in OpenGL 3.0 (see appendix F) have been removed from OpenGL 3.1 entirely, with the following exception:

- Wide lines have not been removed, and calling `LineWidth` with values greater than 1.0 is not an error.

Implementations may restore such removed features using the `GL_ARB_compatibility` extension discussed in section G.2.

Following are brief descriptions of changes and additions to OpenGL 3.1.

G.1 New Features

New features in OpenGL 3.1, including the extension or extensions if any on which they were based, include:

- Support for OpenGL Shading Language 1.30 and 1.40.
- Instanced rendering with a per-instance counter accessible to vertex shaders (`GL_ARB_draw_instanced`).
- Data copying between buffer objects (`GL_ARB_copy_buffer`).
- Primitive restart (`GL_NV_primitive_restart`). Because client enable/disable no longer exists in OpenGL 3.1, the `PRIMITIVE_RESTART`
state has become server state, unlike the NV extension where it is client state. As a result, the numeric values assigned to PRIMITIVE_RESTART and PRIMITIVE_RESTART_INDEX differ from the NV versions of those tokens.

- At least 16 texture image units must be accessible to vertex shaders, in addition to the 16 already guaranteed to be accessible to fragment shaders.

- Texture buffer objects (GL_ARB_texture_buffer_object).
- Rectangular textures (GL_ARB_texture_rectangle).
- Uniform buffer objects (GL_ARB_uniform_buffer_object).
- Signed normalized texture component formats.

### G.2 Deprecation Model

The features marked as deprecated in OpenGL 3.0 (see section E) have been removed from OpenGL 3.1 (with the exception of line widths greater than one, which are retained).

As described by the deprecation model, features removed from OpenGL 3.0 have been moved into the new extension GL_ARB_compatibility. If an implementation chooses to provide this extension, it restores all features deprecated by OpenGL 3.0 and removed from OpenGL 3.1. This extension may only be provided in an OpenGL 3.1 or later context version.

Because of the complexity of describing this extension relative to the OpenGL 3.1 core specification, it is not written up as a separate document, unlike other extensions in the extension registry. Instead, an alternate version of this specification document has been generated with the deprecated material still present, but marked in a distinct color.

No additional features are deprecated in OpenGL 3.1.

### G.3 Change Log

Changes in the specification update of May 28, 2009:

- Update MAX_CLIP_DISTANCES from 6 to 8 in section 2.20 and table 6.41, to match GLSL (bug 4803).

- Accept null pointers in CompressedTexImage* (section 3.8.5) and treat them the same as for the corresponding TexImage* commands (bug 4863).
• Relax error conditions when specifying RGTC format texture images (section 3.8.4) and subimages (section 3.8.5) so that non-power-of-two RGTC images may be specified (also see section C.1), and edits to partial tiles at the edge of such an image made (bug 4856).

• Relaxed texture magnification switch-over point calculation in section 3.8.12 (bug 4392).

• Clarify initial value of stencil value masks in section 4.1.4 and table 6.20 (bug 4378).

• Change FramebufferTextureLayer in section 4.4.2 to generate INVALID_VALUE for negative layer only if texture is non-zero (bug 4084).

• Clarify RenderbufferStorageMultisample language in section 4.4.2 to allow, but not require creation of multisampled integer renderbuffers with more one sample (bug 4396).

• Added language to section 6.1.4 disallowing data-type format mismatches between internal and external texture formats in GetTexImage (bug 4163).

• Change initial value of FRAMEBUFFER_ATTACHMENT_TEXTURE_CUBE_MAP_FACE in table 6.25 to NONE (bug 4407).

• Brought extension list in appendix K.3 up to date and correctly described extensions introduced along with OpenGL 3.0 and OpenGL 3.1 which implement subsets of new functionality in those versions to enable older hardware.

• Added missing contributors to the OpenGL 3.1 contributor list.

G.4 Credits and Acknowledgements

OpenGL 3.1 is the result of the contributions of many people and companies. Members of the Khronos OpenGL ARB Working Group during the development of OpenGL 3.1, including the company that they represented at the time of their contributions, follow. Some major contributions made by individuals are listed together with their name, including specific functionality developed in the form of new ARB extensions together with OpenGL 3.1. In addition, many people participated in developing earlier vendor and EXT extensions on which the OpenGL 3.1 functionality is based in part; those individuals are listed in the respective extension specifications in the OpenGL Extension Registry.
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The ARB gratefully acknowledges administrative support by the members of Gold Standard Group, including Andrew Riegel, Elizabeth Riegel, Glenn Fredericks, and Michelle Clark, and technical support from James Riordon, webmaster of Khronos.org and OpenGL.org.
Appendix H

Version 3.2

OpenGL version 3.2, released on August 3, 2009, is the tenth revision since the original version 1.0.

Separate versions of the OpenGL 3.2 Specification exist for the core and compatibility profiles described in appendix E, respectively subtitled the “Core Profile” and the “Compatibility Profile”. This document describes the Core Profile. An OpenGL 3.2 implementation must be able to create a context supporting the core profile, and may also be able to create a context supporting the compatibility profile.

Material specific to the compatibility profile specification is marked in a distinct color to clearly call out differences between the two profiles.

The OpenGL 3.2 core profile is upward compatible with OpenGL 3.1, but not with earlier versions (see appendices G and F).

