OpenGL® ES™ 3.0 Programming Guide

Second Edition

Dan Ginsburg ▪ Budirijanto Purnomo

With Earlier Contributions from Dave Shreiner and Aaftab Munshi

Foreword by Neil Trevett, President, Khronos Group

Praise for *OpenGL® ES™ 3.0 Programming Guide, Second Edition*

"As a graphics technologist and intense OpenGL ES developer, I can honestly say that if you buy only one book on OpenGL ES 3.0 programming, then this should be the book. Dan and Budirijanto have written a book clearly by programmers for programmers. It is simply required reading for anyone interested in OpenGL ES 3.0. It is informative, well organized, and comprehensive, but best of all practical. You will find yourself reaching for this book over and over again instead of the actual OpenGL ES specification during your programming sessions. I give it my highest recommendation."

—Rick Tewell, Graphics Technology Architect, Freescale

"This book provides outstanding coverage of the latest version of OpenGL ES, with clear, comprehensive explanations and extensive examples. It belongs on the desk of anyone developing mobile applications."

—Dave Astle, Graphics Tools Lead, Qualcomm Technologies, Inc., and Founder, GameDev.net

"The second edition of *OpenGL® ES™ 3.0 Programming Guide* provides a solid introduction to OpenGL ES 3.0 specifications, along with a wealth of practical information and examples to help any level of developer begin programming immediately. We'd recommend this guide as a primer on OpenGL ES 3.0 to any of the thousands of developers creating apps for the many mobile and embedded products using our PowerVR Rogue graphics."

—Kristof Beets, Business Development, Imagination Technologies

"This is a solid OpenGL ES 3.0 reference book. It covers all aspects of the API and will help any developer get familiar with and understand the API, including specifically the new ES 3.0 functionality."

—Jed Fisher, Managing Partner, 4D Pipeline

"This is a clear and thorough reference for OpenGL ES 3.0, and an excellent presentation of the concepts present in all modern OpenGL programming. This is the guide I'd want by my side when diving into embedded OpenGL."

—Todd Furlong, President & Principal Engineer, Inv3rsion LLC

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Addison-Wesley

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Foreword

Five years have passed since the OpenGL ES 2.0 version of this reference book helped alert developers everywhere that programmable 3D graphics on mobile and embedded systems had not just arrived, but was here to stay.

Five years later, more than *1 billion* people around the world use OpenGL ES every day to interact with their computing devices, for both information and entertainment. Nearly every pixel on nearly every smartphone screen has been generated, manipulated, or composited by this ubiquitous graphics API.

Now, OpenGL ES 3.0 has been developed by Khronos Group and is shipping on the latest mobile devices, continuing the steady flow of advanced graphics features into the hands of consumers everywhere—features that were first developed and proven on high-end systems shipping with desktop OpenGL.

In fact, OpenGL is now easily the most widely deployed family of 3D APIs, with desktop OpenGL and OpenGL ES being joined by WebGL to bring the power of OpenGL ES to web content everywhere. OpenGL ES 3.0 will be instrumental in powering the evolution of WebGL, enabling HTML5 developers to tap directly into the power of the latest GPUs from the first truly portable 3D applications.

OpenGL ES 3.0 not only places more graphics capabilities into the hands of developers across a huge range of devices and platforms, but also enables faster, more power-efficient 3D applications that are easier to write, port, and maintain—and this book will show you how.

There has never been a more fascinating and rewarding time to be a 3D developer. My thanks and congratulations go to the authors for continuing to be a vital part of the evolving story of OpenGL ES, and for working hard to produce this book that helps ensure developers everywhere can better understand and leverage the full power of OpenGL ES 3.0.

—Neil Trevett
President, Khronos Group
Vice President Mobile Ecosystem, NVIDIA

Preface

OpenGL ES 3.0 is a software interface for rendering sophisticated 3D graphics on handheld and embedded devices. OpenGL ES is the primary graphics library for handheld and embedded devices with programmable 3D hardware including cell phones, personal digital assistants (PDAs), consoles, appliances, vehicles, and avionics. This book details the entire OpenGL ES 3.0 application programming interface (API) and pipeline, including detailed examples, to provide a guide for developing a wide range of high-performance 3D applications for handheld devices.

Intended Audience

This book is intended for programmers who are interested in learning OpenGL ES 3.0. We expect the reader to have a solid grounding in computer graphics. In the text we explain many of the relevant graphics concepts as they relate to various parts of OpenGL ES 3.0, but we expect the reader to understand basic 3D concepts. The code examples in the book are all written in C. We assume that the reader is familiar with C or C++ and cover language topics only where they are relevant to OpenGL ES 3.0.

The reader will learn about setting up and programming every aspect of the graphics pipeline. The book details how to write vertex and fragment shaders and how to implement advanced rendering techniques such as per-pixel lighting and particle systems. In addition, it provides performance tips and tricks for efficient use of the API and hardware. After finishing the book, the reader will be ready to write OpenGL ES 3.0 applications that fully harness the programmable power of embedded graphics hardware.

Organization of This Book

This book is organized to cover the API in a sequential fashion, building up your knowledge of OpenGL ES 3.0 as we go.

Chapter 1—Introduction to OpenGL ES 3.0

Chapter 1 introduces OpenGL ES and provides an overview of the OpenGL ES 3.0 graphics pipeline. We discuss the philosophies and constraints that went into the design of OpenGL ES 3.0. Finally, the chapter covers some general conventions and types used in OpenGL ES 3.0.

Chapter 2—Hello Triangle: An OpenGL ES 3.0 Example

Chapter 2 walks through a simple OpenGL ES 3.0 example program that draws a triangle. Our purpose here is to show what an OpenGL ES 3.0 program looks like, introduce the reader to some API concepts, and describe how to build and run an example OpenGL ES 3.0 program.

Chapter 3—An Introduction to EGL

Chapter 3 presents EGL, the API for creating surfaces and rendering contexts for OpenGL ES 3.0. We describe how to communicate with the native windowing system, choose a configuration, and create EGL rendering contexts and surfaces. We teach you enough EGL so that you can do everything you will need to do to get up and rendering with OpenGL ES 3.0.

Chapter 4—Shaders and Programs

Shader objects and program objects form the most fundamental objects in OpenGL ES 3.0. In Chapter 4, we describe how to create a shader object, compile a shader, and check for compile errors. The chapter also explains how to create a program object, attach shader objects to it, and link a final program object. We discuss how to query the program object for information and how to load uniforms. In addition, you will learn about the difference between source shaders and program binaries and how to use each.

Chapter 5—OpenGL ES Shading Language

Chapter 5 covers the shading language basics needed for writing shaders. These shading language basics include variables and types, constructors, structures, arrays, uniforms, uniform blocks, and input/output variables. This chapter also describes some more nuanced parts of the shading language, such as precision qualifiers and invariance.

Chapter 6—Vertex Attributes, Vertex Arrays, and Buffer Objects

Starting with Chapter 6 (and ending with Chapter 11), we begin our walk through the pipeline to teach you how to set up and program each part of the graphics pipeline. This journey begins with a description of how geometry is input into the graphics pipeline, and includes discussion of vertex attributes, vertex arrays, and buffer objects.

Chapter 7—Primitive Assembly and Rasterization

After discussing how geometry is input into the pipeline in the previous chapter, in Chapter 7 we consider how that geometry is assembled into primitives. All of the primitive types available in OpenGL ES 3.0, including point sprites, lines, triangles, triangle strips, and triangle fans, are covered. In addition, we describe how coordinate transformations are performed on vertices and introduce the rasterization stage of the OpenGL ES 3.0 pipeline.

Chapter 8—Vertex Shaders

The next portion of the pipeline that is covered is the vertex shader. Chapter 8 provides an overview of how vertex shaders fit into the pipeline and the special variables available to vertex shaders in the OpenGL ES Shading Language. Several examples of vertex shaders, including computation of per-vertex lighting and skinning, are covered. We also give examples of how the OpenGL ES 1.0 (and 1.1) fixed-function pipeline can be implemented using vertex shaders.

Chapter 9—Texturing

Chapter 9 begins the introduction to fragment shaders by describing all of the texturing functionality available in OpenGL ES 3.0. This chapter provides details on how to create textures, how to load them with data, and how to render with them. It describes texture wrap modes, texture filtering, texture formats, compressed textures, sampler objects, immutable textures, pixel unpack buffer objects, and mipmapping. This chapter covers all of the texture types supported in OpenGL ES 3.0: 2D textures, cubemaps, 2D texture arrays, and 3D textures.

Chapter 10—Fragment Shaders

Chapter 9 focused on how to use textures in a fragment shader; Chapter 10 covers the rest of what you need to know to write fragment shaders. We give an overview of fragment shaders and all of the special built-in variables available to them. We also demonstrate how to implement all of the fixed-function techniques that were available in OpenGL ES 1.1 using fragment shaders. Examples of multitexturing, fog, alpha test, and user clip planes are all implemented in fragment shaders.

Chapter 11—Fragment Operations

Chapter 11 discusses the operations that can be applied either to the entire framebuffer, or to individual fragments after the execution of the fragment shader in the OpenGL ES 3.0 fragment pipeline. These operations include the scissor test, stencil test, depth test, multisampling, blending, and dithering. This chapter covers the final phase in the OpenGL ES 3.0 graphics pipeline.

Chapter 12—Framebuffer Objects

Chapter 12 discusses the use of framebuffer objects for rendering to off-screen surfaces. Framebuffer objects have several uses, the most common of which is for rendering to a texture. This chapter provides a complete overview of the framebuffer object portion of the API. Understanding framebuffer objects is critical for implementing many advanced effects such as reflections, shadow maps, and postprocessing.

Chapter 13—Sync Objects and Fences

Chapter 13 provides an overview of sync objects and fences, which are efficient primitives for synchronizing within the host application and GPU execution in OpenGL ES 3.0. We discuss how to use sync objects and fences and conclude with an example.

Chapter 14—Advanced Programming with OpenGL ES 3.0

Chapter 14 is the capstone chapter, tying together many of the topics presented throughout the book. We have selected a sampling of advanced rendering techniques and show examples that demonstrate how to implement these features. This chapter includes rendering techniques such as per-pixel lighting using normal maps, environment mapping, particle systems, image postprocessing, procedural textures, shadow mapping, terrain rendering and projective texturing.

Chapter 15—State Queries

A large number of state queries are available in OpenGL ES 3.0. For just about everything you set, there is a corresponding way to get the current value. Chapter 15 is provided as a reference for the various state queries available in OpenGL ES 3.0.

Chapter 16—OpenGL ES Platforms

In the final chapter, we move away from the details of the API to talk about how to build the OpenGL ES sample code in this book for iOS7, Android 4.3 NDK, Android 4.3 SDK, Windows, and Linux. This chapter is intended to serve as a reference to get you up and running with the book sample code on the OpenGL ES 3.0 platform of your choosing.

Appendix A—GL_HALF_FLOAT_OES

Appendix A details the half-float format and provides a reference for how to convert from IEEE floating-point values into half-floats (and back).

Appendix B—Built-In Functions

Appendix B provides a reference for all of the built-in functions available in the OpenGL ES Shading Language.

Appendix C—ES Framework API

Appendix C provides a reference for the utility framework we developed for the book and describes what each function does.

OpenGL ES 3.0 Reference Card

Included as a color insert in the middle of the book is the OpenGL ES 3.0 Reference Card, copyrighted by Khronos and reprinted with permission. This reference contains a complete list of all of the functions in OpenGL ES 3.0, along with all of the types, operators, qualifiers, built-ins, and functions in the OpenGL ES Shading Language.

Example Code and Shaders

This book is filled with example programs and shaders. You can download the examples from the book's website at opengles-book.com, which provides a link to the github.com site hosting the book code. As of this writing, the example programs have been built and tested on iOS7, Android 4.3 NDK, Android 4.3 SDK, Windows (OpenGL ES 3.0 Emulation), and Ubuntu Linux. Several of the advanced shader examples in the book are implemented in PVRShaman, a shader development tool from PowerVR available for Windows, Mac OS X, and Linux. The book's website (opengles-book.com) provides links through which to download any of the required tools.

Errata

If you find something in the book that you believe is in error, please send us a note at errors@opengles-book.com. The list of errata for the book can be found on the book's website: opengles-book.com.

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— Dan Ginsburg

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— Budi Purnomo

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Dan is the founder of Upsample Software, LLC, a software company offering consulting services in 3D graphics and GPU computing. Dan has coauthored several other books, including the *OpenCL Programming Guide* and *OpenGL Shading Language, Third Edition*. In previous roles Dan has worked on developing OpenGL drivers, desktop and handheld 3D demos, GPU developer tools, 3D medical visualization, and games. He holds a B.S. in computer science from Worcester Polytechnic Institute and an M.B.A. from Bentley University.

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Dave Shreiner

Dave has been working with OpenGL for almost two decades, and more recently with OpenGL ES. He authored the first commercial training course on OpenGL while working at Silicon Graphics Computer Systems (SGI), and has worked as an author on the *OpenGL Programming Guide*. He has presented introductory and advanced courses on OpenGL programming worldwide at numerous conferences, including SIGGRAPH.

Dave is now a media systems architect at ARM, Inc. He holds a B.S. in mathematics from the University of Delaware.

Chapter 1

Introduction to OpenGL ES 3.0

OpenGL for Embedded Systems (OpenGL ES) is an application programming interface (API) for advanced 3D graphics targeted at handheld and embedded devices. OpenGL ES is the dominant graphics API in today's smartphones and has even extended its reach onto the desktop. The list of platforms supporting OpenGL ES includes iOS, Android, BlackBerry, bada, Linux, and Windows. OpenGL ES also underpins WebGL, a web standard for browser-based 3D graphics.

Since the release of the iPhone 3GS in June 2009 and Android 2.0 in March 2010, OpenGL ES 2.0 has been supported on iOS and Android devices. The first edition of this book covered OpenGL ES 2.0 in detail. The current edition focuses on OpenGL ES 3.0, the next revision of OpenGL ES. It is almost inevitable that every handheld platform that continues to evolve will support OpenGL ES 3.0. Indeed, OpenGL ES 3.0 is already supported on devices using Android 4.3+ and on the iPhone 5s with iOS7. OpenGL ES 3.0 is backward compatible with OpenGL ES 2.0, meaning that applications written for OpenGL ES 2.0 will continue to work with OpenGL ES 3.0.

OpenGL ES is one of a set of APIs created by the Khronos Group. The Khronos Group, founded in January 2000, is a member-funded industry consortium that is focused on the creation of open standard and royalty-free APIs. The Khronos Group also manages OpenGL, a cross-platform standard 3D API for desktop systems running Linux, various flavors of UNIX, Mac OS X, and Microsoft Windows. It is a widely accepted standard 3D API that has seen significant real-world usage.

Due to the widespread adoption of OpenGL as a 3D API, it made sense to start with the desktop OpenGL API in developing an open standard 3D

API for handheld and embedded devices and then modify it to meet the needs and constraints of the handheld and embedded device space. In the earlier versions of OpenGL ES (1.0, 1.1, and 2.0), the device constraints that were considered in the design included limited processing capabilities and memory availability, low memory bandwidth, and sensitivity to power consumption. The working group used the following criteria in the definition of the OpenGL ES specification(s):

- The OpenGL API is very large and complex, and the goal of the OpenGL ES working group was to create an API suitable for constrained devices. To achieve this goal, the working group removed any redundancy from the OpenGL API. In any case where the same operation could be performed in more than one way, the most useful method was taken and the redundant techniques were removed. A good example of this is seen with specifying geometry, where in OpenGL an application can use immediate mode, display lists, or vertex arrays. In OpenGL ES, only vertex arrays exist; immediate mode and display lists were removed.
- Removing redundancy was an important goal, but maintaining compatibility with OpenGL was also important. As much as possible, OpenGL ES was designed so that applications written to the embedded subset of functionality in OpenGL would also run on OpenGL ES. This was an important goal because it allows developers to leverage both APIs and to develop applications and tools that use the common subset of functionality.
- New features were introduced to address specific constraints of handheld and embedded devices. For example, to reduce the power consumption and increase the performance of shaders, precision qualifiers were introduced to the shading language.
- The designers of OpenGL ES aimed to ensure a minimum set of features for image quality. In early handheld devices, the screen sizes were limited, making it essential that the quality of the pixels drawn on the screen was as good as possible.
- The OpenGL ES working group wanted to ensure that any OpenGL ES implementation would meet certain acceptable and agreed-on standards for image quality, correctness, and robustness. This was achieved by developing appropriate conformance tests that an OpenGL ES implementation must pass to be considered compliant.

Khronos has released four OpenGL ES specifications so far: OpenGL ES 1.0 and ES 1.1 (referred to jointly as OpenGL ES 1.x in this book), OpenGL ES 2.0, and OpenGL ES 3.0. The OpenGL ES 1.0 and 1.1 specifications implement a fixed function pipeline and are derived from the OpenGL 1.3 and 1.5 specifications, respectively.

The OpenGL ES 2.0 specification implements a programmable graphics pipeline and is derived from the OpenGL 2.0 specification. Being derived from a revision of the OpenGL specification means that the corresponding OpenGL specification was used as the baseline for determining the feature set included in the particular revision of OpenGL ES.

OpenGL ES 3.0 is the next step in the evolution of handheld graphics and is derived from the OpenGL 3.3 specification. While OpenGL ES 2.0 was successful in bringing capabilities similar to DirectX9 and the Microsoft Xbox 360 to handheld devices, graphics capabilities have continued to evolve on desktop GPUs. Significant features that enable techniques such as shadow mapping, volume rendering, GPU-based particle animation, geometry instancing, texture compression, and gamma correction were missing from OpenGL ES 2.0. OpenGL ES 3.0 brings these features to handheld devices, while continuing the philosophy of adapting to the constraints of embedded systems.

Of course, some of the constraints that were taken into consideration while designing previous versions of OpenGL ES are no longer relevant today. For example, handheld devices now feature large screen sizes (some offer a higher resolution than most desktop PC monitors). Additionally, many handheld devices now feature high-performance multicore CPUs and large amounts of memory. The focus for the Khronos Group in developing OpenGL ES 3.0 shifted toward appropriate market timing of features relevant to handheld applications rather than addressing the limited capabilities of devices.

The following sections introduce the OpenGL ES 3.0 pipeline.

OpenGL ES 3.0

As noted earlier, OpenGL ES 3.0 is the API covered in this book. Our goal is to cover the OpenGL ES 3.0 specification in thorough detail, give specific examples of how to use the features in OpenGL ES 3.0, and discuss various performance optimization techniques. After reading this book, you should have an excellent grasp of the OpenGL ES 3.0 API, be able to easily write compelling OpenGL ES 3.0 applications, and not have to worry about reading multiple specifications to understand how a feature works.

OpenGL ES 3.0 implements a graphics pipeline with programmable shading and consists of two specifications: the **OpenGL ES 3.0**

API specification and the **OpenGL ES Shading Language 3.0 Specification (OpenGL ES SL)**. Figure 1-1 shows the OpenGL ES 3.0 graphics pipeline. The shaded boxes in this figure indicate the programmable stages of the pipeline in OpenGL ES 3.0. An overview of each stage in the OpenGL ES 3.0 graphics pipeline is presented next.

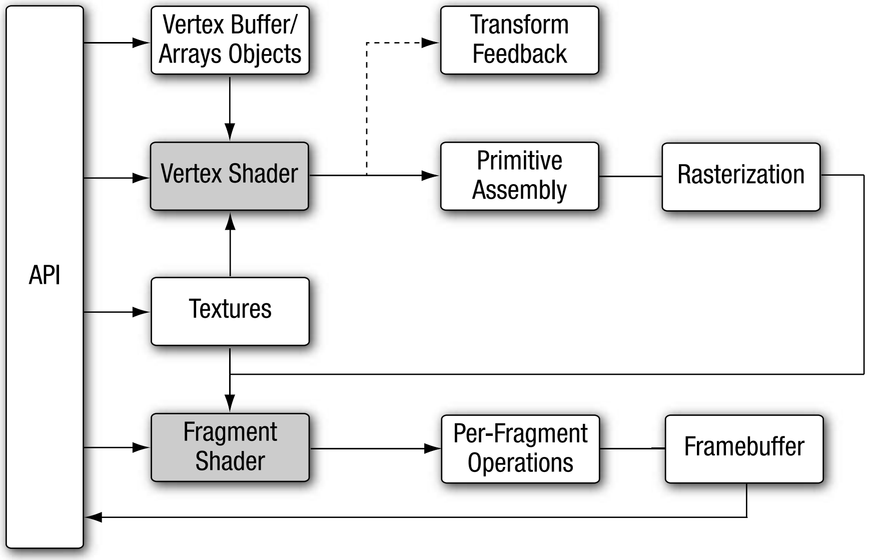

Figure 1-1 OpenGL ES 3.0 Graphics Pipeline

Vertex Shader

This section gives a high-level overview of vertex shaders. Vertex and fragment shaders are covered in depth in later chapters. The vertex shader implements a general-purpose programmable method for operating on vertices.

The inputs to the vertex shader consist of the following:

- Shader program—Vertex shader program source code or executable that describes the operations that will be performed on the vertex.
- Vertex shader inputs (or attributes)—Per-vertex data supplied using vertex arrays.
- Uniforms—Constant data used by the vertex (or fragment) shader.
- Samplers—Specific types of uniforms that represent textures used by the vertex shader.

The outputs of the vertex shader were called varying variables in OpenGL ES 2.0, but were renamed vertex shader output variables in OpenGL ES 3.0. In the primitive rasterization stage, the vertex shader output values are calculated for each generated fragment and are passed in as inputs to the fragment shader. The mechanism used to generate a value for each fragment from the vertex shader outputs that is assigned to each vertex of the primitive is called interpolation. Additionally, OpenGL ES 3.0 adds a new feature called transform feedback, which allows the vertex shader outputs to be selectively written to an output buffer (in addition to, or instead of, being passed to the fragment shader). For example, as covered in the transform feedback example in Chapter 14, a particle system can be implemented in the vertex shader in which particles are output to a buffer object using transform feedback. The inputs and outputs of the vertex shader are shown in Figure 1-2.

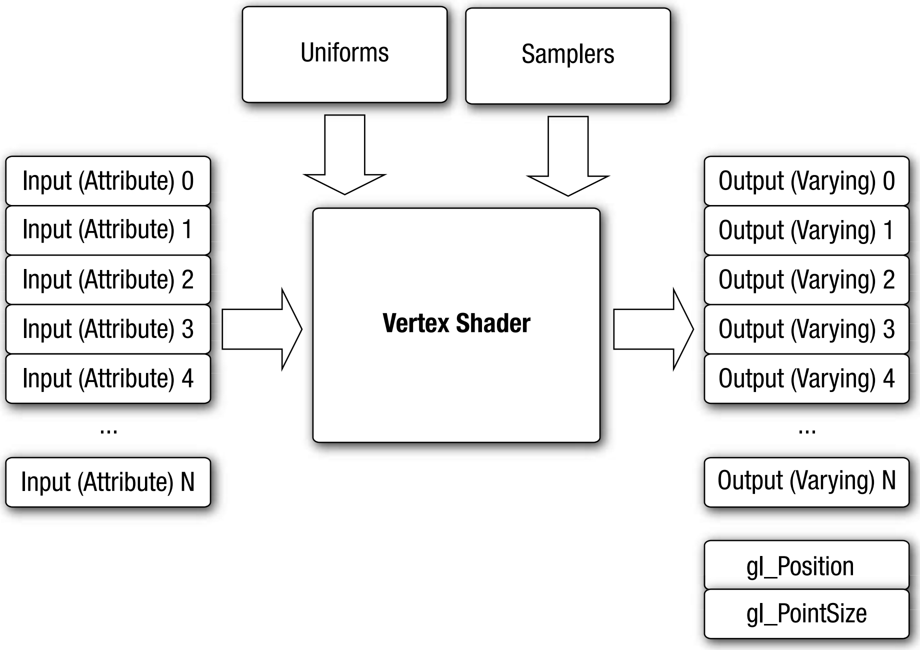

Figure 1-2 OpenGL ES 3.0 Vertex Shader

Vertex shaders can be used for traditional vertex-based operations such as transforming the position by a matrix, computing the lighting equation to generate a per-vertex color, and generating or transforming texture coordinates. Alternatively, because the vertex shader is specified by the application, vertex shaders can be used to perform custom math that enables new transforms, lighting, or vertex-based effects not allowed in more traditional fixed-function pipelines.

Example 1-1 shows a vertex shader written using the OpenGL ES shading language. We explain vertex shaders in significant detail later in the book. We present this shader here just to give you an idea of what a vertex shader looks like. The vertex shader in Example 1-1 takes a position and its associated color data as input attributes, transforms the position using a 4 × 4 matrix, and outputs the transformed position and color.

Example 1-1 A Vertex Shader Example

```
1.   #version 300 es
2.   uniform mat4 u_mvpMatrix; // matrix to convert a_position
3.                             // from model space to normalized
4.                             // device space
5.
6.   // attributes input to the vertex shader
7.   in vec4 a_position;       // position value
8.   in vec4 a_color;          // input vertex color
9.
10.  // output of the vertex shader - input to fragment
11.  // shader
12.  out vec4 v_color;         // output vertex color
13.  void main()
14.  {
15.     v_color = a_color;
16.     gl_Position = u_mvpMatrix * a_position;
17.  }
```

Line 1 provides the version of the Shading Language—information that must appear on the first line of the shader (`#version 300 es` indicates the OpenGL ES Shading Language v3.00). Line 2 describes a uniform variable `u_mvpMatrix` that stores the combined model view and projection matrix. Lines 7 and 8 describe the inputs to the vertex shader and are referred to as vertex attributes. `a_position` is the input vertex position attribute and `a_color` is the input vertex color attribute. On line 12, we declare the output `v_color` to store the output of the vertex shader that describes the per-vertex color. The built-in variable called `gl_Position` is declared automatically, and the shader must write the transformed position to this variable. A vertex or fragment shader has a single entry point called the main function. Lines 13–17 describe the vertex shader `main` function. In line 15, we read the vertex attribute input `a_color` and write it as the vertex output color `v_color`. In line 16, the transformed vertex position is output by writing it to `gl_Position`.

Primitive Assembly

After the vertex shader, the next stage in the OpenGL ES 3.0 graphics pipeline is primitive assembly. A primitive is a geometric object such as a triangle, line, or point sprite. Each vertex of a primitive is sent to a different copy of the vertex shader. During primitive assembly, these vertices are grouped back into the primitive.

For each primitive, it must be determined whether the primitive lies within the view frustum (the region of 3D space that is visible on the screen). If the primitive is not completely inside the view frustum, it might need to be clipped to the view frustum. If the primitive is completely outside this region, it is discarded. After clipping, the vertex position is converted to screen coordinates. A culling operation can also be performed that discards primitives based on whether they face forward or backward. After clipping and culling, the primitive is ready to be passed to the next stage of the pipeline—the rasterization stage.

Rasterization

The next stage, shown in Figure 1-3, is the rasterization phase, where the appropriate primitive (point sprite, line, or triangle) is drawn. Rasterization is the process that converts primitives into a set of two-dimensional fragments, which are then processed by the fragment shader. These two-dimensional fragments represent pixels that can be drawn on the screen.

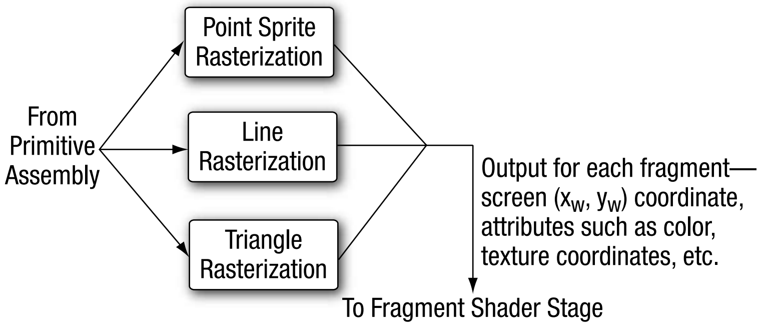
From Primitive Assembly
Point Sprite Rasterization
Line Rasterization
Triangle Rasterization
Output for each fragment—screen (x_w, y_w) coordinate, attributes such as color, texture coordinates, etc.
To Fragment Shader Stage

Figure 1-3 OpenGL ES 3.0 Rasterization Stage

Fragment Shader

The fragment shader implements a general-purpose programmable method for operating on fragments. As shown in Figure 1-4, this shader is executed for each generated fragment by the rasterization stage and takes the following inputs:

- Shader program—Fragment shader program source code or executable that describes the operations that will be performed on the fragment.
- Input variables—Outputs of the vertex shader that are generated by the rasterization unit for each fragment using interpolation.
- Uniforms—Constant data used by the fragment (or vertex) shader.
- Samplers—Specific types of uniforms that represent textures used by the fragment shader.

The fragment shader can either discard the fragment or generate one or more color values referred to as outputs. Typically, the fragment shader outputs just

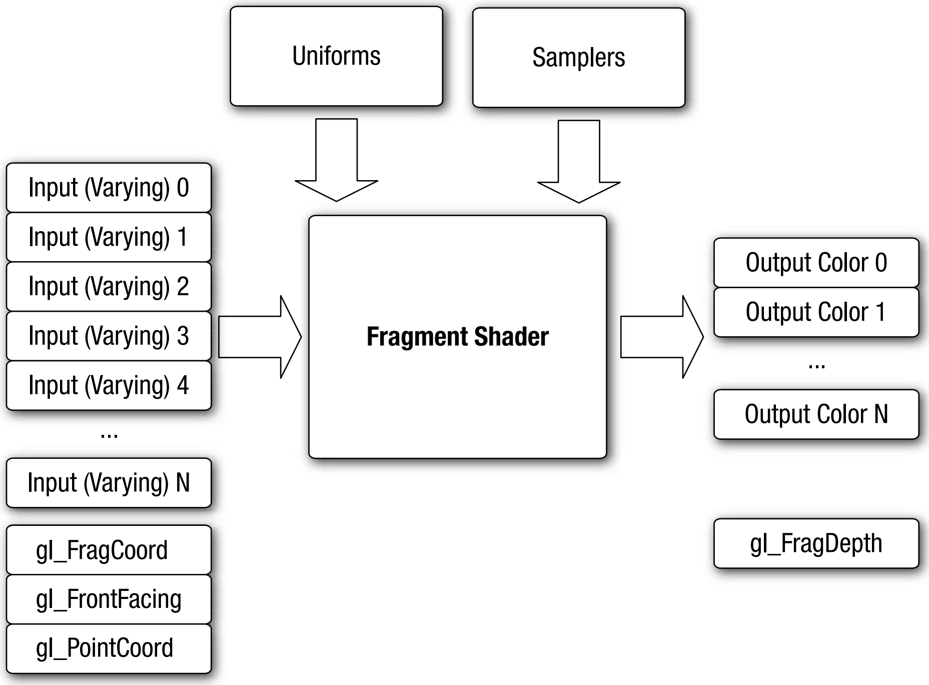

Figure 1-4 OpenGL ES 3.0 Fragment Shader

a single color value, except when rendering to multiple render targets (see the section *Multiple Render Targets* in Chapter 11); in the latter case, a color value is output for each render target. The color, depth, stencil, and screen coordinate location (x_w, y_w) generated by the rasterization stage become inputs to the per-fragment operations stage of the OpenGL ES 3.0 pipeline.

Example 1-2 describes a simple fragment shader that can be coupled with the vertex shader described in Example 1-1 to draw a Gouraud-shaded triangle. Again, we will go into much more detail on fragment shaders later in the book. We present this example just to give you a basic idea of what a fragment shader looks like.

Example 1-2 A Fragment Shader Example

```
1.  #version 300 es
2.  precision mediump float;
3.
4.  in vec4 v_color;    // input vertex color from vertex shader
5.
6.  out vec4 fragColor; // output fragment color
7.  void main()
8.  {
9.     fragColor = v_color;
10. }
```

Just as in the vertex shader, line 1 provides the version of the Shading Language; this information must appear on the first line of the fragment shader (`#version 300 es` indicates the OpenGL ES Shading Language v3.00). Line 2 sets the default precision qualifier, which is explained in detail in Chapter 4, "Shaders and Programs." Line 4 describes the input to the fragment shader. The vertex shader must write out the same set of variables that are read in by the fragment shader. Line 6 provides the declaration for the output variable of the fragment shader, which will be the color passed on to the next stage. Lines 7–10 describe the fragment shader `main` function. The output color is set to the input color `v_color`. The inputs to the fragment shader are linearly interpolated across the primitive before being passed into the fragment shader.

Per-Fragment Operations

After the fragment shader, the next stage is per-fragment operations. A fragment produced by rasterization with (x_w, y_w) screen coordinates can only modify the pixel at location (x_w, y_w) in the framebuffer. Figure 1-5 describes the OpenGL ES 3.0 per-fragment operations stage.

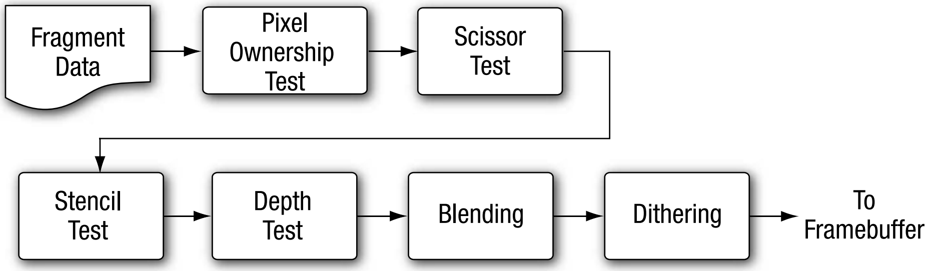

Figure 1-5 OpenGL ES 3.0 Per-Fragment Operations

During the per-fragment operations stage, the following functions (and tests) are performed on each fragment, as shown in Figure 1-5:

- Pixel ownership test—This test determines whether the pixel at location (x_w, y_w) in the framebuffer is currently owned by OpenGL ES. This test allows the window system to control which pixels in the framebuffer belong to the current OpenGL ES context. For example, if a window displaying the OpenGL ES framebuffer window is obscured by another window, the windowing system may determine that the obscured pixels are not owned by the OpenGL ES context and, therefore, the pixels might not be displayed at all. While the pixel ownership test is part of OpenGL ES, it is not controlled by the developer, but rather takes place internally inside of OpenGL ES.
- Scissor test—The scissor test determines whether (x_w, y_w) lies within the scissor rectangle defined as part of the OpenGL ES state. If the fragment is outside the scissor region, the fragment is discarded.
- Stencil and depth tests—These tests are performed on the stencil and depth value of the incoming fragment to determine whether the fragment should be rejected.
- Blending—Blending combines the newly generated fragment color value with the color values stored in the framebuffer at location (x_w, y_w).
- Dithering—Dithering can be used to minimize the artifacts that occur as a result of using limited precision to store color values in the framebuffer.

At the end of the per-fragment stage, either the fragment is rejected or a fragment color(s), depth, or stencil value is written to the framebuffer at location (x_w, y_w). Writing of the fragment color(s), depth, and stencil values depends on whether the appropriate write masks are enabled. Write masks allow finer control over the color, depth, and stencil values written into the associated buffers. For example, the write mask for the color buffer could be set such that no red values are written into the color buffer. In addition, OpenGL ES 3.0 provides an interface to read back the pixels from the framebuffer.

Note: Alpha test and LogicOp are no longer part of the per-fragment operations stage. These two stages exist in OpenGL 2.0 and OpenGL ES 1.x. The alpha test stage is no longer needed because the fragment shader can discard fragments; thus the alpha test can be performed in the fragment shader. In addition, LogicOp was removed because it is used only rarely by applications, and the OpenGL ES working group did not receive requests from independent software vendors (ISVs) to support this feature in OpenGL ES 2.0.

What's New in OpenGL ES 3.0

OpenGL ES 2.0 ushered in the era of programmable shaders for handheld devices and has been wildly successful in powering games, applications, and user interfaces across a wide range of devices. OpenGL ES 3.0 extends OpenGL ES 2.0 to support many new rendering techniques, optimizations, and visual quality enhancements. The following sections provide a categorized overview of the major new features that have been added to OpenGL ES 3.0. Each of these features will be described in detail later in the book.

Texturing

OpenGL ES 3.0 introduces many new features related to texturing:

- sRGB textures and framebuffers—Allow the application to perform gamma-correct rendering. Textures can be stored in gamma-corrected sRGB space, uncorrected to linear space upon being fetched in the shader, and then converted back to sRGB gamma-corrected space on output to the framebuffer. This enables potentially higher visual fidelity by properly computing lighting and other calculations in linear space.
- 2D texture arrays—A texture target that stores an array of 2D textures. Such arrays might, for example, be used to perform texture animation. Prior to 2D texture arrays, such animation was typically done by tiling the frames of an animation in a single 2D texture and modifying the texture coordinates to change animation frames. With 2D texture arrays, each frame of the animation can be specified in a 2D slice of the array.

- 3D textures—While some OpenGL ES 2.0 implementations supported 3D textures through an extension, OpenGL ES 3.0 has made this a mandatory feature. 3D textures are essential in many medical imaging applications, such as those that perform direct volume rendering of 3D voxel data (e.g., CT, MRI, or PET data).
- Depth textures and shadow comparison—Enable the depth buffer to be stored in a texture. The most common use for depth textures is in rendering shadows, where a depth buffer is rendered from the viewpoint of the light source and then used for comparison when rendering the scene to determine whether a fragment is in shadow. In addition to depth textures, OpenGL ES 3.0 allows the comparison against the depth texture to be done at the time of fetch, thereby allowing bilinear filtering to be done on depth textures (also known as percentage closest filtering [PCF]).
- Seamless cubemaps—In OpenGL ES 2.0, rendering with cubemaps could produce artifacts at the boundaries between cubemap faces. In OpenGL ES 3.0, cubemaps can be sampled such that filtering uses data from adjacent faces and removes the seaming artifact.
- Floating-point textures—OpenGL ES 3.0 greatly expands on the texture formats supported. Floating-point half-float (16-bit) textures are supported and can be filtered, whereas full-float (32-bit) textures are supported but not filterable. The ability to access floating-point texture data has many applications, including high dynamic range texturing to general-purpose computation.
- ETC2/EAC texture compression—While several OpenGL ES 2.0 implementations provided support for vendor-specific compressed texture formats (e.g., ATC by Qualcomm, PVRTC by Imagination Technologies, and Ericsson Texture Compression by Sony Ericsson), there was no standard compression format that developers could rely on. In OpenGL ES 3.0, support for ETC2/EAC is mandatory. The ETC2/EAC formats provide compression for RGB888, RGBA8888, and one- and two-channel signed/unsigned texture data. Texture compression offers several advantages, including better performance (due to better utilization of the texture cache) as well as a reduction in GPU memory utilization.
- Integer textures—OpenGL ES 3.0 introduces the capability to render to and fetch from textures stored as unnormalized signed or unsigned 8-bit, 16-bit, and 32-bit integer textures.
- Additional texture formats—In addition to those formats already mentioned, OpenGL ES 3.0 includes support for 11-11-10 RGB

floating-point textures, shared exponent RGB 9-9-9-5 textures, 10-10-10-2 integer textures, and 8-bit-per-component signed normalized textures.