The OpenGL 3.2 compatibility profile is upward compatible with the combination of OpenGL 3.1 and the GL_ARB_compatibility extension, as well as with all earlier versions of OpenGL.

Following are brief descriptions of changes and additions to OpenGL 3.2.

H.1 New Features

New features in OpenGL 3.2, including the extension or extensions if any on which they were based, include:

- Introduction of core and compatibility profiles, superseding the GL_ARB_compatibility extension introduced with OpenGL 3.1.

- Support for OpenGL Shading Language 1.50.
H.2. DEPRECIATION MODEL

In addition to restoring features removed from OpenGL 3.1 core, the compatibility profile defines some additional interactions between those features and new features introduced by OpenGL 3.2.

The following features are newly deprecated by the OpenGL 3.2 core profile:

- Global component limit query - the implementation-dependent values `MAX_VARYING_COMPONENTS` and `MAX_VARYING_FLOATS`.

No features are deprecated by the OpenGL 3.2 compatibility profile.

H.3 Changed Tokens

New token names are introduced to be used in place of old, less general names. However, the old token names continue to be supported, for backwards compatibility with code written for previous versions of OpenGL. The new names, and the old names they replace, are shown in table H.1.
Minor corrections to the OpenGL 3.2 Specification were made after its initial release in the update of December 7, 2009:

- Clean up description of GL command syntax in section 2.3, generalize the list of object types in the introduction to section 2.5 instead of enumerating them all redundantly, fix `BindBuffer` (section 2.9.1), `BeginQuery` (section 2.15), and `BindTexture` (section 3.8.1) to only generate errors for user generated names in the core profile, increase minimum number of clip half-spaces to 8 in section 2.20, improve formatting and correct column heading in tables 6.14 and 6.15, and a variety of minor editorial corrections not enumerated here (Bug 5761).

- Remove “just as if they were unused” from description of names generated by `GenVertexArrays`, `GenFramebuffers`, and `GenRenderbuffers` in sections 2.10, 4.4.1, and 4.4.2 (Bug 5201).

- Moved error language resulting from trying to put client pointers into VAOs from section 2.10 to section 2.8 (Bug 3975). This results in a forward reference, unfortunately.

- Remove reference to borders from texel fetch language in section 2.11.8 of the core specification (Bug 5343).

- Remove `INVALID_VALUE` error when passing a program object to `TransformFeedbackVaryings` in section 2.11.7 (Bug 5661).

- Changed number of query types from two to three in section 2.15 (Bug 5624).

- Change flat-shading source value description from “generic attribute” to “varying” in sections 3.5.1 and 3.6.1 (Bug 5359).

- Remove leftover references in core spec sections 3.8.5 and 6.1.3 to deprecated texture border state (Bug 5579). Still need to fix gl3.h accordingly.
• Fix typo in second paragraph of section 3.8.8 (Bug 5625).

• Simplify and clean up equations in the coordinate wrapping and mipmapping calculations of section 3.8.11, especially in the core profile where wrap mode CLAMP does not exist (Bug 5615).

• Fix computation of \( u(x, y) \) and \( v(x, y) \) in scale factor calculations of section 3.8.11 for rectangular textures (Bug 5700).

• Restructure definition of texture completeness in section 3.8.14 to separate mipmap consistency from filter requirements and cover new texture target types, and simplify how completeness applies to texture fetches (section 2.11.8) and lookups (sections 2.11.8 and 3.9.2) (Bugs 4264, 5749).

• Update sampling language in sections 3.8.14, 2.11.8, and 3.9.2 to not require texture completeness when non-mipmapped access to the texture is being done (Bug 4264, based on ES bugs 4282 and 3499).

• Add fixed sample location state for multisample textures to section 3.8.15 (Bug 5454).

• Don’t use the sign of the input component in the description of dithering in section 4.1.9 (Bug 5594).

• Change error condition for certain invalid buffers to DrawBuffers in section 4.2.1 from INVALID_OPERATION to INVALID_ENUM (Bug 5576).

• Clarify error conditions in section 4.2.3 when the clear mask is zero or contains invalid bits (Bug 5567).

• Change BlitFramebuffer in section 4.3.2 so format conversion is supported only within the three equivalence classes of fixed-point and floating point buffers, unsigned integer buffers, and signed integer buffers (Bug 5577).

• Remove a reference to unreachable INVALID_OPERATION errors from the core profile only in section 6.1.2 (Bug 5365).

• Specify that compressed texture component type queries in section 6.1.3 return how components are interpreted after decompression (Bug 5453).

• Increase value of MAX_UNIFORM_BUFFER_BINDINGS and MAX_COMBINED_UNIFORM_BLOCKS in table 6.49 from 24 to 36 to reflect addition of geometry shaders (Bug 5607).

• Update sharing rule 2 in appendix D.3.3 to read sensibly (Bug 5397).
• Update sharing rule 4 in appendix D.3.3 to cover the case where an object is only attached or bound in a single place, clarify comments about transform feedback, and state that reattachment is required to guarantee seeing changes made in other contexts, but does not preclude implementations from making changes visible without reattachment (Bugs 5546, 5777).

Changes in the specification for public release on August 3, 2009:

• Public release of OpenGL 3.2.