- Non-power-of-2 textures (NPOT)—Textures can now be specified with non-power-of-2 dimensions. This is useful in many situations, such as when texturing from a video or camera feed that is captured/recorded at a non-power-of-2 dimension.
- Texture level of detail (LOD) features—The texture LOD parameter used to determine which mipmap to fetch from can now be clamped. Additionally, the base and maximum mipmap level can be clamped. These two features, in combination, make it possible to stream mipmaps. As larger mipmap levels become available, the base level can be increased and the LOD value can be smoothly increased to provide smooth-looking streaming textures. This is very useful, for example, when downloading texture mipmap data over a network connection.
- Texture swizzles—A new texture object state was introduced to allow independent control of where each channel (R, G, B, and A) of texture data is mapped to in the shader.
- Immutable textures—Provide a mechanism for the application to specify the format and size of a texture before loading it with data. In doing so, the texture format becomes immutable and the OpenGL ES driver can perform all consistency and memory checks up-front. This can improve performance by allowing the driver to skip consistency checks at draw time.
- Increased minimum sizes—All OpenGL ES 3.0 implementations are required to support much larger texture resources than OpenGL ES 2.0. For example, the minimum supported 2D texture dimension in OpenGL ES 2.0 was 64 but was increased to 2048 in OpenGL ES 3.0.

Shaders

OpenGL ES 3.0 includes a major update to the OpenGL ES Shading Language (ESSL; to v3.00) and new API features to support new shader features:

- Program binaries—In OpenGL ES 2.0, it was possible to store shaders in a binary format, but it was still required to link them into program at runtime. In OpenGL ES 3.0, the entire linked program binary (containing the vertex and fragment shader) can be stored in an offline binary format with no link step required at runtime. This can potentially help reduce the load time of applications. Additionally, OpenGL ES 3.0 provides an interface to retrieve the program binary from the driver so no offline tools are required to use program binaries.

- Mandatory online compiler—OpenGL ES 2.0 made it optional whether the driver would support online compilation of shaders. The intent was to reduce the memory requirements of the driver, but this achievement came at a major cost to developers in terms of having to rely on vendor-specific tools to generate shaders. In OpenGL ES 3.0, all implementations will have an online shader compiler.
- Non-square matrices—New matrix types other than square matrices are supported, and associated uniform calls were added to the API to support loading them. Non-square matrices can reduce the instruction count required for performing transformations. For example, if performing an affine transformation, a 4 × 3 matrix can be used in place of a 4 × 4 where the last row is (0, 0, 0, 1), thus reducing the instructions required to perform the transformation.
- Full integer support—Integer (and unsigned integer) scalar and vector types, along with full integer operations, are supported in ESSL 3.00. There are various built-in functions such as conversion from int to float, and from float to int, as well as the ability to read integer values from textures and output integer values to integer color buffers.
- Centroid sampling—To avoid rendering artifacts when multisampling, the output variables from the vertex shader (and inputs to the fragment shader) can be declared with centroid sampling.
- Flat/smooth interpolators—In OpenGL ES 2.0, all interpolators were implicitly linearly interpolated across the primitive. In ESSL 3.00, interpolators (vertex shader outputs/fragment shader inputs) can be explicitly declared to have either smooth or flat shading.
- Uniform blocks—Uniform values can be grouped together into uniform blocks. Uniform blocks can be loaded more efficiently and also shared across multiple shader programs.
- Layout qualifiers—Vertex shader inputs can be declared with layout qualifiers to explicitly bind the location in the shader source without requiring making API calls. Layout qualifiers can also be used for fragment shader outputs to bind the outputs to each target when rendering to multiple render targets. Further, layout qualifiers can be used to control the memory layout for uniform blocks.

- Instance and vertex ID—The vertex index is now accessible in the vertex shader as well as the instance ID if using instance rendering.
- Fragment depth—The fragment shader can explicitly control the depth value for the current fragment rather than relying on the interpolation of its depth value.
- New built-in functions—ESSL 3.00 introduces many new built-in functions to support new texture features, fragment derivatives, half-float data conversion, and matrix and math operations.
- Relaxed limitations—ESSL 3.0 greatly relaxes the restrictions on shaders. Shaders are no longer limited in terms of instruction length, fully support looping and branching on variables, and support indexing on arrays.

Geometry

OpenGL ES 3.0 introduces several new features related to geometry specification and control of primitive rendering:

- Transform feedback—Allows the output of the vertex shader to be captured in a buffer object. This is useful for a wide range of techniques that perform animation on the GPU without any CPU intervention—for example, particle animation or physics simulation using render-to-vertex-buffer.
- Boolean occlusion queries—Enable the application to query whether any pixels of a draw call (or a set of draw calls) passes the depth test. This feature can be used within a variety of techniques, such as visibility determination for a lens flare effect as well as optimization to avoid performing geometry processing on objects whose bounding volume is obscured.
- Instanced rendering—Efficiently renders objects that contain similar geometry but differ by attributes (such as transformation matrix, color, or size). This feature is useful in rendering large quantities of similar objects, such as for crowd rendering.
- Primitive restart—When using triangle strips in OpenGL ES 2.0 for a new primitive, the application would have to insert indices into the index buffer to represent a degenerate triangle. In OpenGL ES 3.0, a special index value can be used that indicates the beginning of a new primitive. This obviates the need for generating degenerate triangles when using triangle strips.

- New vertex formats—New vertex formats, including 10-10-10-2 signed and unsigned normalized vertex attributes; 8-bit, 16-bit, and 32-bit integer attributes; and 16-bit half-float, are supported in OpenGL ES 3.0.

Buffer Objects

OpenGL ES 3.0 introduces many new buffer objects to increase the efficiency and flexibility of specifying data to various parts of the graphics pipeline:

- Uniform buffer objects—Provide an efficient method for storing/binding large blocks of uniforms. Uniform buffer objects can be used to reduce the performance cost of binding uniform values to shaders, which is a common bottleneck in OpenGL ES 2.0 applications.
- Vertex array objects—Provide an efficient method for binding and switching between vertex array states. Vertex array objects are essentially container objects for vertex array states. Using them allows an application to switch the vertex array state in a single API call rather than making several calls.
- Sampler objects—Separate the sampler state (texture wrap mode and filtering) from the texture object. This provides a more efficient method of sharing the sampler state across textures.
- Sync objects—Provide a mechanism for the application to check on whether a set of OpenGL ES operations has finished executing on the GPU. A related new feature is a fence, which provides a way for the application to inform the GPU that it should wait until a set of OpenGL ES operations has finished executing before queuing up more operations for execution.
- Pixel buffer objects—Enable the application to perform asynchronous transfer of data to pixel operations and texture transfer operations. This optimization is primarily intended to provide faster transfer of data between the CPU and the GPU, where the application can continue doing work during the transfer operation.
- Buffer subrange mapping—Allows the application to map a subregion of a buffer for access by the CPU. This can provide better performance than traditional buffer mapping, in which the whole buffer needs to be available to the client.
- Buffer object to buffer object copies—Provide a mechanism to efficiently transfer data from one buffer object to another without intervention on the CPU.

Framebuffer

OpenGL ES 3.0 adds many new features related to off-screen rendering to framebuffer objects:

- Multiple render targets (MRTs)—Allow the application to render simultaneously to several color buffers at one time. With MRTs, the fragment shader outputs several colors, one for each attached color buffer. MRTs are used in many advanced rendering algorithms, such as deferred shading.
- Multisample renderbuffers—Enable the application to render to off-screen framebuffers with multisample anti-aliasing. The multisample renderbuffers cannot be directly bound to textures, but they can be resolved to single-sample textures using the newly introduced framebuffer blit.
- Framebuffer invalidation hints—Many implementations of OpenGL ES 3.0 are based on GPUs that use tile-based rendering (TBR; explained in the *Framebuffer Invalidation* section in Chapter 12). It is often the case that TBR incurs a significant performance cost when having to unnecessarily restore the contents of the tiles for further rendering to a framebuffer. Framebuffer invalidation gives the application a mechanism to inform the driver that the contents of the framebuffer are no longer needed. This allows the driver to take optimization steps to skip unnecessary restore operations on the tiles. Such functionality is very important to achieve peak performance in many applications, especially those that do significant amounts of off-screen rendering.
- New blend equations—The min/max functions are supported in OpenGL ES 3.0 as a blend equation.

OpenGL ES 3.0 and Backward Compatibility

OpenGL ES 3.0 is backward compatible with OpenGL ES 2.0. This means that just about any application written to use OpenGL ES 2.0 will run on implementations of OpenGL ES 3.0. There are some very minor changes to the later version that will affect a small number of applications in terms of backward compatibility. Namely, framebuffer objects are no longer shared between contexts, cubemaps are always filtered using seamless filtering, and there are minor changes in the way signed fixed-point numbers are converted to floating-point numbers.

The fact that OpenGL ES 3.0 is backward compatible with OpenGL ES 2.0 differs from what was done for OpenGL ES 2.0 with respect to its backward compatibility with previous versions of OpenGL ES. OpenGL ES 2.0 is not backward compatible with OpenGL ES 1.x. OpenGL ES 2.0/3.0 do not support the fixed-function pipeline that OpenGL ES 1.x supports. The OpenGL ES 2.0/3.0 programmable vertex shader replaces the fixed-function vertex units implemented in OpenGL ES 1.x. The fixed-function vertex units implement a specific vertex transformation and lighting equation that can be used to transform the vertex position, transform or generate texture coordinates, and calculate the vertex color. Similarly, the programmable fragment shader replaces the fixed-function texture combine units implemented in OpenGL ES 1.x. The fixed-function texture combine units implement a texture combine stage for each texture unit. The texture color is combined with the diffuse color and the output of the previous texture combine stage with a fixed set of operations such as add, modulate, subtract, and dot.

The OpenGL ES working group decided against backward compatibility between OpenGL ES 2.0/3.0 and OpenGL ES 1.x for the following reasons:

- Supporting the fixed-function pipeline in OpenGL ES 2.0/3.0 implies that the API would support more than one way of implementing a feature, in violation of one of the criteria used by the working group in determining which features should be supported. The programmable pipeline allows applications to implement the fixed-function pipeline using shaders, so there is really no compelling reason to be backward compatible with OpenGL ES 1.x.
- Feedback from ISVs indicated that most games do not mix programmable and fixed-function pipelines. That is, games are written either for a fixed-function pipeline or for a programmable pipeline. Once you have a programmable pipeline, there is no reason to use a fixed-function pipeline, as you have much more flexibility in the effects that can be rendered.
- The OpenGL ES 2.0/3.0 driver's memory footprint would be much larger if it had to support both the fixed-function and programmable pipelines. For the devices targeted by OpenGL ES, minimizing memory footprint is an important design criterion. Separating the fixed-function support into the OpenGL ES 1.x API and placing the programmable shader support into the OpenGL ES 2.0/3.0 APIs meant that vendors that do not require OpenGL ES 1.x support no longer need to include this driver.

EGL

OpenGL ES commands require a rendering context and a drawing surface. The rendering context stores the appropriate OpenGL ES state. The drawing surface is the surface to which primitives will be drawn. The drawing surface specifies the types of buffers that are required for rendering, such as a color buffer, depth buffer, and stencil buffer. The drawing surface also specifies the bit depths of each of the required buffers.

The OpenGL ES API does not mention how a rendering context is created or how the rendering context gets attached to the native windowing system. EGL is one interface between the Khronos rendering APIs such as OpenGL ES and the native window system; there is no hard-and-fast requirement to provide EGL when implementing OpenGL ES. Developers should refer to the platform vendor's documentation to determine which interface is supported. As of this writing, the only known platform supporting OpenGL ES that does not support EGL is iOS.

Any OpenGL ES application will need to perform the following tasks using EGL before any rendering can begin:

- Query the displays that are available on the device and initialize them. For example, a flip phone might have two LCD panels, and it is possible that we might use OpenGL ES to render to surfaces that can be displayed on either or both panels.
- Create a rendering surface. Surfaces created in EGL can be categorized as on-screen surfaces or off-screen surfaces. On-screen surfaces are attached to the native window system, whereas off-screen surfaces are pixel buffers that do not get displayed but can be used as rendering surfaces. These surfaces can be used to render into a texture and can be shared across multiple Khronos APIs.
- Create a rendering context. EGL is needed to create an OpenGL ES rendering context. This context needs to be attached to an appropriate surface before rendering can actually begin.

The EGL API implements the features just described as well as additional functionality such as power management, support for multiple rendering contexts in a process, sharing objects (such as textures or vertex buffers) across rendering contexts in a process, and a mechanism to get function pointers to EGL or OpenGL ES extension functions supported by a given implementation.

The latest version of the EGL specification is EGL version 1.4.

Programming with OpenGL ES 3.0

To write any OpenGL ES 3.0 application, you need to know which header files must be included and with which libraries your application needs to link. It is also useful to understand the syntax used by the EGL and GL command names and command parameters.

Libraries and Include Files

OpenGL ES 3.0 applications need to link with the following libraries: the OpenGL ES 3.0 library named `libGLESv2.lib` and the EGL library named `libEGL.lib`.

OpenGL ES 3.0 applications also need to include the appropriate ES 3.0 and EGL header files. The following include files must be included by any OpenGL ES 3.0 application:

```
#include <EGL/egl.h>
#include <GLES3/gl3.h>
```

`egl.h` is the EGL header file and `gl3.h` is the OpenGL ES 3.0 header file. Applications can optionally include `gl2ext.h`, which is the header file that describes the list of Khronos-approved extensions for OpenGL ES 2.0/3.0.

The header file and library names are platform dependent. The OpenGL ES working group has tried to define the library and header names and indicate how they should be organized, but this arrangement might not be found on all OpenGL ES platforms. Developers should, however, refer to the platform vendor's documentation for information on how the libraries and include files are named and organized. The official OpenGL ES header files are maintained by Khronos and available from http://khronos.org/registry/gles/. The sample code for the book also includes a copy of the header files (working with the sample code is described in the next chapter).

EGL Command Syntax

All EGL commands begin with the prefix `egl` and use an initial capital letter for each word making up the command name (e.g., `eglCreateWindowSurface`). Similarly, EGL data types also begin with the prefix `Egl` and use an initial capital letter for each word making up the type name, except for `EGLint` and `EGLenum`.

Table 1-1 briefly describes the EGL data types used.

Table 1-1 EGL Data Types

Data Type	C-Language Type	EGL Type
32-bit integer	`int`	`EGLint`
32-bit unsigned integer	`unsignedint`	`EGLBoolean, EGLenum`
Pointer	`void *`	`EGLConfig,` `EGLContext,` `EGLDisplay,` `EGLSurface,` `EGLClientBuffer`

OpenGL ES Command Syntax

All OpenGL ES commands begin with the prefix `gl` and use an initial capital letter for each word making up the command name (e.g., `glBlendEquation`). Similarly, OpenGL ES data types also begin with the prefix `GL`.

In addition, some commands might take arguments in different flavors. The flavors or types vary in terms of the number of arguments taken (one to four arguments), the data type of the arguments used (byte [`b`], unsigned byte [`ub`], short [`s`], unsigned short [`us`], int [`i`], and float [`f`]), and whether the arguments are passed as a vector (`v`). A few examples of command flavors allowed in OpenGL ES follow.

The following two commands are equivalent except that one specifies the uniform value as floats and the other as integers:

```
glUniform2f(location, 1.0f, 0.0f);
glUniform2i(location, 1, 0)
```

The following lines describe commands that are also equivalent, except that one passes command arguments as a vector and the other does not:

```
GLfloat   coord[4] = { 1.0f, 0.75f, 0.25f, 0.0f };
glUniform4fv(location, coord);
glUniform4f(location, coord[0], coord[1], coord[2], coord[3]);
```

Table 1-2 describes the command suffixes and argument data types used in OpenGL ES.

Finally, OpenGL ES defines the type `GLvoid`. This type is used for OpenGL ES commands that accept pointers.

In the rest of this book, OpenGL ES commands are referred to by their base names only, and an asterisk is used to indicate that this base name refers

Table 1-2 OpenGL ES Command Suffixes and Argument Data Types

Suffix	Data Type	C-Language Type	GL Type
`b`	8-bit signed integer	`signed char`	`GLbyte`
`ub`	8-bit unsigned integer	`unsigned char`	`GLubyte`, `GLboolean`
`s`	16-bit signed integer	`short`	`GLshort`
`us`	16-bit unsigned integer	`unsigned short`	`GLushort`
`i`	32-bit signed integer	`int`	`GLint`
`ui`	32-bit unsigned integer	`unsigned int`	`GLuint`, `GLbitfield`, `GLenum`
`x`	16.16 fixed point	`int`	`GLfixed`
`f`	32-bit floating point	`float`	`GLfloat`, `GLclampf`
`i64`	64-bit integer	`khronos_int64_t` (platform dependent)	`GLint64`
`ui64`	64-bit unsigned integer	`khronos_uint64_t` (platform dependent)	`GLuint64`

to multiple flavors of the command name. For example, `glUniform*()` stands for all variations of the command you use to specify uniforms and `glUniform*v()` refers to all the vector versions of the command you use to specify uniforms. If a particular version of a command needs to be discussed, we use the full command name with the appropriate suffixes.

Error Handling

OpenGL ES commands incorrectly used by applications generate an error code. This error code is recorded and can be queried using `glGetError`. No other errors will be recorded until the application has queried the first error code using `glGetError`. Once the error code has been queried, the current error code is reset to `GL_NO_ERROR`. The command that generated the error is ignored and does not affect the OpenGL ES state except for the `GL_OUT_OF_MEMORY` error described later in this section.

The `glGetError` command is described next.

```
GLenum       glGetError (void)
```

Returns the current error code and resets the current error code to `GL_NO_ERROR`. If `GL_NO_ERROR` is returned, there has been no detectable error since the last call to `glGetError`.

Table 1-3 lists the basic error codes and their description. Other error codes besides the basic ones listed in this table are described in the chapters that cover OpenGL ES commands that generate these specific errors.

Table 1-3 OpenGL ES Basic Error Codes

Error Code	Description
`GL_NO_ERROR`	No error has been generated since the last call to `glGetError`.
`GL_INVALID_ENUM`	A `GLenum` argument is out of range. The command that generated the error is ignored.
`GL_INVALID_VALUE`	A numeric argument is out of range. The command that generated the error is ignored.
`GL_INVALID_OPERATION`	The specific command cannot be performed in the current OpenGL ES state. The command that generated the error is ignored.
`GL_OUT_OF_MEMORY`	There is insufficient memory to execute this command. The state of the OpenGL ES pipeline is considered to be undefined if this error is encountered except for the current error code.

Basic State Management

Figure 1-1 showed the various pipeline stages in OpenGL ES 3.0. Each pipeline stage has a state that can be enabled or disabled and appropriate state values that are maintained per context. Examples of states are blending enable, blend factors, cull enable, and cull face. The state is initialized with default values when an OpenGL ES context (`EGLContext`) is initialized. The state enables can be set using the `glEnable` and `glDisable` commands.

```
void    glEnable(GLenum cap)
void    glDisable(GLenum cap)
```

`glEnable` and `glDisable` enable and disable various capabilities. The initial value for each capability is set to `GL_FALSE` except for `GL_DITHER`, which is set to `GL_TRUE`. The error code `GL_INVALID_ENUM` is generated if `cap` is not a valid state enum.

`cap`	state to enable or disable, can be:
	`GL_BLEND`
	`GL_CULL_FACE`
	`GL_DEPTH_TEST`
	`GL_DITHER`
	`GL_POLYGON_OFFSET_FILL`
	`GL_PRIMITIVE_RESTART_FIXED_INDEX`
	`GL_RASTERIZER_DISCARD`
	`GL_SAMPLE_ALPHA_TO_COVERAGE`
	`GL_SAMPLE_COVERAGE`
	`GL_SCISSOR_TEST`
	`GL_STENCIL_TEST`

Later chapters will describe the specific state enables for each pipeline stage shown in Figure 1-1. You can also check whether a state is currently enabled or disabled by using the `glIsEnabled` command.

```
GLboolean   glIsEnabled(GLenum cap)
```

Returns `GL_TRUE` or `GL_FALSE` depending on whether the state being queried is enabled or disabled. Generates the error code `GL_INVALID_ENUM` if `cap` is not a valid state enum.

Specific state values such as blend factor, depth test values, and so on can also be queried using appropriate `glGet***` commands. These commands are described in detail in Chapter 15, “State Queries.”

Further Reading

The OpenGL ES 1.0, 1.1, 2.0, and 3.0 specifications can be found at khronos.org/opengles/. In addition, the Khronos website (khronos.org) has the latest information on all Khronos specifications, developer message boards, tutorials, and examples.

- Khronos OpenGL ES 1.1 website: http://khronos.org/opengles/1_X/
- Khronos OpenGL ES 2.0 website: http://khronos.org/opengles/2_X/
- Khronos OpenGL ES 3.0 website: http://khronos.org/opengles/3_X/
- Khronos EGL website: http://khronos.org/egl/

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Chapter 2

Hello Triangle: An OpenGL ES 3.0 Example

To introduce the basic concepts of OpenGL ES 3.0, we begin with a simple example. This chapter shows what is required to create an OpenGL ES 3.0 program that draws a single triangle. The program we will write is just about the most basic example of an OpenGL ES 3.0 application that draws geometry. This chapter covers the following concepts:

- Creating an on-screen render surface with EGL
- Loading vertex and fragment shaders
- Creating a program object, attaching vertex and fragment shaders, and linking a program object
- Setting the viewport
- Clearing the color buffer
- Rendering a simple primitive
- Making the contents of the color buffer visible in the EGL window surface

As it turns out, a significant number of steps are required before we can start drawing a triangle with OpenGL ES 3.0. This chapter goes over the basics of each of these steps. Later in this book, we fill in the details on each of these steps and further document the API. Our purpose here is to get you up and running with your first simple example so that you get an idea of what goes into creating an application with OpenGL ES 3.0.

Code Framework

Throughout this book, we build a library of utility functions that form a framework of useful functions for writing OpenGL ES 3.0 programs. In developing example programs for the book, we had several goals for this code framework:

1. It should be simple, small, and easy to understand. We wanted to focus our examples on the relevant OpenGL ES 3.0 calls, rather than on a large code framework that we invented. Thus we focused our framework on simplicity and sought to make the example programs easy to read and understand. The goal of the framework is to allow you to focus your attention on the important OpenGL ES 3.0 API concepts in each example.
2. It should be portable. To the extent possible, we wanted the sample code to be available on all platforms where OpenGL ES 3.0 is present.

As we go through the examples in the book, we will formally introduce any new code framework functions that we use. In addition, you can find full documentation for the code framework in Appendix C. Any functions called in the example code that have names beginning with `es` (e.g., `esCreateWindow()`) are part of the code framework we wrote for the sample programs in this book.

Where to Download the Examples

You can find links to download the examples from the book website at opengles-book.com.

As of this writing, the source code is available for Windows, Linux, Android 4.3+ NDK, Android 4.3+ SDK (Java), and iOS7. On Windows, the code is compatible with the Qualcomm OpenGL ES 3.0 Emulator, ARM OpenGL ES 3.0 Emulator, and PowerVR OpenGL ES 3.0 Emulator. On Linux, the currently available emulators are the Qualcomm OpenGL ES 3.0 Emulator and the PowerVR OpenGL ES 3.0 Emulator. The code should be compatible with any Windows- or Linux-based OpenGL ES 3.0 implementations in addition to those mentioned here. The choice of development tool is up to the reader. We have used cmake, a cross-platform build generation tool, on Windows and Linux, which allows you to use IDEs including Microsoft Visual Studio, Eclipse, Code::Blocks, and Xcode.

On Android and iOS, we provide projects compatible with those platforms (Eclipse ADT and Xcode). As of this writing, many devices support OpenGL ES 3.0, including iPhone 5s, Google Nexus 4 and 7, Nexus 10, HTC One, LG G2, Samsung Galaxy S4 (Snapdragon), and Samsung Galaxy Note 3. On iOS7, you can run the OpenGL ES 3.0 examples on your Mac using the iOS Simulator. On Android, you will need a device compatible with OpenGL ES 3.0 to run the samples. Details on building the sample code for each platform are provided in Chapter 16, "OpenGL ES Platforms."

Hello Triangle Example

Let's look at the full source code for our Hello Triangle example program, which is listed in Example 2-1. Those readers who are familiar with fixed-function desktop OpenGL will probably think this is a lot of code just to draw a simple triangle. Those of you who are not familiar with desktop OpenGL will also probably think this is a lot of code just to draw a triangle! Remember, OpenGL ES 3.0 is fully shader based, which means you cannot draw any geometry without having the appropriate shaders loaded and bound. This means that more setup code is required to render than in desktop OpenGL using fixed-function processing.

Example 2-1 Hello_Triangle.c Example

```
#include "esUtil.h"

typedef struct
{
   // Handle to a program object
   GLuint programObject;

} UserData;

///
// Create a shader object, load the shader source, and
// compile the shader
//
GLuint LoadShader ( GLenum type, const char *shaderSrc )
{
   GLuint shader;
   GLint compiled;

   // Create the shader object
   shader = glCreateShader ( type );
```

(continues)

Example 2-1 Hello_Triangle.c Example *(continued)*

```
   if ( shader == 0 )
        return 0;

   // Load the shader source
   glShaderSource ( shader, 1, &shaderSrc, NULL );

   // Compile the shader
   glCompileShader ( shader );

   // Check the compile status
   glGetShaderiv ( shader, GL_COMPILE_STATUS, &compiled );

   if ( !compiled )
   {
      GLint infoLen = 0;

      glGetShaderiv ( shader, GL_INFO_LOG_LENGTH, &infoLen );

      if ( infoLen > 1 )
      {
         char* infoLog = malloc (sizeof(char) * infoLen );

         glGetShaderInfoLog( shader, infoLen, NULL, infoLog );
         esLogMessage ( "Error compiling shader:\n%s\n", infoLog );

         free ( infoLog );

      }

      glDeleteShader ( shader );
      return 0;
   }

   return shader;

}

///
// Initialize the shader and program object
//
int Init ( ESContext *esContext )
{
   UserData *userData = esContext->userData;
   char vShaderStr[] =
      "#version 300 es                          \n"
      "layout(location = 0) in vec4 vPosition;  \n"
      "void main()                              \n"
      "{                                        \n"
```

Example 2-1 Hello_Triangle.c Example *(continued)*

```
      "   gl_Position = vPosition;              \n"
      "}                                        \n";

   char fShaderStr[] =
      "#version 300 es                                   \n"
      "precision mediump float;                          \n"
      "out vec4 fragColor;                               \n"
      "void main()                                       \n"
      "{                                                 \n"
      "   fragColor = vec4 ( 1.0, 0.0, 0.0, 1.0 );       \n"
      "}                                                 \n";

   GLuint vertexShader;
   GLuint fragmentShader;
   GLuint programObject;
   GLint linked;

   // Load the vertex/fragment shaders
   vertexShader = LoadShader ( GL_VERTEX_SHADER, vShaderStr );
   fragmentShader = LoadShader ( GL_FRAGMENT_SHADER, fShaderStr );

   // Create the program object
   programObject = glCreateProgram ( );

   if ( programObject == 0 )
        return 0;

   glAttachShader ( programObject, vertexShader );
   glAttachShader ( programObject, fragmentShader );

   // Link the program
   glLinkProgram ( programObject );

   // Check the link status
   glGetProgramiv ( programObject, GL_LINK_STATUS, &linked );

   if ( !linked )
   {
      GLint infoLen = 0;

      glGetProgramiv ( programObject, GL_INFO_LOG_LENGTH, &infoLen );

      if ( infoLen > 1 )
      {
         char* infoLog = malloc (sizeof(char) * infoLen );

         glGetProgramInfoLog ( programObject, infoLen, NULL, infoLog );
```

(continues)

Example 2-1 Hello_Triangle.c Example *(continued)*

```
         esLogMessage ( "Error linking program:\n%s\n", infoLog );

         free ( infoLog );
      }

      glDeleteProgram ( programObject );
      return FALSE;

   }

   // Store the program object
   userData->programObject = programObject;

   glClearColor ( 0.0f, 0.0f, 0.0f, 0.0f );
   return TRUE;
}

///
// Draw a triangle using the shader pair created in Init()
//
void Draw ( ESContext *esContext )
{
   UserData *userData = esContext->userData;
   GLfloat vVertices[] = { 0.0f,  0.5f, 0.0f,
                          -0.5f, -0.5f, 0.0f,
                           0.5f, -0.5f, 0.0f };

   // Set the viewport
   glViewport ( 0, 0, esContext->width, esContext->height );

   // Clear the color buffer
   glClear ( GL_COLOR_BUFFER_BIT );

   // Use the program object
   glUseProgram ( userData->programObject );

   // Load the vertex data
   glVertexAttribPointer ( 0, 3, GL_FLOAT, GL_FALSE, 0, vVertices );
   glEnableVertexAttribArray ( 0 );

   glDrawArrays ( GL_TRIANGLES, 0, 3 );
}

void Shutdown ( ESContext *esContext )
{
   UserData *userData = esContext->userData;

   glDeleteProgram( userData->programObject );
}
```

Example 2-1 Hello_Triangle.c Example *(continued)*

```
int esMain( ESContext *esContext )
{
   esContext->userData = malloc ( sizeof( UserData ) );

   esCreateWindow ( esContext, "Hello Triangle", 320, 240,
                    ES_WINDOW_RGB );

   if ( !Init ( esContext ) )
        return GL_FALSE;

   esRegisterShutdownFunc( esContext, Shutdown );
   esRegisterDrawFunc ( esContext, Draw );

   return GL_TRUE;
}
```

The remainder of this chapter describes the code in this example. If you run the Hello Triangle example, you should see the window shown in Figure 2-1. Instructions on how to build and run the sample code for Windows, Linux, Android 4.3+, and iOS are provided in Chapter 16, "OpenGL ES Platforms." Please refer to the instructions in that chapter for your platform to get up and running with the sample code.

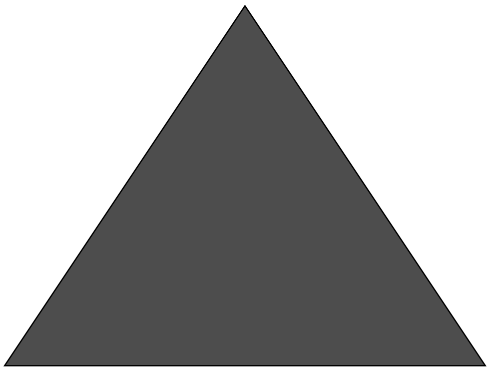

Figure 2-1 Hello Triangle Example

The standard GL3 (`GLES3/gl3.h`) and EGL (`EGL/egl.h`) header files provided by Khronos are used as an interface to OpenGL ES 3.0 and EGL. The OpenGL ES 3.0 examples are organized in the following directories:

- `Common/`—Contains the OpenGL ES 3.0 Framework project, code, and the emulator.
- `chapter_x/`—Contains the example programs for each chapter.

Using the OpenGL ES 3.0 Framework

Each application that uses our code framework declares a main entry point named `esMain`. In the main function in Hello Triangle, you will see calls to several ES utility functions. The `esMain` function takes an `ESContext` as an argument.

```
int esMain( ESContext *esContext )
```

The `ESContext` has a member variable named `userData` that is a `void*`. Each of the sample programs will store any of the data that are needed for the application in `userData`. The other elements in the `ESContext` structure are described in the header file and are intended only to be read by the user application. Other data in the `ESContext` structure include information such as the window width and height, EGL context, and callback function pointers.

The `esMain` function is responsible for allocating the `userData`, creating the window, and initializing the draw callback function:

```
esContext->userData = malloc ( sizeof( UserData ) );

esCreateWindow( esContext, "Hello Triangle", 320, 240,
                ES_WINDOW_RGB );

if ( !Init( esContext ) )
     return GL_FALSE;

esRegisterDrawFunc(esContext, Draw);
```

The call to `esCreateWindow` creates a window of the specified width and height (in this case, 320 × 240). The "Hello Triangle" parameter is used to name the window; on platforms supporting it (Windows and Linux), this name will be displayed in the top band of the window. The last parameter is a bit field that specifies options for the window creation. In this case, we request an RGB framebuffer. Chapter 3, "An Introduction to EGL," discusses what `esCreateWindow` does in more detail. This function uses EGL to create an on-screen render surface that is attached to a window. EGL is a platform-independent API for creating rendering surfaces and contexts. For now, we will simply say that this function creates a rendering surface and leave the details on how it works for the next chapter.

After calling `esCreateWindow`, the main function next calls `Init` to initialize everything needed to run the program. Finally, it registers a callback function, Draw, that will be called to render the frame. After exiting esMain, the framework enters into the main loop, which will call the registered callback functions (Draw, Update) until the window is closed.

Creating a Simple Vertex and Fragment Shader

In OpenGL ES 3.0, no geometry can be drawn unless a valid vertex and fragment shader have been loaded. In Chapter 1, "Introduction to OpenGL ES 3.0," we covered the basics of the OpenGL ES 3.0 programmable pipeline. There, you learned about the concepts of vertex and fragment shaders. These two shader programs describe the transformation of vertices and drawing of fragments. To do any rendering at all, an OpenGL ES 3.0 program must have at least one vertex shader and one fragment shader.

The biggest task that the Init function in Hello Triangle accomplishes is the loading of a vertex shader and a fragment shader. The vertex shader that is given in the program is very simple:

```
char vShaderStr[] =
   "#version 300 es                          \n"
   "layout(location = 0) in vec4 vPosition;  \n"
   "void main()                              \n"
   "{                                        \n"
   "   gl_Position = vPosition;              \n"
   "}                                        \n";
```

The first line of the vertex shader declares the shader version that is being used (#version 300 es indicates OpenGL ES Shading Language v3.00). The vertex shader declares one input attribute array—a four-component vector named vPosition. Later on, the Draw function in Hello Triangle will send in positions for each vertex that will be placed in this variable. The layout(location = 0) qualifier signifies that the location of this variable is vertex attribute 0. The shader declares a main function that marks the beginning of execution of the shader. The body of the shader is very simple; it copies the vPosition input attribute into a special output variable named gl_Position. Every vertex shader must output a position into the gl_Position variable. This variable defines the position that is passed through to the next stage in the pipeline. The topic of writing shaders is a large part of what we cover in this book, but for now we just want to give you a flavor of what a vertex shader looks like. In Chapter 5, "OpenGL ES Shading Language," we cover the OpenGL ES shading language; in Chapter 8, “Vertex Shaders,” we specifically cover how to write vertex shaders.

The fragment shader in the example is simple:

```
char fShaderStr[] =
   "#version 300 es                              \n"
   "precision mediump float;                     \n"
   "out vec4 fragColor;                          \n"
   "void main()                                  \n"
   "{                                            \n"
   "   fragColor = vec4 ( 1.0, 0.0, 0.0, 1.0 );  \n"
   "}                                            \n";
```

Just as in the vertex shader, the first line of the fragment shader declares the shader version. The next statement in the fragment shader declares the default precision for float variables in the shader. For more details on this topic, please see the section on precision qualifiers in Chapter 5, “OpenGL ES Shading Language.” The fragment shader declares a single output variable `fragColor`, which is a vector of four components. The value written to this variable is what will be written out into the color buffer. In this case, the shader outputs a red color (1.0, 0.0, 0.0, 1.0) for all fragments. The details of developing fragment shaders are covered in Chapter 9, “Texturing,” and Chapter 10, “Fragment Shaders.” Again, here we are just showing you what a fragment shader looks like.

Typically, a game or application would not place shader source strings inline in the way we have done in this example. In most real-world applications, the shader is loaded from some sort of text or data file and then loaded to the API. However, for simplicity and to make the example program self-contained, we provide the shader source strings directly in the program code.

Compiling and Loading the Shaders

Now that we have the shader source code defined, we can go about loading the shaders to OpenGL ES. The `LoadShader` function in the Hello Triangle example is responsible for loading the shader source code, compiling it, and checking it for errors. It returns a *shader object,* which is an OpenGL ES 3.0 object that can later be used for attachment to a *program object* (these two objects are detailed in Chapter 4, “Shaders and Programs”).

Let’s look at how the `LoadShader` function works. First, `glCreateShader` creates a new shader object of the type specified.

```
GLuint LoadShader(GLenum type, const char *shaderSrc)
{
   GLuint shader;
   GLint compiled;

   // Create the shader object
   shader = glCreateShader(type);

   if(shader == 0)
      return 0;
```

The shader source code itself is loaded to the shader object using `glShaderSource`. The shader is then compiled using the `glCompileShader` function.

```
   // Load the shader source
   glShaderSource(shader, 1, &shaderSrc, NULL);

   // Compile the shader
   glCompileShader(shader);
```

After compiling the shader, the status of the compile is determined and any errors that were generated are printed out.

```
   // Check the compile status
   glGetShaderiv(shader, GL_COMPILE_STATUS, &compiled);

   if(!compiled)
   {
      GLint infoLen = 0;

      glGetShaderiv(shader, GL_INFO_LOG_LENGTH, &infoLen);

      if(infoLen > 1)
      {
         char* infoLog = malloc(sizeof(char) * infoLen);

         glGetShaderInfoLog(shader, infoLen, NULL, infoLog);
         esLogMessage("Error compiling shader:\n%s\n", infoLog);

         free(infoLog);
      }

      glDeleteShader(shader);
      return 0;
   }

      return shader;

}
```

If the shader compiles successfully, a new shader object is returned that will be attached to the program later. The details of these shader object functions are covered in the first sections of Chapter 4, "Shaders and Programs."

Creating a Program Object and Linking the Shaders

Once the application has created a shader object for the vertex and fragment shaders, it needs to create a program object. Conceptually, the program object can be thought of as the final linked program. Once the various shaders are compiled into a shader object, they must be attached to a program object and linked together before drawing.

The process of creating program objects and linking is fully described in Chapter 4, "Shaders and Programs." For now, we provide a brief overview of the process. The first step is to create the program object and attach the vertex shader and fragment shader to it.

```
// Create the program object
programObject = glCreateProgram();

if(programObject == 0)
   return 0;

glAttachShader(programObject, vertexShader);
glAttachShader(programObject, fragmentShader);
```

Finally, we are ready to link the program and check for errors:

```
// Link the program
glLinkProgram(programObject);

// Check the link status
glGetProgramiv(programObject, GL_LINK_STATUS, &linked);

if(!linked)
{
   GLint infoLen = 0;

   glGetProgramiv(programObject, GL_INFO_LOG_LENGTH,&infoLen);

   if(infoLen > 1)
   {
      char* infoLog = malloc(sizeof(char) * infoLen);

      glGetProgramInfoLog(programObject, infoLen, NULL,infoLog);
      esLogMessage("Error linking program:\n%s\n", infoLog);

      free(infoLog) ;
   }

   glDeleteProgram(programObject) ;
   return FALSE;
}

// Store the program object
userData->programObject = programObject;
```

After all of these steps, we have finally compiled the shaders, checked for compile errors, created the program object, attached the shaders, linked the program, and checked for link errors. After successful linking of the program object, we can now finally use the program object for rendering! To use the program object for rendering, we bind it using `glUseProgram`.

```
// Use the program object
glUseProgram(userData->programObject);
```

After calling `glUseProgram` with the program object handle, all subsequent rendering will occur using the vertex and fragment shaders attached to the program object.