H.5 Credits and Acknowledgements

OpenGL 3.2 is the result of the contributions of many people and companies. Members of the Khronos OpenGL ARB Working Group during the development of OpenGL 3.2, including the company that they represented at the time of their contributions, follow. Some major contributions made by individuals are listed together with their name, including specific functionality developed in the form of new ARB extensions together with OpenGL 3.1. In addition, many people participated in developing earlier vendor and EXT extensions on which the OpenGL 3.1 functionality is based in part; those individuals are listed in the respective extension specifications in the OpenGL Extension Registry.

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The ARB gratefully acknowledges administrative support by the members of
Gold Standard Group, including Andrew Riegel, Elizabeth Riegel, Glenn Freder-
icks, and Michelle Clark, and technical support from James Riordon, webmaster
of Khronos.org and OpenGL.org.
Appendix I

Version 3.3

OpenGL version 3.3, released on March 11, 2010 is the eleventh revision since the original version 1.0.

Separate versions of the OpenGL 3.3 Specification exist for the core and compatibility profiles described in appendix E, respectively subtitled the “Core Profile” and the “Compatibility Profile”. This document describes the Core Profile. An OpenGL 3.3 implementation must be able to create a context supporting the core profile, and may also be able to create a context supporting the compatibility profile.

Material specific to the compatibility profile specification is marked in a distinct color to clearly call out differences between the two profiles.

The OpenGL 3.3 compatibility and core profiles are upward compatible with the OpenGL 3.2 compatibility and core profiles, respectively (see appendix H).

Following are brief descriptions of changes and additions to OpenGL 3.3.

I.1 New Features

New features in OpenGL 3.3, including the extension or extensions if any on which they were based, include:

- Support for OpenGL Shading Language 3.30, including built-in functions for getting and setting the bit encoding for floating-point values (GL_ARB_shader_bit_encoding - this extension only affects the shading language, not the API).

- New blending functions whereby a fragment shader may output two colors, one of which is treated as the source color, and the other used as a blend-
I.2. DEPRECATION MODEL

- A method to pre-assign attribute locations to named vertex shader inputs and color numbers to named fragment shader outputs. This allows applications to globally assign a particular semantic meaning, such as diffuse color or vertex normal, to a particular attribute location without knowing how that attribute will be named in any particular shader (GL_ARB_explicit_attrib_location).

- Simple boolean occlusion queries, which are often sufficient in preference to more general counter-based queries (GL_ARB_occlusion_query2).

- Sampler objects, which separate sampler state from texture image data. Samplers may be bound to texture units to supplant the bound texture’s sampling state, and a single sampler may be bound to more than one texture unit simultaneously, allowing different textures to be accessed with a single set of shared sampling parameters, or the same texture image data to be sampled with different sampling parameters (GL_ARB_sampler_objects).

- A new texture format for unsigned 10.10.10.2 integer textures (GL_ARB_texture_rgb10_a2ui).

- A mechanism to swizzle the components of a texture before they are returned to the shader (GL_ARB_texture_swizzle).

- A query object-based mechanism to determine the amount of time it takes to fully complete a set of GL commands without stalling the rendering pipeline (GL_ARB_timer_query).

- Ability to specify an array “divisor” for generic vertex array attributes, which when non-zero specifies that the attribute is instanced. An instanced attribute does not advance per-vertex as usual, but rather after every conceptual draw calls (GL_ARB_instanced_arrays).

- Two new vertex attribute data formats, signed 2.10.10.10 and unsigned 2.10.10.10 (GL_ARB_vertex_type_2_10_10_10_rev).

I.2 Deprecation Model

No new features are deprecated by OpenGL 3.3. Features deprecated by OpenGL 3.2 remain deprecated, but have not yet been removed.
I.3 Change Log

I.4 Credits and Acknowledgements

OpenGL 3.3 is the result of the contributions of many people and companies. Members of the Khronos OpenGL ARB Working Group during the development of OpenGL 3.3, including the company that they represented at the time of their contributions, follow. Some major contributions made by individuals are listed together with their name, including specific functionality developed in the form of new ARB extensions together with OpenGL 3.2. In addition, many people participated in developing earlier vendor and EXT extensions on which the OpenGL 3.3 functionality is based in part; those individuals are listed in the respective extension specifications in the OpenGL Extension Registry.

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The ARB gratefully acknowledges administrative support by the members of Gold Standard Group, including Andrew Riegel, Elizabeth Riegel, Glenn Fredericks, and Michelle Clark, and technical support from James Riordon, webmaster of Khronos.org and OpenGL.org.
Appendix J

Version 4.0

OpenGL version 4.0, released on March 11, 2010, is the twelfth revision since the original version 1.0.

Separate versions of the OpenGL 4.0 Specification exist for the core and compatibility profiles described in appendix E, respectively subtitled the “Core Profile” and the “Compatibility Profile”. This document describes the Core Profile. An OpenGL 4.0 implementation must be able to create a context supporting the core profile, and may also be able to create a context supporting the compatibility profile.

Material specific to the compatibility profile specification is marked in a distinct color to clearly call out differences between the two profiles.

The OpenGL 4.0 compatibility and core profiles are upward compatible with the OpenGL 3.3 compatibility and core profiles, respectively (see appendix I).

Following are brief descriptions of changes and additions to OpenGL 4.0.

J.1 New Features

New features in OpenGL 4.0, including the extension or extensions if any on which they were based, include:

- Support for OpenGL Shading Language 4.00, including new fragment shader texture functions (textureLOD) that return the results of automatic level-of-detail computations that would be performed if a texture lookup were performed (GL_ARB_texture_query_lod - this extension only affects the shading language, not the API).