Setting the Viewport and Clearing the Color Buffer

Now that we have created a rendering surface with EGL and initialized and loaded shaders, we are ready to actually draw something. The `Draw` callback function draws the frame. The first command that we execute in `Draw` is `glViewport`, which informs OpenGL ES of the origin, width, and height of the 2D rendering surface that will be drawn to. In OpenGL ES, the viewport defines the 2D rectangle in which all OpenGL ES rendering operations will ultimately be displayed.

```
// Set the viewport
glviewport(0, 0, esContext->width, esContext->height);
```

The viewport is defined by an origin (*x*, *y*) and a width and height. We cover `glViewport` in more detail in Chapter 7, “Primitive Assembly and Rasterization,” when we discuss coordinate systems and clipping.

After setting the viewport, the next step is to clear the screen. In OpenGL ES, multiple types of buffers are involved in drawing: color, depth, and stencil. We cover these buffers in more detail in Chapter 11, "Fragment Operations." In the Hello Triangle example, only the color buffer is drawn to. At the beginning of each frame, we clear the color buffer using the `glClear` function.

```
// Clear the color buffer
glClear(GL_COLOR_BUFFER_BIT);
```

The buffer will be cleared to the color specified with `glClearColor`. In the example program at the end of `Init`, the clear color was set to (1.0, 1.0, 1.0, 1.0), so the screen is cleared to white. The clear color should be set by the application prior to calling `glClear` on the color buffer.

Loading the Geometry and Drawing a Primitive

Now that we have the color buffer cleared, viewport set, and program object loaded, we need to specify the geometry for the triangle. The vertices for the triangle are specified with three (*x*, *y*, *z*) coordinates in the `vVertices` array.

```
GLfloat vVertices[] = { 0.0f,   0.5f,   0.0f,
                       -0.5f,  -0.5f,   0.0f,
                        0.5f,  -0.5f,   0.0f};
…
// Load the vertex data
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, vVertices);
glEnableVertexAttribArray(0) ;
glDrawArrays(GL_TRIANGLES, 0, 3);
```

The vertex positions need to be loaded to the GL and connected to the `vPosition` attribute declared in the vertex shader. As you will remember, earlier we bound the `vPosition` variable to the input attribute location 0. Each attribute in the vertex shader has a location that is uniquely identified by an unsigned integer value. To load the data into vertex attribute 0, we call the `glVertexAttribPointer` function. In Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects," we cover how to load vertex attributes and use vertex arrays in full.

The final step in drawing the triangle is to actually tell OpenGL ES to draw the primitive. In this example, we use the function `glDrawArrays` for this purpose. This function draws a primitive such as a triangle, line, or strip. We get into primitives in much more detail in Chapter 7, "Primitive Assembly and Rasterization."

Displaying the Back Buffer

We have finally gotten to the point where our triangle has been drawn into the framebuffer. Now there is one final detail we must address: how to actually display the framebuffer on the screen. Before we get into that, let's back up a little bit and discuss the concept of double buffering.

The framebuffer that is visible on the screen is represented by a two-dimensional array of pixel data. One possible way we could think about displaying images on the screen is to simply update the pixel data in the visible framebuffer as we draw. However, there is a significant issue with updating pixels directly on the displayable buffer—that is, in a typical display system, the physical screen is updated from framebuffer memory at a fixed rate. If we were to draw directly into the framebuffer, the user could see artifacts as partial updates to the framebuffer where it is displayed.

To address this problem, we use a system known as double buffering. In this scheme, there are two buffers: a front buffer and a back buffer. All rendering occurs to the back buffer, which is located in an area of memory that is not visible to the screen. When all rendering is complete, this buffer is "swapped" with the front buffer (or visible buffer). The front buffer then becomes the back buffer for the next frame.

Using this technique, we do not display a visible surface until all rendering is complete for a frame. This activity is controlled in an OpenGL ES application through EGL, by using an EGL function called `eglSwapBuffers` (this function is called by our framework after calling the `Draw` callback function):

```
eglSwapBuffers(esContext->eglDisplay, esContext->eglSurface);
```

This function informs EGL to swap the front buffer and back buffers. The parameters sent to `eglSwapBuffers` are the EGL display and surface. These two parameters represent the physical display and the rendering surface, respectively. In the next chapter, we explain `eglSwapBuffers` in more detail and further clarify the concepts of surface, context, and buffer management. For now, suffice it to say that after swapping buffers we finally have our triangle on screen!

Summary

In this chapter, we introduced a simple OpenGL ES 3.0 program that draws a single triangle to the screen. The purpose of this introduction was to familiarize you with several of the key components that make up an OpenGL ES 3.0 application: creating an on-screen render surface with EGL, working with shaders and their associated objects, setting the viewport, clearing the color buffer, and rendering a primitive. Now that you understand the basics of what makes up an OpenGL ES 3.0 application, we will dive into these topics in more detail, starting in the next chapter with more information on EGL.

Chapter 3

An Introduction to EGL

In Chapter 2, "Hello Triangle: An OpenGL ES 3.0 Example," we drew a triangle into a window using OpenGL ES 3.0, but we used some custom functions of our own design to open and manage the window. Although that technique simplifies our examples, it obscures how you might need to work with OpenGL ES 3.0 on your own systems.

As part of the family of APIs provided by the Khronos Group for developing content, a (mostly) platform-independent API, EGL, is available for managing *drawing surfaces* (windows are just one type; we will talk about others later). EGL provides the mechanisms for the following:

- Communicating with the native windowing system of your device
- Querying the available types and configurations of drawing surfaces
- Creating drawing surfaces
- Synchronizing rendering between OpenGL ES 3.0 and other graphics-rendering APIs (such as desktop OpenGL and OpenVG, a cross-platform API for hardware-accelerated vector graphics, or the native drawing commands of your windowing system)
- Managing rendering resources such as texture maps

This chapter introduces the fundamentals required to open a window. As we describe other operations, such as creating texture maps, we discuss the necessary EGL commands.

Communicating with the Windowing System

EGL provides a "glue" layer between OpenGL ES 3.0 (and other Khronos graphics APIs) and the native windowing system running on your computer, like the X Window System commonly found on GNU/Linux systems, Microsoft Windows, or Mac OS X's Quartz. Before EGL can determine which types of drawing surfaces are available—or any other characteristics of the underlying system, for that matter—it needs to open a communications channel with the windowing system. Note that Apple provides its own iOS implementation of the EGL API called EAGL.

Because every windowing system has different semantics, EGL provides a basic opaque type—the `EGLDisplay`—that encapsulates all of the system dependencies for interfacing with the native windowing system. The first operation that any application using EGL will need to perform is to create and initialize a connection with the local EGL display. This is done in a two-call sequence, as shown in Example 3-1.

Example 3-1 Initializing EGL

```
EGLint majorVersion;
EGLint minorVersion;

EGLDisplay display = eglGetDisplay ( EGL_DEFAULT_DISPLAY );
if ( display == EGL_NO_DISPLAY )
{
   // Unable to open connection to local windowing system
}

if ( !eglInitialize ( display, &majorVersion, &minorVersion ) )
{
   // Unable to initialize EGL; handle and recover
}
```

To open a connection to the EGL display server, you call the following function:

`EGLDisplay` **`eglGetDisplay`**`(EGLNativeDisplayType` *`displayId`*`)`

`displayId`	specifies the display connection, use `EGL_DEFAULT_DISPLAY` for the default connection

`EGLNativeDisplayType` is defined to match the native window system's display type. On Microsoft Windows, for example, an `EGLNativeDisplayType` would be defined to be an HDC—a handle to the Microsoft Windows device context. However, to make it easy to move your code to different operating systems and platforms, the token `EGL_DEFAULT_DISPLAY` is accepted and will return a connection to the default native display, as we did.

If a display connection isn't available, `eglGetDisplay` will return `EGL_NO_DISPLAY`. This error indicates that EGL isn't available, and you won't be able to use OpenGL ES 3.0.

Before we continue by discussing more EGL operations, we need to briefly describe how EGL processes and reports errors to your application.

Checking for Errors

Most functions in EGL return `EGL_TRUE` when successful and `EGL_FALSE` otherwise. However, EGL will do more than just tell you if the call failed—it will record an error to indicate the reason for failure. However, that error code is not returned to you directly; you need to query EGL explicitly for the error code, which you can do by calling the following function:

```
EGLint eglGetError()
```

This function returns the error code of the most recent EGL function called in a specific thread. If `EGL_SUCCESS` is returned, then there is no status to return.

You might wonder why this is a prudent approach, as compared to directly returning the error code when the call completes. Although we never encourage anyone to ignore function return codes, allowing optional error code recovery reduces redundant code in applications verified to work properly. You should certainly check for errors during development and debugging, and on an ongoing basis in critical applications, but once you are convinced your application is working as expected, you can likely reduce your error checking.

Initializing EGL

Once you have successfully opened a connection, EGL needs to be initialized, which is done by calling the following function:

```
EGLBoolean eglInitialize(EGLDisplay display,
                         EGLint *majorVersion,
                         EGLint *minorVersion)
```

display	specifies the EGL display connection
majorVersion	specifies the major version number returned by the EGL implementation; may be `NULL`
minorVersion	specifies the minor version number returned by the EGL implementation; may be `NULL`

This function initializes EGL's internal data structures and returns the major and minor version numbers of the EGL implementation. If EGL is unable to be initialized, this call will return `EGL_FALSE`, and set EGL's error code to

- `EGL_BAD_DISPLAY` if `display` doesn't specify a valid `EGLDisplay`.
- `EGL_NOT_INITIALIZED` if the EGL cannot be initialized.

Determining the Available Surface Configurations

Once we have initialized EGL, we are able to determine which types and configurations of rendering surfaces are available to us. There are two ways to go about this:

- Query every surface configuration and find the best choice ourselves.
- Specify a set of requirements and let EGL make a recommendation for the best match.

In many situations, the second option is simpler to implement, and most likely yields what you would have found using the first option. In either case, EGL will return an `EGLConfig`, which is an identifier to an EGL-internal data structure that contains information about a particular surface and its characteristics, such as the number of bits for each color component, or the depth buffer (if any) associated with that `EGLConfig`. You can query any of the attributes of an `EGLConfig`, using the `eglGetConfigAttrib` function, which we describe later.

To query all EGL surface configurations supported by the underlying windowing system, call this function:

```
EGLBoolean eglGetConfigs(EGLDisplay display,
                         EGLConfig *configs,
                         EGLint maxReturnConfigs,
                         EGLint *numConfigs)
```

display	specifies the EGL display connection
configs	specifies the list of *configs*
maxReturnConfigs	specifies the size of *configs*
numConfigs	specifies the size of *configs* returned

This function returns `EGL_TRUE` if the call succeeded. On failure, this call will return `EGL_FALSE` and set EGL's error code to

- `EGL_NOT_INITIALIZED` if *display* is not initialized.
- `EGL_BAD_PARAMETER` if *numConfigs* is `NULL`.

There are two ways to call `eglGetConfigs`. First, if you specify `NULL` for the value of *configs*, the system will return `EGL_TRUE` and set *numConfigs* to the number of available `EGLConfig`s. No additional information about any of the `EGLConfig`s in the system is returned, but knowing the number of available configurations allows you to allocate enough memory to get the entire set of `EGLConfig`s, should you care to do so.

Alternatively, and perhaps more usefully, you can allocate an array of uninitialized `EGLConfig` values and pass them into `eglGetConfigs` as the *configs* parameter. Set *maxReturnConfigs* to the size of the array you allocated, which will also specify the maximum number of configurations that will be returned. When the call completes, *numConfigs* will be updated with the number of entries in *configs* that were modified. You can then begin processing the list of returned values, querying the characteristics of the various configurations to determine which one best matches your needs.

Querying EGLConfig Attributes

We now describe the values that EGL associates with an `EGLConfig` and explain how you can retrieve those values.

An `EGLConfig` contains all of the information about a surface made available by EGL. This includes information about the number of available colors, additional buffers associated with the configuration (such as depth and stencil buffers, which we discuss later), the type of surfaces, and numerous other characteristics. The following is a list of the attributes that can be queried from an `EGLConfig`. We discuss only a subset of these in this chapter, but the entire list appears in Table 3-1 as a reference.

To query a particular attribute associated with an `EGLConfig`, use the following function:

```
EGLBoolean eglGetConfigAttrib(EGLDisplay display,
                              EGLConfig config,
                              EGLint attribute,
                              EGLint *value)
```

display	specifies the EGL display connection
config	specifies the configuration to be queried
attribute	specifies the particular attribute to be returned
value	specifies the value returned

This function returns `EGL_TRUE` if the call succeeded. On failure, `EGL_FALSE` is returned, and an `EGL_BAD_ATTRIBUTE` error is posted if `attribute` is not a valid attribute.

This call will return the value for the specific attribute of the associated `EGLConfig`. This allows you total control over which configuration you choose for ultimately creating rendering surfaces. However, when looking at Table 3-1, you might be somewhat intimidated by the large number of options. EGL provides another routine, `eglChooseConfig`, that allows you to specify what is important for your application, and will return the best matching configuration given your requests.

Table 3-1 EGLConfig Attributes

Attribute	Description	Default Value
EGL_BUFFER_SIZE	Number of bits for all color components in the color buffer	0
EGL_RED_SIZE	Number of red bits in the color buffer	0
EGL_GREEN_SIZE	Number of green bits in the color buffer	0
EGL_BLUE_SIZE	Number of blue bits in the color buffer	0
EGL_LUMINANCE_SIZE	Number of luminance bits in the color buffer	0
EGL_ALPHA_SIZE	Number of alpha bits in the color buffer	0
EGL_ALPHA_MASK_SIZE	Number of alpha-mask bits in the mask buffer	0
EGL_BIND_TO_TEXTURE_RGB	True if bindable to RGB textures	EGL_DONT_CARE
EGL_BIND_TO_TEXTURE_RGBA	True if bindable to RGBA textures	EGL_DONT_CARE
EGL_COLOR_BUFFER_TYPE	Type of the color buffer: either EGL_RGB_BUFFER or EGL_LUMINANCE_BUFFER	EGL_RGB_BUFFER
EGL_CONFIG_CAVEAT	Any caveats associated with the configuration	EGL_DONT_CARE
EGL_CONFIG_ID	The unique EGLConfig identifier value	EGL_DONT_CARE
EGL_CONFORMANT	True if contexts created with this EGLConfig are conformant	—
EGL_DEPTH_SIZE	Number of bits in the depth buffer	0
EGL_LEVEL	Framebuffer level	0
EGL_MAX_PBUFFER_WIDTH	Maximum width for a PBuffer created with this EGLConfig	—
EGL_MAX_PBUFFER_HEIGHT	Maximum height for a PBuffer created with this EGLConfig	—
EGL_MAX_PBUFFER_PIXELS	Maximum size of a PBuffer created with this EGLConfig	—
EGL_MAX_SWAP_INTERVAL	Maximum buffer swap interval	EGL_DONT_CARE

(continues)

Table 3-1 `EGLConfig` Attributes *(continued)*

Attribute	Description	Default Value
`EGL_MIN_SWAP_INTERVAL`	Minimum buffer swap interval	`EGL_DONT_CARE`
`EGL_NATIVE_RENDERABLE`	True if native rendering libraries can render into a surface created with `EGLConfig`	`EGL_DONT_CARE`
`EGL_NATIVE_VISUAL_ID`	Handle of corresponding native window system visual ID	`EGL_DONT_CARE`
`EGL_NATIVE_VISUAL_TYPE`	Type of corresponding native window system visual	`EGL_DONT_CARE`
`EGL_RENDERABLE_TYPE`	A bitmask composed of the tokens `EGL_OPENGL_ES_BIT`, `EGL_OPENGL_ES2_BIT`, `EGL_OPENGL_ES3_BIT_KHR` (requires `EGL_KHR_create_context` extension), `EGL_OPENGL_BIT`, or `EGL_OPENVG_BIT`, which represent the rendering interfaces supported with the configuration	`EGL_OPENGL_ES_BIT`
`EGL_SAMPLE_BUFFERS`	Number of available multisample buffers	0
`EGL_SAMPLES`	Number of samples per pixel	0
`EGL_STENCIL_SIZE`	Number of bits in the stencil buffer	0
`EGL_SURFACE_TYPE`	Type of EGL surfaces supported; can be any of `EGL_WINDOW_BIT`, `EGL_PIXMAP_BIT`, `EGL_PBUFFER_BIT`, `EGL_MULTISAMPLE_RESOLVE_BOX_BIT`, `EGL_SWAP_BEHAVIOR_PRESERVED_BIT`, `EGL_VG_COLORSPACE_LINEAR_BIT`, or `EGL_VG_ALPHA_FORMAT_PRE_BIT`	`EGL_WINDOW_BIT`
`EGL_TRANSPARENT_TYPE`	Type of transparency supported	`EGL_NONE`
`EGL_TRANSPARENT_RED_VALUE`	Red color value interpreted as transparent	`EGL_DONT_CARE`
`EGL_TRANSPARENT_GREEN_VALUE`	Green color value interpreted as transparent	`EGL_DONT_CARE`
`EGL_TRANSPARENT_BLUE_VALUE`	Blue color value interpreted as transparent	`EGL_DONT_CARE`

Note: Various tokens do not have a default value mandated in the EGL specification, as indicated by the dash (—) for their default value.

Letting EGL Choose the Configuration

To have EGL make the choice of matching `EGLConfigs`, use this function:

```
EGLBoolean eglChooseConfig(EGLDisplay display,
                           const EGLint *attribList,
                           EGLConfig *configs,
                           EGLint maxReturnConfigs,
                           EGLint *numConfigs)
```

display	specifies the EGL display connection
attribList	specifies the list of attributes to match by *configs*
configs	specifies the list of configurations
maxReturnConfigs	specifies the size of configurations
numConfigs	specifies the size of configurations returned

This function returns `EGL_TRUE` if the call succeeded. On failure, `EGL_FALSE` is returned, and an `EGL_BAD_ATTRIBUTE` error is posted if `attribList` contains an undefined EGL attribute or an attribute value that is unrecognized or out of range.

You need to provide a list of the attributes, with associated preferred values for all the attributes that are important for the correct operation of your application. For example, if you need an `EGLConfig` that supports a rendering surface having five bits red and blue, and six bits green (the commonly used "RGB 565" format); a depth buffer; and OpenGL ES 3.0, you might declare the array shown in Example 3-2.

For values that are not explicitly specified in the attribute list, EGL will use the default values shown in Table 3-1. Additionally, when specifying a numeric value for an attribute, EGL will guarantee the returned configuration has at least that value at a minimum if there is a matching `EGLConfig` available.

Example 3-2 Specifying EGL Attributes

```
EGLint attribList[] =
{
   EGL_RENDERABLE_TYPE, EGL_OPENGL_ES3_BIT_KHR,
   EGL_RED_SIZE, 5,
   EGL_GREEN_SIZE, 6,
   EGL_BLUE_SIZE, 5,
   EGL_DEPTH_SIZE, 1,
   EGL_NONE
};
```

Note: Using the EGL_OPENGL_ES3_BIT_KHR attribute requires the EGL_KHR_create_context extension. This attribute is defined in eglext.h (EGL v1.4). It is also worth noting that some implementations will always promote OpenGL ES 2.0 contexts to OpenGL ES 3.0 contexts, as OpenGL ES 3.0 is backward compatible with OpenGL ES 2.0.

To use this set of attributes as a selection criteria, follow Example 3-3.

Example 3-3 Querying EGL Surface Configurations

```
const EGLint MaxConfigs = 10;
EGLConfig configs[MaxConfigs]; // We'll accept only 10 configs
EGLint numConfigs;
if ( !eglChooseConfig( display, attribList, configs, MaxConfigs,
                       &numConfigs ) )
{
   // Something did not work ... handle error situation
}
else
{
   // Everything is okay; continue to create a rendering surface
}
```

If eglChooseConfig returns successfully, a set of EGLConfigs matching your criteria will be returned. If more than one EGLConfig matches (with at most the maximum number of configurations you specify), eglChooseConfig will sort the configurations using the following ordering:

1. By the value of EGL_CONFIG_CAVEAT. Precedence is given to configurations where there are no configuration caveats (when the value of EGL_CONFIG_CAVEAT is EGL_NONE), then slow rendering configurations (EGL_SLOW_CONFIG), and finally nonconformant configurations (EGL_NON_CONFORMANT_CONFIG).
2. By the type of buffer as specified by EGL_COLOR_BUFFER_TYPE.
3. By the number of bits in the color buffer in descending sizes. The number of bits in a buffer depends on the EGL_COLOR_BUFFER_TYPE, and will be at least the value specified for a particular color channel. When the buffer type is EGL_RGB_BUFFER, the number of bits is computed as the total of EGL_RED_SIZE, EGL_GREEN_SIZE, and EGL_BLUE_SIZE. When the color buffer type is EGL_LUMINANCE_BUFFER, the number of bits is the sum of EGL_LUMINANCE_SIZE and EGL_ALPHA_SIZE.
4. By the value of EGL_BUFFER_SIZE in ascending order.

5. By the value of EGL_SAMPLE_BUFFERS in ascending order.
6. By the number of EGL_SAMPLES in ascending order.
7. By the value of EGL_DEPTH_SIZE in ascending order.
8. By the value of the EGL_STENCIL_SIZE in ascending order.
9. By the value of the EGL_ALPHA_MASK_SIZE (which is applicable only to OpenVG surfaces).
10. By the EGL_NATIVE_VISUAL_TYPE in an implementation-dependent manner.
11. By the value of the EGL_CONFIG_ID in ascending order.

Parameters not mentioned in this list are not used in the sorting process.

Note: Because of the third sorting rule, to get the best format that matches what you specified, you will need to add extra logic to go through the returned results. For example, if you ask for “565” RGB format, then the “888” format will appear in the returned results first.

As mentioned in Example 3-3, if eglChooseConfig returns successfully, we have enough information to continue to create something to draw into. By default, if you do not specify which type of rendering surface type you would like (by specifying the EGL_SURFACE_TYPE attribute), EGL assumes you want an on-screen window.

Creating an On-Screen Rendering Area: The EGL Window

Once we have a suitable EGLConfig that meets our requirements for rendering, we are ready to create our window. To create a window, call the following function:

```
EGLSurface eglCreateWindowSurface(EGLDisplay display,
                                  EGLConfig config,
                                  EGLNativeWindowType window,
                                  const EGLint *attribList)
```

display	specifies the EGL display connection
config	specifies the configuration
window	specifies the native window
attribList	specifies the list of window attributes; may be NULL

This function takes as arguments our connection to the native display manager and the `EGLConfig` that we obtained in the previous step. Additionally, it requires a window from the native windowing system that was created previously. Because EGL is a software layer between many different windowing systems and OpenGL ES 3.0, demonstrating how to create a native window is outside the scope of this guide. Please refer to the documentation for your native windowing system to determine what is required to create a window in that environment.

Finally, this call takes a list of attributes; however, this list differs from the attributes shown in Table 3-1. Because EGL supports other rendering APIs (notably OpenVG), some attributes accepted by `eglCreateWindowSurface` do not apply when working with OpenGL ES 3.0 (see Table 3-2). For our purposes, `eglCreateWindowSurface` accepts a single attribute, which is used to specify the buffer of the front- or back-buffer we would like to render into.

Table 3-2 Attributes for Window Creation Using `eglCreateWindowSurface`

Token	**Description**	**Default Value**
`EGL_RENDER_BUFFER`	Specifies which buffer should be used for rendering (using the `EGL_SINGLE_BUFFER` value), or back (`EGL_BACK_BUFFER`)	`EGL_BACK_BUFFER`

Note: For OpenGL ES 3.0 window rendering surfaces, only double-buffered windows are supported.

The attribute list might be empty (i.e., passing a `NULL` pointer as the value for *`attribList`*), or it might be a list populated with an `EGL_NONE` token as the first element. In such cases, all of the relevant attributes use their default values.

There are a number of ways in which `eglCreateWindowSurface` could fail, and if any of them occur, `EGL_NO_SURFACE` is returned from the call and the particular error is set. If this situation occurs, we can determine the reason for the failure by calling `eglGetError`, which will return one of the reasons shown in Table 3-3.

Table 3-3 Possible Errors When `eglCreateWindowSurface` Fails

Error Code	Description
`EGL_BAD_MATCH`	This situation occurs when: • The attributes of the native window do not match those of the provided `EGLConfig`. • The provided `EGLConfig` does not support rendering into a window (i.e., the `EGL_SURFACE_TYPE` attribute does not have the `EGL_WINDOW_BIT` set).
`EGL_BAD_CONFIG`	This error is flagged if the provided `EGLConfig` is not supported by the system.
`EGL_BAD_NATIVE_WINDOW`	This error is specified if the provided native window handle is not valid.
`EGL_BAD_ALLOC`	This error occurs if `eglCreateWindowSurface` is unable to allocate the resources for the new EGL window, or if there is already an `EGLConfig` associated with the provided native window.

Putting this all together, our code for creating a window is shown in Example 3-4.

Example 3-4 Creating an EGL Window Surface

```
EGLint attribList[] =
{
   EGL_RENDER_BUFFER, EGL_BACK_BUFFER,
   EGL_NONE
);

EGLSurface window = eglCreateWindowSurface ( display, config,
                                             nativeWindow,
                                             attribList );
if ( window == EGL_NO_SURFACE )
{
   switch ( eglGetError ( ) )
   {
      case EGL_BAD_MATCH:
         // Check window and EGLConfig attributes to determine
         // compatibility, or verify that the EGLConfig
         // supports rendering to a window
         break;

      case EGL_BAD_CONFIG:
         // Verify that provided EGLConfig is valid
         break;
```

(continues)

Example 3-4 Creating an EGL Window Surface *(continued)*

```
      case EGL_BAD_NATIVE_WINDOW:
         // Verify that provided EGLNativeWindow is valid
         break;

      case EGL_BAD_ALLOC:
         // Not enough resources available; handle and recover
         break;
   }
}
```

This creates a place for us to draw into, but we still have two more steps that must be completed before we can successfully use OpenGL ES 3.0 with our window. Windows, however, are not the only rendering surfaces that you might find useful. We introduce another type of rendering surface next before completing our discussion.

Creating an Off-Screen Rendering Area: EGL Pbuffers

In addition to being able to render into an on-screen window using OpenGL ES 3.0, you can render into nonvisible off-screen surfaces called pbuffers (short for *pixel buffer*). Pbuffers can take full advantage of any hardware acceleration available to OpenGL ES 3.0, just as a window does. Pbuffers are most often used for generating texture maps. If all you want to do is render to a texture, we recommend using framebuffer objects (covered in Chapter 12, "Framebuffer Objects") instead of pbuffers because they are more efficient. However, pbuffers can still be useful in some cases where framebuffer objects cannot be used, such as when rendering an off-screen surface with OpenGL ES and then using it as a texture in another API such as OpenVG.

Creating a pbuffer is very similar to creating an EGL window, with a few minor differences. To create a pbuffer, we need to find an `EGLConfig` just as we did for a window, with one modification: We need to augment the value of `EGL_SURFACE_TYPE` to include `EGL_PBUFFER_BIT`. Once we have a suitable `EGLConfig`, we can create a pbuffer using the function

```
EGLSurface eglCreatePbufferSurface(EGLDisplay display,
                                   EGLConfig config,
                                   const EGLint *attribList)
```

display	specifies the EGL display connection
config	specifies the configuration
attribList	specifies the list of pixel buffer attributes; may be `NULL`

As with window creation, this function takes our connection to the native display manager and the `EGLConfig` that we selected. This call also takes a list of attributes, as described in Table 3-4.

Table 3-4 EGL Pixel Buffer Attributes

Token	Description	Default Value
`EGL_WIDTH`	Specifies the desired width (in pixels) of the pbuffer.	`0`
`EGL_HEIGHT`	Specifies the desired height (in pixels) of the pbuffer.	`0`
`EGL_LARGEST_PBUFFER`	Select the largest available pbuffer if one of the requested size is not available. Valid values are `EGL_TRUE` and `EGL_FALSE`.	`EGL_FALSE`
`EGL_TEXTURE_FORMAT`	Specifies the type of texture format (see Chapter 9, "Texturing") if the pbuffer is bound to a texture map. Valid values are `EGL_TEXTURE_RGB`, `EGL_TEXTURE_RGBA`, and `EGL_NO_TEXTURE` (which indicates that the pbuffer will not be used directly as a texture).	`EGL_NO_TEXTURE`
`EGL_TEXTURE_TARGET`	Specifies the associated texture target that the pbuffer should be attached to if used as a texture map (see Chapter 9, "Texturing"). Valid values are `EGL_TEXTURE_2D` and `EGL_NO_TEXTURE`.	`EGL_NO_TEXTURE`

(continues)

Table 3-4 EGL Pixel Buffer Attributes *(continued)*

Token	Description	Default Value
EGL_MIPMAP_TEXTURE	Specifies whether storage for texture mipmap levels (see Chapter 9, "Texturing") should be additionally allocated. Valid values are EGL_TRUE and EGL_FALSE.	EGL_FALSE

There are a number of ways that `eglCreatePbufferSurface` could fail. Just as with window creation, if any of these failures occur, `EGL_NO_SURFACE` is returned from the call and the particular error is set. In this situation, `eglGetError` will return one of the errors listed in Table 3-5.

Table 3-5 Possible Errors When `eglCreatePbufferSurface` Fails

Error Code	Description
EGL_BAD_ALLOC	This error occurs when the pbuffer cannot be allocated due to a lack of resources.
EGL_BAD_CONFIG	This error is flagged if the provided EGLConfig is not a valid EGLConfig supported by the system.
EGL_BAD_PARAMETER	This error is generated if either the EGL_WIDTH or EGL_HEIGHT provided in the attribute list is a negative value.
EGL_BAD_MATCH	This error is generated if any of the following situations occur: if the EGLConfig provided does not support pbuffer surfaces; if the pbuffer will be used as a texture map (EGL_TEXTURE_FORMAT is not EGL_NO_TEXTURE), and the specified EGL_WIDTH and EGL_HEIGHT specify an invalid texture size; or if either EGL_TEXTURE_FORMAT and EGL_TEXTURE_TARGET is EGL_NO_TEXTURE, and the other attribute is not EGL_NO_TEXTURE.
EGL_BAD_ATTRIBUTE	This error occurs if either EGL_TEXTURE_FORMAT, EGL_TEXTURE_TARGET, or EGL_MIPMAP_TEXTURE is specified, but the provided EGLConfig does not support OpenGL ES rendering (e.g., only OpenVG rendering is supported).

Putting this all together, we create a pbuffer, as shown in Example 3-5.

Example 3-5 Creating an EGL Pixel Buffer

```
EGLint attribList[] =
{
   EGL_SURFACE_TYPE, EGL_PBUFFER_BIT,
   EGL_RENDERABLE_TYPE, EGL_OPENGL_ES3_BIT_KHR,
   EGL_RED_SIZE, 5,
   EGL_GREEN_SIZE, 6,
   EGL_BLUE_SIZE, 5,
   EGL_DEPTH_SIZE, 1,
   EGL_NONE
};

const EGLint MaxConfigs = 10;
EGLConfig configs[MaxConfigs]; // We'll accept only 10 configs
EGLint numConfigs;
if ( !eglChooseConfig( display, attribList, configs, MaxConfigs,
                       &numConfigs ) )
{
   // Something did not work ... handle error situation
}
else
{
   // We have found a pbuffer-capable EGLConfig
}

// Proceed to create a 512 x 512 pbuffer
// (or the largest available)
EGLSurface pbuffer;
EGLint attribList[] =
{
   EGL_WIDTH, 512,
   EGL_HEIGHT, 512,
   EGL_LARGEST_PBUFFER, EGL_TRUE,
   EGL_NONE
);

pbuffer = eglCreatePbufferSurface( display, config, attribList);
if ( pbuffer == EGL_NO_SURFACE )
{
   switch ( eglGetError ( ) )
   {
      case EGL_BAD_ALLOC:
      // Not enough resources available; handle and recover
      break;

      case EGL_BAD_CONFIG:
      // Verify that provided EGLConfig is valid
      break;
```

(continues)

Example 3-5 Creating an EGL Pixel Buffer *(continued)*

```
      case EGL_BAD_PARAMETER:
      // Verify that EGL_WIDTH and EGL_HEIGHT are
      // non-negative values
      break;

      case EGL_BAD_MATCH:
      // Check window and EGLConfig attributes to determine
      // compatibility and pbuffer-texture parameters
      break;
   }
}

// Check the size of pbuffer that was allocated
EGLint width;
EGLint height;

if ( !eglQuerySurface ( display, pbuffer, EGL_WIDTH, &width ) ||
     !eglQuerySurface ( display, pbuffer, EGL_HEIGHT, &height ))
{
   // Unable to query surface information
}
```

Pbuffers support all OpenGL ES 3.0 rendering facilities, just as windows do. The major difference—aside from the fact that you cannot display a pbuffer on the screen—is that instead of swapping buffers when you are finished rendering as you do with a window, you either copy the values from a pbuffer to your application or modify the binding of the pbuffer as a texture.

Creating a Rendering Context

A rendering context is a data structure internal to OpenGL ES 3.0 that contains all of the state information required for operation. For example, it contains references to the vertex and fragment shaders and the array of vertex data used in the example program in Chapter 2, "Hello Triangle: An OpenGL ES 3.0 Example." Before OpenGL ES 3.0 can draw, it needs to have a context available for its use.

To create a context, use the following function:

```
EGLContext eglCreateContext(EGLDisplay display,
                            EGLConfig config,
                            EGLContext shareContext,
                            const EGLint *attribList)
```

display	specifies the EGL display connection
config	specifies the configuration
shareContext	allows multiple EGL contexts to share specific types of data, such as shader programs and texture maps; use `EGL_NO_CONTEXT` for no sharing
attribList	specifies the list of attributes for the context to be created; only a single attribute is accepted, `EGL_CONTEXT_CLIENT_VERSION`

Once again, you will need the display connection and the `EGLConfig` that best represents your application's requirements. The third parameter, *shareContext*, allows multiple `EGLContext`s to share specific types of data, such as shader programs and texture maps. For the time being, we pass `EGL_NO_CONTEXT` in as the value for `shareContext`, indicating that we are not sharing resources with any other contexts.

Finally, as with many EGL calls, a list of attributes specific to `eglCreate-Context`'s operation is specified. In this case, a single attribute is accepted, `EGL_CONTEXT_CLIENT_VERSION`, which is discussed in Table 3-6.

Table 3-6 Attributes for Context Creation Using `eglCreateContext`

Token	Description	Default Value
`EGL_CONTEXT_CLIENT_VERSION`	Specifies the type of context associated with the version of OpenGL ES that you are using	1 (specifies an OpenGL ES 1.X context)

Because we want to use OpenGL ES 3.0, we will always have to specify this attribute to obtain the right type of context.

When `eglCreateContext` succeeds, it returns a handle to the newly created context. If a context cannot be created, then `eglCreateContext` returns `EGL_NO_CONTEXT`, and the reason for the failure is set and can be obtained by calling `eglGetError`. With our current knowledge, the only reason that `eglCreateContext` would fail is if the `EGLConfig` we provide is not valid, in which case the error returned by `eglGetError` is `EGL_BAD_CONFIG`.

Example 3-6 shows how to create a context after selecting an appropriate `EGLConfig`.

Example 3-6 Creating an EGL Context

```
const EGLint attribList[] =
{
   // EGL_KHR_create_context is required
   EGL_CONTEXT_CLIENT_VERSION, 3,
   EGL_NONE
};

EGLContext context = eglCreateContext ( display, config,
                                        EGL_NO_CONTEXT,
                                        attribList );

if ( context == EGL_NO_CONTEXT )
{
   EGLError error = eglGetError ( );

   if ( error == EGL_BAD_CONFIG )
   {
       // Handle error and recover
   }
}
```

Other errors may be generated by `eglCreateContext`, but for the moment we will check for only bad `EGLConfig` errors.

After successfully creating an `EGLContext`, we need to complete one final step before we can render.

Making an EGLContext Current

As an application might have created multiple `EGLContext`s for various purposes, we need a way to associate a particular `EGLContext` with our rendering surface—a process commonly called "make current."

To associate a particular `EGLContext` with an `EGLSurface`, use the call

```
EGLBoolean eglMakeCurrent(EGLDisplay display,
                          EGLSurface draw,
                          EGLSurface read,
                          EGLContext context)
```

display	specifies the EGL display connection
draw	specifies the EGL draw surface
read	specifies the EGL read surface
context	specifies the EGL rendering context to be attached to the surfaces

This function returns `EGL_TRUE` if the call succeeded. On failure, it returns `EGL_FALSE`.

You probably noticed that this call takes two `EGLSurface`s. Although this approach allows flexibility that we will exploit in our discussion of advanced EGL usage, we set both read and draw to the same value, the window that we created previously.

Note: Because the EGL specification requires a flush for `eglMakeCurrent` implementation, this call is expensive for tile-based architectures.

Putting All Our EGL Knowledge Together

This chapter concludes with a complete example showing the entire process starting with the initialization of the EGL through binding an `EGLContext` to an `EGLSurface`. We will assume that a native window has already been created, and that if any errors occur, the application will terminate.

In fact, Example 3-7 is similar to what is done in `esCreateWindow`, our homegrown function that wraps the required EGL window creation code, as shown in Chapter 2, "Hello Triangle: An OpenGL ES 3.0 Example," except for those routines that separate the creation of the window and the context (for reasons that we discuss later).

Example 3-7 A Complete Routine for Creating an EGL Window

```
EGLBoolean initializeWindow ( EGLNativeWindow nativeWindow )
{
   const EGLint configAttribs[] =
   {
      EGL_RENDER_TYPE, EGL_WINDOW_BIT,
      EGL_RED_SIZE, 8,
      EGL_GREEN_SIZE, 8,
      EGL_BLUE_SIZE, 8,
      EGL_DEPTH_SIZE, 24,
      EGL_NONE
   };

   const EGLint contextAttribs[] =
   {
      EGL_CONTEXT_CLIENT_VERSION, 3,
      EGL_NONE
   };

   EGLDisplay display = eglGetDisplay ( EGL_DEFAULT_DISPLAY )
   if ( display == EGL_NO_DISPLAY )
   {
      return EGL_FALSE;
   }

   EGLint major, minor;
   if ( !eglInitialize ( display, &major, &minor ) )
   {
      return EGL_FALSE;
   }

   EGLConfig config;
   EGLint numConfigs;
   if ( !eglChooseConfig ( display, configAttribs, &config, 1,
                           &numConfigs ) )
   {
         return EGL_FALSE;
   }

   EGLSurface window = eglCreateWindowSurface ( display, config,
                                                nativeWindow, NULL );
   if (window == EGL_NO_SURFACE)
   {
      return EGL_FALSE;
   }
   EGLContext context = eglCreateContext ( display, config,
                                           EGL_NO_CONTEXT,
                                           contextAttribs);
   if ( context == EGL_NO_CONTEXT )
   {
      return EGL_FALSE;
   }

   if ( !eglMakeCurrent ( display, window, window, context ) )
   {
      return EGL_FALSE;
   }
   return EGL_TRUE;
}
```

This code would be similar if an application made the call in Example 3-8 to open a 512 × 512 window.