- Ability to set individual blend equations and blend functions for each color output (GL_ARB_draw_buffers_blend).
J.1. NEW FEATURES

- Mechanism for supplying the arguments to a DrawArraysInstanced or DrawElementsInstancedBaseVertex drawing command from buffer object memory (GL_ARB_draw_indirect).

- Many new features in OpenGL Shading Language 4.00 and related APIs to support capabilities of current generation GPUs (GL_ARB_gpu_shader5 - see that extension specification for a detailed summary of the features).

- Support for double-precision floating-point uniforms, including vectors and matrices, as well as double-precision floating-point data types in shaders (GL_ARB_gpu_shader_fp64).

- Ability to explicitly request that an implementation use a minimum number of unique set of fragment computation inputs when multisampling a pixel (GL_ARB_sample_shading).

- Support for “indirect subroutine calls”, where a single shader can include many subroutines and dynamically select through the API which subroutine is called from each call site (GL_ARB_shader_subroutine).

- New tessellation stages and two new corresponding shader types, tessellation control and tessellation evaluation shaders, operating on patches (fixed-sized collections of vertices) (GL_ARB_tessellation_shader).


- Cube map array textures, 2-dimensional array textures that may contain many cube map layers. Each cube map layer is a unique cube map image set (GL_ARB_texture_cube_map_array).

- New texture functions (textureGather) that determine the 2x2 footprint used for linear filtering in a texture lookup, and return a vector consisting of the first component from each of the four texels in the footprint (GL_ARB_texture_gather).

- Additional transform feedback functionality including
  - transform feedback objects which encapsulate transform feedback-related state;
  - the ability to pause and resume transform feedback operations; and
  - the ability to draw primitives captured in transform feedback mode without querying the captured primitive count.
J.2 DEPRECATION MODEL

(GL_ARB_transform_feedback2).

- Additional transform feedback functionality including increased flexibility in how vertex attributes can be written to buffer objects and new support for multiple separate vertex streams (GL_ARB_transform_feedback3).

J.2 Deprecation Model

No new features are deprecated by OpenGL 4.0. Features deprecated by OpenGL 3.3 remain deprecated, but have not yet been removed.

J.3 Change Log

J.4 Credits and Acknowledgements

OpenGL 4.0 is the result of the contributions of many people and companies. Members of the Khronos OpenGL ARB Working Group during the development of OpenGL 4.0, including the company that they represented at the time of their contributions, follow. Some major contributions made by individuals are listed together with their name, including specific functionality developed in the form of new ARB extensions together with OpenGL 3.2. In addition, many people participated in developing earlier vendor and EXT extensions on which the OpenGL 4.0 functionality is based in part; those individuals are listed in the respective extension specifications in the OpenGL Extension Registry.

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J.4. CREDITS AND ACKNOWLEDGEMENTS

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The ARB gratefully acknowledges administrative support by the members of Gold Standard Group, including Andrew Riegel, Elizabeth Riegel, Glenn Fredericks, and Michelle Clark, and technical support from James Riordon, webmaster of Khronos.org and OpenGL.org.
Appendix K

Extension Registry, Header Files, and ARB Extensions

K.1 Extension Registry

Many extensions to the OpenGL API have been defined by vendors, groups of vendors, and the OpenGL ARB. In order not to compromise the readability of the GL Specification, such extensions are not integrated into the core language; instead, they are made available online in the OpenGL Extension Registry, together with extensions to window system binding APIs, such as GLX and WGL, and with specifications for OpenGL, GLX, and related APIs.

Extensions are documented as changes to a particular version of the Specification. The Registry is available on the World Wide Web at URL

http://www.opengl.org/registry/

K.2 Header Files

Historically, C and C++ source code calling OpenGL was to include a single header file, <GL/gl.h>. In addition to the core OpenGL API, the APIs for all extensions provided by an implementation were defined in this header.

When platforms became common where the OpenGL SDK (library and header files) were not necessarily obtained from the same source as the OpenGL driver, such as Microsoft Windows and Linux, <GL/gl.h> could not always be kept in sync with new core API versions and extensions supported by drivers. At this time the OpenGL ARB defined a new header, <GL/glext.h>, which could be obtained directly from the OpenGL Extension Registry (see section K.1). The
combination of `<GL/gl.h>` and `<GL/glext.h>` always defines all APIs for all profiles of the latest OpenGL version, as well as for all extensions defined in the Registry.

`<GL3/gl3.h>` defines APIs for the core profile of OpenGL, together with ARB extensions compatible with the core profile. It does not include APIs for features only in the compatibility profile or for other extensions.

`<GL3/gl3ext.h>` defines APIs for additional ARB, EXT, and vendor extensions compatible with the core profile, but not defined in `<GL3/gl3.h>`. Most older extensions are not compatible with the core profile.

Applications using the compatibility profile (see appendices I and E) should `#include` the traditional `<GL/gl.h>` and `<GL/glext.h>` headers.

Applications using the core profile should `#include` the new `<GL3/gl3.h>` and `<GL3/gl3ext.h>` headers introduced with OpenGL 3.1.