Example 3-8 Creating a Window Using the `esUtil` Library

```
ESContext esContext;
const char* title = "OpenGL ES Application Window Title";

if (esCreateWindow(&esContext, title, 512, 512,
                   ES_WINDOW_RGB | ES_WINDOW_DEPTH))
{
   // Window creation failed
}
```

The last parameter to `esCreateWindow` specifies the characteristics we want in our window, and specifies as a bitmask of the following values:

- `ES_WINDOW_RGB`—Specify an RGB-based color buffer.
- `ES_WINDOW_ALPHA`—Allocate a destination alpha buffer.
- `ES_WINDOW_DEPTH`—Allocate a depth buffer.
- `ES_WINDOW_STENCIL`—Allocate a stencil buffer.
- `ES_WINDOW_MULTISAMPLE`—Allocate a multisample buffer.

Specifying these values in the window configuration bitmask will add the appropriate tokens and values into the `EGLConfig` attributes list (i.e., `configAttribs` in the preceding example).

Synchronizing Rendering

You might encounter situations in which you need to coordinate the rendering of multiple graphics APIs into a single window. For example, you might find it easier to use OpenVG or find the native windowing system's font rendering functions better suited for drawing characters into a window than OpenGL ES 3.0. In such cases, you will need to have your application allow the various libraries to render into the shared window. EGL has a few functions to help with your synchronization tasks.

If your application is rendering only with OpenGL ES 3.0, then you can guarantee that all rendering has occurred by simply calling `glFinish` (or more efficient sync objects and fences, which are discussed in Chapter 13, "Sync Objects and Fences").

However, if you are using more than one Khronos API for rendering (such as OpenVG) and you might not know which API is used before switching to the window system's native rendering API, you can call this function:

```
EGLBoolean eglWaitClient()
```

Delays execution of the client until all rendering through a Khronos API (e.g., OpenGL ES 3.0, OpenGL, or OpenVG) is completed. On success, it returns `EGL_TRUE`. On failure, it returns `EGL_FALSE` and an `EGL_BAD_CURRENT_SURFACE` error is posted.

This function's operation is similar to that of `glFinish`, but it works regardless of which Khronos API is currently in operation.

Likewise, if you need to guarantee that the native windowing system's rendering is completed, call this function:

```
EGLBoolean eglWaitNative(EGLint engine)
```

`engine`	specifies the renderer to wait for rendering completion

EGL_CORE_NATIVE_ENGINE is always accepted, and represents the most common engine supported; other engines are implementation specific, and are specified through EGL extensions. EGL_TRUE is returned on success. On failure, EGL_FALSE is returned and an EGL_BAD_PARAMETER error is posted.

Summary

In this chapter, you learned about EGL, the API for creating surfaces and rendering contexts for OpenGL ES 3.0. Now, you know how to initialize EGL; query various EGL attributes; and create an on-screen, off-screen rendering area and rendering context using EGL. You have learned enough EGL to do everything you will need for rendering with OpenGL ES 3.0. In the next chapter, we show you how to create OpenGL ES shaders and programs.

Chapter 4

Shaders and Programs

Chapter 2, "Hello, Triangle: An OpenGL ES 3.0 Example," introduced you to a simple program that draws a single triangle. In that example, we created two shader objects (one for the vertex shader and one for the fragment shader) and a single program object to render the triangle. Shader objects and program objects are fundamental concepts when working with shaders in OpenGL ES 3.0. In this chapter, we provide the full details on how to create shaders, compile them, and link them together into a program object. The details of writing vertex and fragment shaders come later in this book. For now, we focus on the following topics:

- Shader and program object overview
- Creating and compiling a shader
- Creating and linking a program
- Getting and setting uniforms
- Getting and setting attributes
- Shader compiler and program binaries

Shaders and Programs

There are two fundamental object types you need to create to render with shaders: *shader objects* and *program objects*. The best way to think of a shader object and a program object is by comparison to a C compiler and linker. A C compiler generates object code (e.g., `.obj` or `.o` files) for a piece of source code. After the object files have been created, the C linker then links the object files into a final program.

A similar paradigm is used in OpenGL ES for representing shaders. The shader object is an object that contains a single shader. The source code is given to the shader object, and then the shader object is compiled into object form (like an `.obj` file). After compilation, the shader object can then be attached to a program object. A program object gets multiple shader objects attached to it. In OpenGL ES, each program object will need to have one vertex shader object and one fragment shader object attached to it (no more and no less), unlike in desktop OpenGL. The program object is linked into a final "executable," which can then be used to render.

The general process to get a linked shader object involves six steps:

1. Create a vertex shader object and a fragment shader object.
2. Attach source code to each of the shader objects.
3. Compile the shader objects.
4. Create a program object.
5. Attach the compiled shader objects to the program object.
6. Link the program object.

If there are no errors, you can then tell the GL to use this program for drawing any time you like. The next sections detail the API calls you use to execute this process.

Creating and Compiling a Shader

The first step in working with a shader object is to create it. This is done using `glCreateShader`.

```
GLuint    glCreateShader(GLenum type)
```

type	the type of the shader to create, either `GL_VERTEX_SHADER` or `GL_FRAGMENT_SHADER`

Calling `glCreateShader` causes a new vertex or fragment shader to be created, depending on the `type` passed in. The return value is a handle to the new shader object. When you are finished with a shader object, you can delete it using `glDeleteShader`.

```
void   glDeleteShader(GLuint shader)
```

shader	handle to the shader object to delete

Note that if a shader is attached to a program object (more on this later), calling `glDeleteShader` will not immediately delete the shader. Rather, the shader will be marked for deletion and its memory will be freed once the shader is no longer attached to any program objects.

Once you have a shader object created, typically the next thing you will do is provide the shader source code using `glShaderSource`.

```
void   glShaderSource(GLuint shader,   GLsizei count,
                      const GLchar* const *string,
                      const GLint *length)
```

shader	handle to the shader object.
count	the number of shader source strings. A shader can be composed of a number of source strings, although each shader can have only one `main` function.
string	pointer to an array of strings holding *count* number of shader source strings.
length	pointer to an array of *count* integers that holds the size of each respective shader string. If *length* is `NULL`, the shader strings are assumed to be null terminated. If *length* is not `NULL`, then each element of *length* holds the number of characters in the corresponding shader in the *string* array. If the value of *length* for any element is less than zero, then that string is assumed to be null terminated.

Once the shader source has been specified, the next step is to compile the shader using `glCompileShader`.

```
void   glCompileShader(GLuint shader)
```

shader	handle to the shader object to compile

Calling glCompileShader will cause the shader source code that has been stored in the shader object to be compiled. As with any normal language compiler, the first thing you want to know after compiling is whether there were any errors. You can use glGetShaderiv to query for this information, along with other information about the shader object.

```
void   glGetShaderiv(GLuint shader,   GLenum pname,
                     GLint *params)
```

shader	handle to the shader object to get information about
pname	the parameter to get information about; can be GL_COMPILE_STATUS GL_DELETE_STATUS GL_INFO_LOG_LENGTH GL_SHADER_SOURCE_LENGTH GL_SHADER_TYPE
params	pointer to integer storage location for the result of the query

To check whether a shader has compiled successfully, you can call glGetShaderiv on the shader object with the GL_COMPILE_STATUS argument for *pname*. If the shader compiled successfully, the result will be GL_TRUE. If the shader failed to compile, the result will be GL_FALSE. If the shader does fail to compile, the compile errors will be written into the *info log*. The info log is a log written by the compiler that contains any error messages or warnings. It can be written with information even if the compile operation is successful. To check the info log, its length can be queried using GL_INFO_LOG_LENGTH. The info log itself can be retrieved using glGetShaderInfoLog (described next). Querying for GL_SHADER_TYPE will return whether the shader is a GL_VERTEX_SHADER or GL_FRAGMENT_SHADER. Querying for GL_SHADER_SOURCE_LENGTH returns the length of the shader source code, including the null terminator. Finally, querying for GL_DELETE_STATUS returns whether the shader has been marked for deletion using glDeleteShader.

After compiling the shader and checking the info log length, you might want to retrieve the info log (especially if compilation failed, to find out why). To do so, you first need to query for the GL_INFO_LOG_LENGTH and allocate a string with sufficient storage to store the info log. The info log can then be retrieved using glGetShaderInfoLog.

```
void   glGetShaderInfoLog(GLuint shader,   GLsizei maxLength,
                          GLsizei *length,   GLchar *infoLog)
```

shader	handle to the shader object for which to get the info log
maxLength	the size of the buffer in which to store the info log
length	the length of the info log written (minus the null terminator); if the length does not need to be known, this parameter can be `NULL`
infoLog	pointer to the character buffer in which to store the info log

The info log does not have any mandated format or required information. Nevertheless, most OpenGL ES 3.0 implementations will return error messages that contain the line number of the source code on which the compiler was working when it detected the error. Some implementations will also provide warnings or additional information in the log. For example, the following error message is produced by the compiler when the shader source code contains an undeclared variable:

```
ERROR: 0:10: 'i_position' : undeclared identifier
ERROR: 0:10: 'assign' : cannot convert from '4X4 matrix of float'
to 'vertex out/varying 4-component vector of float'
ERROR: 2 compilation errors. No code generated.
```

At this point, we have shown you all of the functions you need to create a shader, compile it, find out the compile status, and query the info log. For review, Example 4-1 shows the code from Chapter 2, "Hello Triangle: An OpenGL ES 3.0 Example," to load a shader that uses the functions just described.

Example 4-1 Loading a Shader

```
GLuint LoadShader ( GLenum type, const char *shaderSrc )
{
   GLuint shader;
   GLint compiled;

   // Create the shader object
   shader = glCreateShader ( type );

   if ( shader == 0 )
   {
      return 0;
   }
```

(continues)

Example 4-1 Loading a Shader *(continued)*

```
   // Load the shader source
   glShaderSource ( shader, 1, &shaderSrc, NULL );

   // Compile the shader
   glCompileShader ( shader );

   // Check the compile status
   glGetShaderiv ( shader, GL_COMPILE_STATUS, &compiled );

   if ( !compiled )
   {
      // Retrieve the compiler messages when compilation fails
      GLint infoLen = 0;

      glGetShaderiv ( shader, GL_INFO_LOG_LENGTH, &infoLen );

      if ( infoLen > 1 )
      {
         char* infoLog = malloc ( sizeof ( char ) * infoLen );

         glGetShaderInfoLog ( shader, infoLen, NULL, infoLog );
         esLogMessage("Error compiling shader:\n%s\n", infoLog);

         free ( infoLog );
      }

      glDeleteShader ( shader );
      return 0;

   }

   return shader;

}
```

Creating and Linking a Program

Now that we have shown you how to create shader objects, the next step is to create a program object. As previously described, a program object is a container object to which you attach shaders and link a final executable program. The function calls to manipulate program objects are similar to shader objects. You create a program object by using `glCreateProgram`.

```
GLuint   glCreateProgram()
```

You might notice that `glCreateProgram` does not take any arguments; it simply returns a handle to a new program object. You delete a program object by using `glDeleteProgram`.

```
Void   glDeleteProgram(GLuint program)
```

program	handle to the program object to delete

Once you have a program object created, the next step is to attach shaders to it. In OpenGL ES 3.0, each program object needs to have one vertex shader and one fragment shader object attached to it. To attach shaders to a program, you use `glAttachShader`.

```
void   glAttachShader(GLuint program,   GLuint shader)
```

program	handle to the program object
shader	handle to the shader object to attach to the program

This function attaches the shader to the given program. Note that a shader can be attached at any point—it does not necessarily need to be compiled or even have source code before being attached to a program. The only requirement is that every program object must have one and only one vertex shader and fragment shader object attached to it. In addition to attaching shaders, you can detach shaders using `glDetachShader`.

```
void   glDetachShader(GLuint program,   GLuint shader)
```

program	handle to the program object
shader	handle to the shader object to detach from the program

Once the shaders have been attached (and the shaders have been successfully compiled), we are finally ready to link the shaders together. Linking a program object is accomplished using `glLinkProgram`.

```
void   glLinkProgram(GLuint program)
```

program	handle to the program object to link

The link operation is responsible for generating the final executable program. The linker will check for a number of things to ensure successful linkage. We mention some of these conditions now, but until we describe vertex and fragment shaders in detail, these conditions might be a bit confusing to you. The linker will make sure that any vertex shader output variables that are consumed by the fragment shader are written by the vertex shader (and declared with the same type). The linker will also make sure that any uniforms and uniform buffers declared in both the vertex and fragment shaders have matching types. In addition, the linker will make sure that the final program fits within the limits of the implementation (e.g., the number of attributes, uniforms, or input and output shader variables). Typically, the link phase is the time at which the final hardware instructions are generated to run on the hardware.

After linking a program, you need to check whether the link succeeded. To check the link status, you use `glGetProgramiv`.

```
void   glGetProgramiv(GLuint program,   GLenum pname,
                      GLint *params)
```

program	handle to the program object to get information about

pname	the parameter to get information about; can be
	`GL_ACTIVE_ATTRIBUTES`
	`GL_ACTIVE_ATTRIBUTE_MAX_LENGTH`
	`GL_ACTIVE_UNIFORM_BLOCK`
	`GL_ACTIVE_UNIFORM_BLOCK_MAX_LENGTH`
	`GL_ACTIVE_UNIFORMS`
	`GL_ACTIVE_UNIFORM_MAX_LENGTH`
	`GL_ATTACHED_SHADERS`
	`GL_DELETE_STATUS`
	`GL_INFO_LOG_LENGTH`
	`GL_LINK_STATUS`
	`GL_PROGRAM_BINARY_RETRIEVABLE_HINT`
	`GL_TRANSFORM_FEEDBACK_BUFFER_MODE`
	`GL_TRANSFORM_FEEDBACK_VARYINGS`
	`GL_TRANSFORM_FEEDBACK_VARYING_MAX_LENGTH`
	`GL_VALIDATE_STATUS`

params	pointer to integer storage location for the result of the query

To check whether a link was successful, you can query for GL_LINK_STATUS. A large number of other queries can also be executed on program objects. Querying for GL_ACTIVE_ATTRIBUTES returns a count of the number of active attributes in the vertex shader. Querying for GL_ACTIVE_ATTRIBUTE_MAX_LENGTH returns the maximum length (in characters) of the largest attribute name; this information can be used to determine how much memory to allocate to store attribute name strings. Likewise, GL_ACTIVE_UNIFORMS and GL_ACTIVE_UNIFORM_MAX_LENGTH return the number of active uniforms and the maximum length of the largest uniform name, respectively. The number of shaders attached to the program object can be queried using GL_ATTACHED_SHADERS. The GL_DELETE_STATUS query returns whether a program object has been marked for deletion. As with shader objects, program objects store an info log, the length of which can be queried for using GL_INFO_LOG_LENGTH. Querying for GL_TRANSFORM_FEEDBACK_BUFFER_MODE returns either GL_SEPARATE_ATTRIBS or GL_INTERLEAVED_ATTRIBS, which is the buffer mode when transform feedback is active. Queries for GL_TRANSFORM_FEEDBACK_VARYINGS and GL_TRANSFORM_FEEDBACK_VARYING_MAX_LENGTH return the number of output variables to capture in transform feedback mode for the program and the maximum length of the output variable names, respectively. The transform feedback is described in Chapter 8, "Vertex Shaders." The number of uniform blocks for programs containing active uniforms and the maximum length of the uniform block names can be queried using GL_ACTIVE_UNIFORM_BLOCKS and GL_ACTIVE_UNIFORM_BLOCK_MAX_LENGTH, respectively. Uniform blocks are described in a later section. Querying for GL_PROGRAM_BINARY_RETRIEVABLE_HINT returns a value indicating whether the binary retrieval hint is currently enabled for program. Finally, the status of the last validation operation can be queried for using GL_VALIDATE_STATUS. The validation of program objects is described later in this section.

After linking the program, we next want to get information from the program info log (particularly if a link failure occurred). Doing so is similar to getting the info log for shader objects.

```
void   glGetProgramInfoLog(GLuint program, GLsizei maxLength,
                           GLsizei *length,
                           GLchar *infoLog)
```

program	handle to the program object for which to get information
maxLength	the size of the buffer in which to store the info log

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`length`	the length of the info log written (minus the null terminator); if the length does not need to be known, this parameter can be `NULL`
`infoLog`	pointer to the character buffer in which to store the info log

Once we have linked the program successfully, we are almost ready to render with it. Before doing so, however, we might want to check whether the program validates. That is, there are certain aspects of execution that a successful link cannot guarantee. For example, perhaps the application never binds valid texture units to samplers. This behavior will not be known at link time, but instead will become apparent at draw time. To check that your program will execute with the current state, you can call `glValidateProgram`.

```
void   glValidateProgram(GLuint program)
```

`program`	handle to the program object to validate

The result of the validation can be checked using `GL_VALIDATE_STATUS` described earlier. The info log will also be updated.

Note: You really want to use `glValidateProgram` only for debugging purposes. It is a slow operation and certainly not something you want to check before every render. In fact, you can get away with never using it if your application is successfully rendering. We want to make you aware that this function does exist, though.

So far, we have shown you the functions needed for creating a program object, attaching shaders to it, linking, and getting the info log. There is one more thing you need to do with a program object before rendering, and that is to set it as the active program using `glUseProgram`.

```
void   glUseProgram(GLuint program)
```

`program`	handle to the program object to make active

Now that we have our program active, we are set to render. Once again, Example 4-2 shows the code from our sample in Chapter 2, “Hello Triangle: An OpenGL ES 3.0 Example,” that uses these functions.

Example 4-2 Create, Attach Shaders to, and Link a Program

```
// Create the program object
programObject = glCreateProgram ( );

if ( programObject == 0 )
{
   return 0;
}

glAttachShader ( programObject, vertexShader );
glAttachShader ( programObject, fragmentShader );

// Link the program
glLinkProgram ( programObject );

// Check the link status
glGetProgramiv ( programObject, GL_LINK_STATUS, &linked );

if ( !linked )
{
   // Retrieve compiler error messages when linking fails
   GLint infoLen = 0;

   glGetProgramiv( programObject, GL_INFO_LOG_LENGTH, &infoLen);

   if ( infoLen > 1 )
   {
      char* infoLog = malloc ( sizeof ( char ) * infoLen );

      glGetProgramInfoLog ( programObject, infoLen, NULL,
                            infoLog );
      esLogMessage ( "Error linking program:\n%s\n", infoLog );

      free ( infoLog );
   }

   glDeleteProgram ( programObject );
   return FALSE;
}

// ...

// Use the program object
glUseProgram ( programObject );
```

Uniforms and Attributes

Once you have a linked program object, there are number of queries that you might want to do on it. First, you will likely need to find out about the active uniforms in your program. Uniforms—as we detail more in the next chapter on the shading language—are variables that store read-only constant values that are passed in by the application through the OpenGL ES 3.0 API to the shader.