By using `<GL3/gl3.h>` and `<GL3/gl3ext.h>`, instead of the legacy `<GL/gl.h>` and `<GL/glext.h>`, newly developed applications are given increased protection against accidentally using a “legacy” feature that has been removed from the core profile. This can assist in developing applications on a GL implementation that supports the compatibility profile when the application is also intended to run on other platforms supporting only the core profile.

Developers should always be able to download `<GL3/gl3.h>` and `<GL3/gl3ext.h>` from the Registry, with these headers replacing, or being used in place of older versions that may be provided by a platform SDK.

### K.3 ARB Extensions

OpenGl extensions that have been approved by the OpenGL Architectural Review Board (ARB) are summarized in this section. ARB extensions are not required to be supported by a conformant OpenGL implementation, but are expected to be widely available; they define functionality that is likely to move into the required feature set in a future revision of the specification.

#### K.3.1 Naming Conventions

To distinguish ARB extensions from core OpenGL features and from vendor-specific extensions, the following naming conventions are used:

- A unique *name string* of the form "GL_ARB_name" is associated with each extension. If the extension is supported by an implementation, this string will be among the `EXTENSIONS` strings returned by `GetStringi`, as described in section 6.1.5.
K.3. ARB EXTENSIONS

- All functions defined by the extension will have names of the form FunctionARB.

- All enumerants defined by the extension will have names of the form NAME_ARB.

- In addition to OpenGL extensions, there are also ARB extensions to the related GLX and WGL APIs. Such extensions have name strings prefixed by "GLX_" and "WGL_" respectively. Not all GLX and WGL ARB extensions are described here, but all such extensions are included in the registry.

K.3.2 Promoting Extensions to Core Features

ARB extensions can be promoted to required core features in later revisions of OpenGL. When this occurs, the extension specifications are merged into the core specification. Functions and enumerants that are part of such promoted extensions will have the ARB affix removed.

GL implementations of such later revisions should continue to export the name strings of promoted extensions in the EXTENSIONS strings and continue to support the ARB-affixed versions of functions and enumerants as a transition aid.

For descriptions of extensions promoted to core features in OpenGL 1.3 and beyond, see the corresponding version of the OpenGL specification, or the descriptions of that version in version-specific appendices to later versions of the specification.

K.3.3 Multitexture

The name string for multitexture is GL_ARB_multitexture. It was promoted to a core feature in OpenGL 1.3.

K.3.4 Transpose Matrix

The name string for transpose matrix is GL_ARB_transpose_matrix. It was promoted to a core feature in OpenGL 1.3.

K.3.5 Multisample

The name string for multisample is GL_ARB_multisample. It was promoted to a core feature in OpenGL 1.3.
K.3.6 Texture Add Environment Mode

The name string for texture add mode is GL_ARB_texture_env_add. It was promoted to a core feature in OpenGL 1.3.

K.3.7 Cube Map Textures

The name string for cube mapping is GL_ARB_texture_cube_map. It was promoted to a core feature in OpenGL 1.3.

K.3.8 Compressed Textures

The name string for compressed textures is GL_ARB_texture_compression. It was promoted to a core feature in OpenGL 1.3.

K.3.9 Texture Border Clamp

The name string for texture border clamp is GL_ARB_texture_border_clamp. It was promoted to a core feature in OpenGL 1.3.

K.3.10 Point Parameters

The name string for point parameters is GL_ARB_point_parameters. It was promoted to a core feature in OpenGL 1.4.

K.3.11 Vertex Blend

Vertex blending replaces the single model-view transformation with multiple vertex units. Each unit has its own transform matrix and an associated current weight. Vertices are transformed by all the enabled units, scaled by their respective weights, and summed to create the eye-space vertex. Normals are similarly transformed by the inverse transpose of the model-view matrices.

The name string for vertex blend is GL_ARB_vertex_blend.

K.3.12 Matrix Palette

Matrix palette extends vertex blending to include a palette of model-view matrices. Each vertex may be transformed by a different set of matrices chosen from the palette.

The name string for matrix palette is GL_ARB_matrix_palette.
K.3.13 Texture Combine Environment Mode

The name string for texture combine mode is GL_ARB_texture_env_combine. It was promoted to a core feature in OpenGL 1.3.

K.3.14 Texture Crossbar Environment Mode

The name string for texture crossbar is GL_ARB_texture_env_crossbar. It was promoted to a core feature in OpenGL 1.4.

K.3.15 Texture Dot3 Environment Mode

The name string for DOT3 is GL_ARB_texture_env_dot3. It was promoted to a core feature in OpenGL 1.3.

K.3.16 Texture Mirrored Repeat

The name string for texture mirrored repeat is GL_ARB_texture_mirror repeating. It was promoted to a core feature in OpenGL 1.4.

K.3.17 Depth Texture

The name string for depth texture is GL_ARB_depth_texture. It was promoted to a core feature in OpenGL 1.4.

K.3.18 Shadow

The name string for shadow is GL_ARB_shadow. It was promoted to a core feature in OpenGL 1.4.

K.3.19 Shadow Ambient

Shadow ambient extends the basic image-based shadow functionality by allowing a texture value specified by the TEXTURE_COMPARE_FAIL_VALUE_ARB texture parameter to be returned when the texture comparison fails. This may be used for ambient lighting of shadowed fragments and other advanced lighting effects.

The name string for shadow ambient is GL_ARB_shadow_ambient.

K.3.20 Window Raster Position

The name string for window raster position is GL_ARB_window_pos. It was promoted to a core feature in OpenGL 1.4.
K.3.21 Low-Level Vertex Programming

Application-defined vertex programs may be specified in a new low-level programming language, replacing the standard fixed-function vertex transformation, lighting, and texture coordinate generation pipeline. Vertex programs enable many new effects and are an important first step towards future graphics pipelines that will be fully programmable in an unrestricted, high-level shading language.

The name string for low-level vertex programming is GL_ARB_vertex_program.

K.3.22 Low-Level Fragment Programming

Application-defined fragment programs may be specified in the same low-level language as GL_ARB_vertex_program, replacing the standard fixed-function vertex texturing, fog, and color sum operations.

The name string for low-level fragment programming is GL_ARB_fragment_program.

K.3.23 Buffer Objects

The name string for buffer objects is GL_ARB_vertex_buffer_object. It was promoted to a core feature in OpenGL 1.5.

K.3.24 Occlusion Queries

The name string for occlusion queries is GL_ARB_occlusion_query. It was promoted to a core feature in OpenGL 1.5.

K.3.25 Shader Objects

The name string for shader objects is GL_ARB_shader_objects. It was promoted to a core feature in OpenGL 2.0.

K.3.26 High-Level Vertex Programming

The name string for high-level vertex programming is GL_ARB_vertex_shader. It was promoted to a core feature in OpenGL 2.0.

K.3.27 High-Level Fragment Programming

The name string for high-level fragment programming is GL_ARB_fragment_shader. It was promoted to a core feature in OpenGL 2.0.
K.3.28 OpenGL Shading Language

The name string for the OpenGL Shading Language is GL_ARB_shading_language_100. The presence of this extension string indicates that programs written in version 1 of the Shading Language are accepted by OpenGL. It was promoted to a core feature in OpenGL 2.0.

K.3.29 Non-Power-Of-Two Textures

The name string for non-power-of-two textures is GL_ARB_texture_non_power_of_two. It was promoted to a core feature in OpenGL 2.0.

K.3.30 Point Sprites

The name string for point sprites is GL_ARB_point_sprite. It was promoted to a core feature in OpenGL 2.0.

K.3.31 Fragment Program Shadow

Fragment program shadow extends low-level fragment programs defined with GL_ARB_fragment_program to add shadow 1D, 2D, and 3D texture targets, and remove the interaction with GL_ARB_shadow.

The name string for fragment program shadow is GL_ARB_fragment_program_shadow.

K.3.32 Multiple Render Targets

The name string for multiple render targets is GL_ARB_draw_buffers. It was promoted to a core feature in OpenGL 2.0.

K.3.33 Rectangular Textures

Rectangular textures define a new texture target TEXTURE_RECTANGLE_ARB that supports 2D textures without requiring power-of-two dimensions. Rectangular textures are useful for storing video images that do not have power-of-two sizes (POTS). Resampling artifacts are avoided and less texture memory may be required. They are also useful for shadow maps and window-space texturing. These textures are accessed by dimension-dependent (aka non-normalized) texture coordinates.

Rectangular textures are a restricted version of non-power-of-two textures. The differences are that rectangular textures are supported only for 2D; they require a new texture target; and the new target uses non-normalized texture coordinates.
The name string for texture rectangles is GL_ARB_texture_rectangle. It was promoted to a core feature in OpenGL 3.1.

**K.3.34 Floating-Point Color Buffers**

Floating-point color buffers can represent values outside the normal \([0, 1]\) range of colors in the fixed-function OpenGL pipeline. This group of related extensions enables controlling clamping of vertex colors, fragment colors throughout the pipeline, and pixel data read back to client memory, and also includes WGL and GLX extensions for creating frame buffers with floating-point color components (referred to in GLX as framebuffer configurations, and in WGL as pixel formats).

The name strings for floating-point color buffers are GL_ARB_color_buffer_float, GLX_ARB_fbconfig_float, and WGL_ARB_pixel_format_float. GL_ARB_color_buffer_float was promoted to a core feature in OpenGL 3.0.

**K.3.35 Half-Precision Floating Point**

This extension defines the representation of a 16-bit floating point data format, and a corresponding type argument which may be used to specify and read back pixel and texture images stored in this format in client memory. Half-precision floats are smaller than full precision floats, but provide a larger dynamic range than similarly sized (short) data types.

The name string for half-precision floating point is GL_ARB_half_float_pixel. It was promoted to a core feature in OpenGL 3.0.

**K.3.36 Floating-Point Textures**

Floating-point textures stored in both 32- and 16-bit formats may be defined using new internalformat arguments to commands which specify and read back texture images.

The name string for floating-point textures is GL_ARB_texture_float. It was promoted to a core feature in OpenGL 3.0.

**K.3.37 Pixel Buffer Objects**

The buffer object interface is expanded by adding two new binding targets for buffer objects, the pixel pack and unpack buffers. This permits buffer objects to be used to store pixel data as well as vertex array data. Pixel-drawing and -reading commands using data in pixel buffer objects may operate at greatly improved performance compared to data in client memory.
The name string for pixel buffer objects is `GL_ARB_pixel_buffer_object`. It was promoted to a core feature in OpenGL 2.1.

**K.3.38 Floating-Point Depth Buffers**

The name string for floating-point depth buffers is `GL_ARB_depth_buffer_float`. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier `GL_NV_depth_buffer_float` extension, and is provided to enable this functionality in older drivers.

**K.3.39 Instanced Rendering**

The name string for instanced rendering is `GL_ARB_draw_instanced`. It was promoted to a core feature in OpenGL 3.1.

**K.3.40 Framebuffer Objects**

The name string for framebuffer objects is `GL_ARB_framebuffer_object`. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier `GL_EXT_framebuffer_object`, `GL_EXT_framebuffer_multisample`, and `GL_EXT_framebuffer_blit` extensions, and is provided to enable this functionality in older drivers.

**K.3.41 sRGB Framebuffers**

The name string for sRGB framebuffers is `GL_ARB_framebuffer_sRGB`. It was promoted to a core feature in OpenGL 3.0. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier `GL_EXT_framebuffer_sRGB` extension, and is provided to enable this functionality in older drivers.

To create sRGB format surface for use on display devices, an additional pixel format (config) attribute is required in the window system integration layer. The name strings for the GLX and WGL sRGB pixel format interfaces are `GLX_ARB_framebuffer_sRGB` and `WGL_ARB_framebuffer_sRGB` respectively.

**K.3.42 Geometry Shaders**

This extension defines a new shader type called a *geometry shader*. Geometry shaders are run after vertices are transformed, but prior to the remaining fixed-function vertex processing, and may generate new vertices for, or remove vertices from the primitive assembly process.
The name string for geometry shaders is GL_ARB_geometry_shader4.

K.3.43 Half-Precision Vertex Data

The name string for half-precision vertex data GL_ARB_half_float_vertex. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier GL_NV_half_float extension, and is provided to enable this functionality in older drivers.

K.3.44 Instanced Rendering

This instanced rendering interface is a less-capable form of GL_ARB_draw_instanced which can be supported on older hardware.

The name string for instanced rendering is GL_ARB_instanced_arrays.

K.3.45 Flexible Buffer Mapping

The name string for flexible buffer mapping is GL_ARB_map_buffer_range. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier GL_APPLE_flush_buffer_range extension, and is provided to enable this functionality in older drivers.

K.3.46 Texture Buffer Objects

The name string for texture buffer objects is GL_ARB_texture_buffer_object. It was promoted to a core feature in OpenGL 3.1.

K.3.47 RGTC Texture Compression Formats

The name string for RGTC texture compression formats is GL_ARB_texture_compression_rgTC. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier GL_EXT_texture_compression_rgtc extension, and is provided to enable this functionality in older drivers.

It was promoted to a core feature in OpenGL 3.0.

K.3.48 One- and Two-Component Texture Formats

The name string for one- and two-component texture formats is GL_ARB_texture_rg. It was promoted to a core feature in OpenGL 3.0. This extension is
equivalent to new core functionality introduced in OpenGL 3.0, and is provided to enable this functionality in older drivers.

K.3.49 Vertex Array Objects

The name string for vertex array objects is GL_ARB_vertex_array_object. This extension is equivalent to new core functionality introduced in OpenGL 3.0, based on the earlier GL_APPLE_vertex_array_object extension, and is provided to enable this functionality in older drivers.

It was promoted to a core feature in OpenGL 3.0.

K.3.50 Versioned Context Creation

Starting with OpenGL 3.0, a new context creation interface is required in the window system integration layer. This interface specifies the context version required as well as other attributes of the context.

The name strings for the GLX and WGL context creation interfaces are GLX_ARB_create_context and WGL_ARB_create_context respectively.

K.3.51 Uniform Buffer Objects

The name string for uniform buffer objects is GL_ARB_uniform_buffer_object. This extension is equivalent to new core functionality introduced in OpenGL 3.1 and is provided to enable this functionality in older drivers.

K.3.52 Restoration of features removed from OpenGL 3.0

OpenGL 3.1 removes a large number of features that were marked deprecated in OpenGL 3.0 (see appendix G.2). GL implementations needing to maintain these features to support existing applications may do so, following the deprecation model, by exporting an extension string indicating those features are present. Applications written for OpenGL 3.1 should not depend on any of the features corresponding to this extension, since they will not be available on all platforms with 3.1 implementations.

The name string for restoration of features deprecated by OpenGL 3.0 is GL_ARB_compatibility.

The profile terminology introduced with OpenGL 3.2 eliminates the necessity for evolving this extension. Instead, interactions between features removed by OpenGL 3.1 and new features introduced in later OpenGL versions are defined by the compatibility profile corresponding to those versions.
K.3.53 Fast Buffer-to-Buffer Copies

The name string for fast buffer-to-buffer copies is GL_ARB_copy_buffer. This extension is equivalent to new core functionality introduced in OpenGL 3.1 and is provided to enable this functionality in older drivers.

K.3.54 Shader Texture Level of Detail Control

The name string for shader texture level of detail control is GL_ARB_shader_texture_lod. This extension is equivalent to new core functions introduced in OpenGL Shading Language 1.30 and is provided to enable this functionality in older versions of the shading language.

K.3.55 Depth Clamp Control

The name string for depth clamp control is GL_ARB_depth_clamp. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.56 Base Vertex Offset Drawing Commands

The name string for base vertex offset drawing commands is GL_ARB_draw_elements_base_vertex. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.57 Fragment Coordinate Convention Control

The name string for fragment coordinate convention control is GL_ARB_fragment_coord_conventions. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.58 Provoking Vertex Control

The name string for provoking vertex control is GL_ARB_provoking_vertex. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.
K.3.59 Seamless Cube Maps

The name string for seamless cube maps is GL_ARB_seamless_cube_map. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.60 Fence Sync Objects

The name string for fence sync objects is GL_ARB_sync. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.61 Multisample Textures

The name string for multisample textures is GL_ARB_texture_multisample. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.62 BGRA Attribute Component Ordering

The name string for BGRA attribute component ordering is GL_ARB_vertex_array_bgra. This extension is equivalent to new core functionality introduced in OpenGL 3.2 and is provided to enable this functionality in older drivers.

K.3.63 Per-Buffer Blend Control

The blending interface is extended to specify blend equation and blend function on a per-draw-buffer basis.

The name string for per-buffer blend control is GL_ARB_draw_buffers_blend.

K.3.64 Sample Shading Control

Sample shading control adds the ability to request that an implementation use a minimum number of unique sets of fragment computation inputs when multisampling a pixel.

The name string for sample shading control is GL_ARB_sample_shading.

K.3.65 Cube Map Array Textures

A cube map array texture is a two-dimensional array texture that may contain many cube map layers. Each cube map layer is a unique cube map image set.
The name string for cube map array textures is `GL_ARB_texture_cube_map_array`.

**K.3.66 Texture Gather**

Texture gather adds a new set of texture functions (textureGather) to the OpenGL Shading Language that determine the $2 \times 2$ footprint used for linear filtering in a texture lookup, and return a vector consisting of the first component from each of the four texels in the footprint.

The name string for texture gather is `GL_ARB_texture_gather`.

**K.3.67 Texture Level-Of-Detail Queries**

Texture level-of-detail queries adds a new set of fragment shader texture functions (textureLOD) to the OpenGL Shading Language that return the results of automatic level-of-detail computations that would be performed if a texture lookup were to be done.

The name string for texture level-of-detail queries is `GL_ARB_texture_query_lod`.

**K.3.68 Profiled Context Creation**

Starting with OpenGL 3.2, API profiles are defined. Profiled context creation extends the versioned context creation interface to specify a profile which must be implemented by the context.

The name strings for the GLX and WGL profiled context creation interfaces are `GLX_ARB_create_context_profile` and `WGL_ARB_create_context_profile` respectively.

**K.3.69 Shading Language Include**

Shading language include adds support for `#include` directives to shaders, and a named string API for defining the text corresponding to `#include` pathnames.

The name string for shading language include is `GL_ARB_shading_language_include`.

**K.3.70 BPTC texture compression**

BPTC texture compression provides new block compressed specific texture formats which can improve quality in images with sharp edges and strong chrominance transitions, and support high dynamic range floating-point formats.
The name string for bptc texture compression is `GL_ARB_texture_compression_bptc`.

**K.3.71 Extended Blend Functions**

The name string for extended blend functions is `GL_ARB_blend_func_extended`. This extension is equivalent to new core functionality introduced in OpenGL 3.3, and is provided to enable this functionality in older drivers.

**K.3.72 Explicit Attribute Location**

The name string for explicit attribute location is `GL_ARB_explicit_attrib_location`. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

**K.3.73 Boolean Occlusion Queries**

The name string for boolean occlusion queries is `GL_ARB_occlusion_query2`. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

**K.3.74 Sampler Objects**

The name string for sampler objects is `GL_ARB_sampler_objects`. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

**K.3.75 Shader Bit Encoding**

The name string for shader bit encoding is `GL_ARB_shader_bit_encoding`. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

**K.3.76 RGB10A2 Integer Textures**

The name string for RGB10A2 integer textures is `GL_ARB_texture_rgb10_a2ui`. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.
K.3.77  Texture Swizzle
The name string for texture swizzle is GL_ARB_texture_swizzle. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

K.3.78  Timer Queries
The name string for timer queries is GL_ARB_timer_query. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

K.3.79  Packed 2.10.10.10 Vertex Formats
The name string for packed 2.10.10.10 vertex formats is GL_ARB_vertex_type_2_10_10_10_rev. This extension is equivalent to new core functionality introduced in OpenGL 3.3 and is provided to enable this functionality in older drivers.

K.3.80  Draw Indirect
The name string for draw indirect is GL_ARB_draw_indirect. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.

K.3.81  GPU Shader5 Miscellaneous Functionality
The name string for gpu shader5 miscellaneous functionality is GL_ARB_gpu_shader5. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.

K.3.82  Double-Precision Floating-Point Shader Support
The name string for double-precision floating-point shader support is GL_ARB_gpu_shader_fp64. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.

K.3.83  Shader Subroutines
The name string for shader subroutines is GL_ARB_shader_subroutine. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.
K.3.84  **Tessellation Shaders**

The name string for tessellation shaders is `GL_ARB_tessellation_shader`. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.

K.3.85  **RGB32 Texture Buffer Objects**

The name string for RGB32 texture buffer objects is `GL_ARB_texture_buffer_object_rgb32`. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.

K.3.86  **Transform Feedback 2**

The name string for transform feedback 2 is `GL_ARB_transform_feedback2`. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.

K.3.87  **Transform Feedback 3**

The name string for transform feedback 3 is `GL_ARB_transform_feedback3`. This extension is equivalent to new core functionality introduced in OpenGL 4.0 and is provided to enable this functionality in older drivers.
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