Sets of uniforms are grouped into two categories of uniform blocks. The first category is the named uniform block, where the uniform's value is backed by a buffer object called a uniform buffer object (more on that next). The named uniform block is assigned a uniform block index. The following example declares a named uniform block with the name `TransformBlock` containing three uniforms (`matViewProj`, `matNormal`, and `matTexGen`):

```
uniform TransformBlock
{
    mat4 matViewProj;
    mat3 matNormal;
    mat3 matTexGen;
};
```

The second category is the default uniform block for uniforms that are declared outside of a named uniform block. Unlike with the named uniform block, there is no name or uniform block index for default uniform blocks. The following example declares the same three uniforms outside of a named uniform block:

```
uniform mat4 matViewProj;
uniform mat3 matNormal;
uniform mat3 matTexGen;
```

We describe uniform blocks in more detail in the section *Uniform Blocks* in Chapter 5.

If a uniform is declared in both a vertex shader and a fragment shader, it must have the same type, and its value will be the same in both shaders. During the link phase, the linker will assign uniform locations to each of the active uniforms associated with the default uniform block in the program. These locations are the identifiers the application will use to load the uniform with a value. The linker will also assign offsets and strides (for array and matrix type uniforms) for active uniforms associated with the named uniform blocks.

Getting and Setting Uniforms

To query for the list of active uniforms in a program, you first call glGetProgramiv with the GL_ACTIVE_UNIFORMS parameter (as described in the previous section). This will tell you the number of active uniforms in the program. The list includes uniforms in named uniform blocks, default block uniforms declared in shader code, and built-in uniforms used in shader code. A uniform is considered "active" if it was used by the program. In other words, if you declare a uniform in one of your shaders but never use it, the linker will likely optimize that away and not return it in the active uniform list. You can also find out the number of characters (including the null terminator) that the largest uniform name has in the program; this can be done by calling glGetProgramiv with the GL_ACTIVE_UNIFORM_MAX_LENGTH parameter.

Once we know the number of active uniforms and the number of characters needed to store the uniform names, we can find out the details on each uniform using glGetActiveUniform and glGetActiveUniformsiv.

```
void   glGetActiveUniform(GLuint program,   GLuint index,
                          GLsizei bufSize,   GLsizei *length,
                          GLint *size,   GLenum *type,
                          GLchar *name)
```

program	handle to the program object
index	the uniform index to be queried
bufSize	the number of characters in the name array
length	if not NULL, will be written with the number of characters written into the name array (less the null terminator)
size	if the uniform variable being queried is an array, this variable will be written with the maximum array element used in the program (plus 1); if the uniform variable being queried is not an array, this value will be 1
type	will be written with the uniform type; can be GL_FLOAT, GL_FLOAT_VEC2, GL_FLOAT_VEC3, GL_FLOAT_VEC4, GL_INT, GL_INT_VEC2, GL_INT_VEC3, GL_INT_VEC4, GL_UNSIGNED_INT, GL_UNSIGNED_INT_VEC2, GL_UNSIGNED_INT_VEC3, GL_UNSIGNED_INT_VEC4, GL_BOOL, GL_BOOL_VEC2, GL_BOOL_VEC3, GL_BOOL_VEC4, GL_FLOAT_MAT2,

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	`GL_FLOAT_MAT3, GL_FLOAT_MAT4, GL_FLOAT_MAT2x3, GL_FLOAT_MAT2x4, GL_FLOAT_MAT3x2, GL_FLOAT_MAT3x4, GL_FLOAT_MAT4x2, GL_FLOAT_MAT4x3, GL_SAMPLER_2D, GL_SAMPLER_3D, GL_SAMPLER_CUBE, GL_SAMPLER_2D_SHADOW, GL_SAMPLER_2D_ARRAY, GL_SAMPLER_2D_ARRAY_SHADOW, GL_SAMPLER_CUBE_SHADOW, GL_INT_SAMPLER_2D, GL_INT_SAMPLER_3D, GL_INT_SAMPLER_CUBE, GL_INT_SAMPLER_2D_ARRAY, GL_UNSIGNED_INT_SAMPLER_2D, GL_UNSIGNED_INT_SAMPLER_3D, GL_UNSIGNED_INT_SAMPLER_CUBE, GL_UNSIGNED_INT_SAMPLER_2D_ARRAY`
name	will be written with the name of the uniform up to *bufSize* number of characters; this will be a null-terminated string

```
void   glGetActiveUniformsiv(GLuint program,   GLsizei count,
                             const GLuint *indices,
                             GLenum pname,   GLint *params)
```

program	handle to the program object
count	the number of elements in the array of `indices`
indices	a list of uniform indices
pname	property of each uniform in the uniform indices to be written into the elements of `params`; can be `GL_UNIFORM_TYPE, GL_UNIFORM_SIZE, GL_UNIFORM_NAME_LENGTH, GL_UNIFORM_BLOCK_INDEX, GL_UNIFORM_OFFSET, GL_UNIFORM_ARRAY_STRIDE, GL_UNIFORM_MATRIX_STRIDE, GL_UNIFORM_IS_ROW_MAJOR`
params	will be written with the result specified by *pname* corresponding to each uniform in the uniform indices

Using `glGetActiveUniform`, you can determine nearly all of the properties of the uniform. You can determine the name of the uniform variable along with its type. In addition, you can find out if the variable is an array, and if so what the maximum element used in the array was. The name of the uniform is necessary to find the uniform's location, and the type and size are needed to figure out how to load it with data. Once we have the name of the uniform, we can find its location using `glGetUniformLocation`. The uniform location is an integer value used to identify the location of the uniform in the program (note that uniforms in the named uniform blocks are not assigned a location). That location value is used by subsequent calls for loading uniforms with values (e.g., `glUniform1f`).

```
GLint   glGetUniformLocation(GLuint program,
                             const GLchar* name)
```

program	handle to the program object
name	the name of the uniform for which to get the location

This function will return the location of the uniform given by *name*. If the uniform is not an active uniform in the program, then the return value will be –1. Once we have the uniform location along with its type and array size, we can then load the uniform with values. A number of different functions for loading uniforms are available, with different functions for each uniform type.

```
void  glUniform1f(GLint location, GLfloat x)
void  glUniform1fv(GLint location, GLsizei count,
                   const GLfloat* value)
void  glUniform1i(GLint location, GLint x)
void  glUniform1iv(GLint location, GLsizei count,
                   const GLint* value)
void  glUniform1ui(GLint location, GLuint x)
void  glUniform1uiv(GLint location, GLsizei count,
                    const GLuint* value)
void  glUniform2f(GLint location, GLfloat x, GLfloat y)
void  glUniform2fv(GLint location, GLsizei count,
                   const GLfloat* value)
void  glUniform2i(GLint location, GLint x, GLint y)
void  glUniform2iv(GLint location, GLsizei count,
                   const GLint* value)
void  glUniform2ui(GLint location, GLuint x, GLuint y)
void  glUniform2uiv(GLint location, GLsizei count,
                     const GLuint* value)
```

(continues)

(continued)

```
void  glUniform3f(GLint location, GLfloat x, GLfloat y,
                  GLfloat z)
void  glUniform3fv(GLint location, GLsizei count,
                   const GLfloat* value)
void  glUniform3i(GLint location, GLint x, GLint y,
                  GLint z)
void  glUniform3iv(GLint location, GLsizei count,
                   const GLint* value)
void  glUniform3ui(GLint location, GLuint x, GLuint y,
                   GLuint z)
void  glUniform3uiv(GLint location, GLsizei count,
                    const GLuint* value)
void  glUniform4f(GLint location, GLfloat x, GLfloat y,
                  GLfloat z, GLfloat w);
void  glUniform4fv(GLint location, GLsizei count,
                   const GLfloat* value)
void  glUniform4i(GLint location, GLint x, GLint y,
                  GLint z, GLint w)
void  glUniform4iv(GLint location, GLsizei count,
                   const GLint* value)
void  glUniform4ui(GLint location, GLuint x, GLuint y,
                   GLuint z, GLuint w)
void  glUniform4uiv(GLint location, GLsizei count,
                    const GLuint* value)
void  glUniformMatrix2fv(GLint location, GLsizei count,
                         GLboolean transpose,
                         const GLfloat* value)
void  glUniformMatrix3fv(GLint location, GLsizei count,
                         GLboolean transpose,
                         const GLfloat* value)
void  glUniformMatrix4fv(GLint location, GLsizei count,
                         GLboolean transpose,
                         const GLfloat* value)
void  glUniformMatrix2x3fv(GLint location, GLsizei count,
                           GLboolean transpose,
                           const GLfloat* value)
void  glUniformMatrix3x2fv(GLint location, GLsizei count,
                           GLboolean transpose,
                           const GLfloat* value)
```

```
void  glUniformMatrix2x4fv(GLint location, GLsizei count,
                           GLboolean transpose,
                           const GLfloat* value)
void  glUniformMatrix4x2fv(GLint location, GLsizei count,
                           GLboolean transpose,
                           const GLfloat* value)
void  glUniformMatrix3x4fv(GLint location, GLsizei count,
                           GLboolean transpose,
                           const GLfloat* value)
void  glUniformMatrix4x3fv(GLint location, GLsizei count,
                           GLboolean transpose,
                           const GLfloat* value)
```

location	the location of the uniform to load with a value.
count	specifies the number of array elements to be loaded (for vector commands) or the number of matrices to be modified (for matrix commands).
transpose	for matrix commands, specifies whether the matrix is in column major order (with `GL_FALSE`) or row major order (with `GL_TRUE`).
x, y, z, w	updated uniform values
value	a pointer to an array of count elements

The functions for loading uniforms are mostly self-explanatory. The determination of which function you need to use for loading the uniform is based on the `type` returned by the `glGetActiveUniform` function. For example, if the type is `GL_FLOAT_VEC4`, then either `glUniform4f` or `glUniform4fv` can be used. If the `size` returned by `glGetActiveUniform` is greater than 1, then `glUniform4fv` would be used to load the entire array in one call. If the uniform is not an array, then either `glUniform4f` or `glUniform4fv` could be used.

One point worth noting here is that the `glUniform*` calls do not take a program object handle as a parameter. The reason is that the `glUniform*` calls always act on the current program that is bound with `glUseProgram`. The uniform values themselves are kept with the program object. That is, once you set a uniform to a value in a program object, that value will remain with it even if you make another program active. In that sense, we can say that uniform values are *local to a program object.*

The block of code in Example 4-3 demonstrates how you would go about querying for uniform information on a program object using the functions we have described.

Example 4-3 Querying for Active Uniforms

```
GLint maxUniformLen;
GLint numUniforms;
char *uniformName;
GLint index;

glGetProgramiv ( progObj, GL_ACTIVE_UNIFORMS, &numUniforms );
glGetProgramiv ( progObj, GL_ACTIVE_UNIFORM_MAX_LENGTH,
                 &maxUniformLen );

uniformName = malloc ( sizeof ( char ) * maxUniformLen );

for ( index = 0; index < numUniforms; index++ )
{
   GLint size;
   GLenum type;
   GLint location;

   // Get the uniform info
   glGetActiveUniform ( progObj, index, maxUniformLen, NULL,
                        &size, &type, uniformName );

   // Get the uniform location
   location = glGetUniformLocation ( progObj, uniformName );

   switch ( type )
   {
   case GL_FLOAT:
      //
      break;

   case GL_FLOAT_VEC2:
      //
      break;

   case GL_FLOAT_VEC3:
      //
      break;

   case GL_FLOAT_VEC4:
      //
      break;

   case GL_INT:
      //
      break;

   // ... Check for all the types ...
```

Example 4-3 Querying for Active Uniforms *(continued)*

```
   default:
      // Unknown type
      break;

   }

}
```

Uniform Buffer Objects

You can share uniforms between shaders in a program or even between programs by using a buffer object to store uniform data. Such buffer objects are called uniform buffer objects. Using uniform buffer objects, you can potentially reduce the API overhead when updating large blocks of uniforms. In addition, this approach increases the potential storage available for uniforms because you are not limited by the default uniform block size.

To update the uniform data in a uniform buffer object, you can modify the contents of the buffer object using commands such as `glBufferData`, `glBufferSubData`, `glMapBufferRange`, and `glUnmapBuffer` (these commands are described in Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects") rather than using the `glUniform*` commands described in the previous section.

In the uniform buffer objects, uniforms are represented in memory as follows:

- Members of type `bool`, `int`, `uint`, and `float` are stored in memory at the specified offset as single `uint`-typed, `int`-typed, `uint`-typed, and `float`-typed components, respectively.
- Vectors with basic data types of `bool`, `int`, `uint`, or `float` are stored in consecutive memory locations beginning at the specified offset, with the first component at the lowest offset.
- Column-major matrices with C columns and R rows are treated as an array of C floating-point column vectors, each consisting of R components. Similarly, row-major matrices with R rows and C columns are treated as an array of R floating-point row vectors, each consisting of C components. While the column or row vectors are stored consecutively, they may be stored with gaps by the implementation. The offset between two vectors in the matrix is referred to as the column or row stride (`GL_UNIFORM_MATRIX_STRIDE`) and can be queried in a linked program using `glGetActiveUniformsiv`.

- Arrays of scalars, vectors, and matrices are stored in memory by element order, with array member zero placed at the lowest offset. The offset between each pair of elements in the array is constant and referred to as the array stride (`GL_UNIFORM_ARRAY_STRIDE`) and can be queried in a linked program using `glGetActiveUniformsiv`.

Unless you use the `std140` uniform block layout (the default), you will need to query the program object for the byte offsets and strides to set uniform data in the uniform buffer object. The `std140` layout guarantees a specific packing behavior with an explicit layout specification defined by the OpenGL ES 3.0 specification. Thus using `std140` layout allows you to share the uniform block between different OpenGL ES 3.0 implementations. Other packing formats (see Table 5-4) may allow some OpenGL ES 3.0 implementations to pack the data more tightly together than the `std140` layout.

The following is an example of a named uniform block `LightBlock` using the `std140` layout:

```
layout (std140) uniform LightBlock
{
   vec3 lightDirection;
   vec4 lightPosition;
};
```

The `std140` layout is specified as follows (adapted from the OpenGL ES 3.0 specification). When the uniform block contains the following member:

1. A scalar variable—The base alignment is the size of the scalar. For example, `sizeof(GLint)`.
2. A two-component vector—The base alignment is twice the size of the underlying component type size.
3. A three-component or four-component vector—The base alignment is four times the size of the underlying component type size.
4. An array of scalars or vectors—The base alignment and array stride are set to match the base alignment of a single element array. The entire array is padded to a multiple of the size of a `vec4`.
5. A column-major matrix with C columns and R rows—Stored as an array of C vectors with R components according to rule 4.
6. An array of M column-major matrices with C columns and R rows—Stored as M × C vectors with R components according to rule 4.

7. A row-major matrix with C columns and R rows—Stored as an array of R vectors with C components according to rule 4.
8. An array of M row-major matrices with C columns and R rows—Stored as M × R vectors with C components according to rule 4.
9. A single structure—The offset and size are calculated according to the preceding rules. The structure's size will be padded to a multiple of the size of a `vec4`.
10. An array of S structures—The base alignment is calculated according to the alignment of the element of the array. The element of the array is calculated according to rule 9.

Similar to how a uniform location value is used to refer to a uniform, a uniform block index is used to refer to a uniform block. You can retrieve the uniform block index using `glGetUniformBlockIndex`.

```
GLuint   glGetUniformBlockIndex(GLuint program,
                                const GLchar *blockName)
```

program	handle to the program object
blockName	the name of the uniform block for which to get the index

From the uniform block index, you can determine the details of the active uniform block using `glGetActiveUniformBlockName` (to get the block name) and `glGetActiveUniformBlockiv` (to get many properties of the uniform block).

```
void   glGetActiveUniformBlockName(GLuint program,
                                   GLuint index,
                                   GLsizei bufSize,
                                   GLsizei *length,
                                   GLchar *blockName)
```

program	handle to the program object
index	the uniform block index to be queried
bufSize	the number of characters in the name array
length	if not `NULL`, will be written with the number of characters written into the name array (less the null terminator)

(continues)

(continued)

blockName	will be written with the name of the uniform up to *bufSize* number of characters; this will be a null-terminated string

```
void   glGetActiveUniformBlockiv(GLuint program,
                                 GLuint index,
                                 GLenum pname,
                                 GLint *params)
```

program	handle to the program object
index	the uniform block index to be queried

pname	property of the uniform block index to be written into `params`; can be
	`GL_UNIFORM_BLOCK_BINDING`
	`GL_UNIFORM_BLOCK_DATA_SIZE`
	`GL_UNIFORM_BLOCK_NAME_LENGTH`
	`GL_UNIFORM_BLOCK_ACTIVE_UNIFORMS`
	`GL_UNIFORM_BLOCK_ACTIVE_UNIFORM_INDICES`
	`GL_UNIFORM_BLOCK_REFERENCED_BY_VERTEX_SHADER`
	`GL_UNIFORM_BLOCK_REFERENCED_BY_FRAGMENT_SHADER`

params	will be written with the result specified by *pname*

Querying for `GL_UNIFORM_BLOCK_BINDING` returns the last buffer binding point for the uniform block (zero, if this block does not exist). The `GL_UNIFORM_BLOCK_DATA_SIZE` argument returns the minimum total buffer object size to hold all the uniforms for the uniform block, while querying for `GL_UNIFORM_BLOCK_NAME_LENGTH` returns the total length (including the null terminator) of the name of the uniform block. The number of active uniforms in the uniform block can be queried using `GL_UNIFORM_BLOCK_ACTIVE_UNIFORMS`. The `GL_UNIFORM_BLOCK_ACTIVE_NUMBER_INDICES` query returns a list of the active uniform indices in the uniform block. Finally, querying for `GL_UNIFORM_BLOCK_REFERENCED_BY_VERTEX_SHADER` and `GL_UNIFORM_BLOCK_REFERENCED_BY_FRAGMENT_SHADER` returns a boolean value, whether the uniform block is referenced by the vertex or fragment shader in the program, respectively.

Once you have the uniform block index, you can associate the index with a uniform block binding point in the program by calling `glUniformBlockBinding`.

```
void   glUniformBlockBinding(GLuint program,
                             GLuint blockIndex,
                             GLuint blockBinding)
```

program	handle to the program object
blockIndex	index of the uniform block
blockBinding	uniform buffer object binding point

Finally, you can bind the uniform buffer object to the `GL_UNIFORM_BUFFER` target and a uniform block binding point in the program using `glBindBufferRange` or `glBindBufferBase`.

```
void   glBindBufferRange(GLenum target, GLuint index,
                         GLuint buffer, GLintptr offset,
                         GLsizeiptr size)
void   glBindBufferBase(GLenum target, GLuint index,
                        GLuint buffer)
```

target	must be `GL_UNIFORM_BUFFER` or `GL_TRANSFORM_FEEDBACK_BUFFER`
index	the binding index
buffer	the handle to the buffer object
offset	a starting offset in bytes into the buffer object (`glBindBufferRange` only)
size	the amount of data in bytes that can be read from or written to the buffer object (`glBindBufferRange` only)

When programming the uniform blocks, you should pay attention to the following limitations:

- The maximum number of active uniform blocks used by a vertex or fragment shader can be queried using `glGetIntegerv` with `GL_MAX_VERTEX_UNIFORM_BLOCKS` or `GL_MAX_FRAGMENT_UNIFORM_BLOCKS`, respectively. The minimum supported number for any implementation is 12.
- The maximum number of combined active uniform blocks used by all shaders in a program can be queried using `glGetIntegerv` with `GL_MAX_COMBINED_UNIFORM_BLOCKS`. The minimum supported number for any implementation is 24.

- The maximum available storage per uniform buffer can be queried using `glGetInteger64v` with `GL_MAX_UNIFORM_BLOCK_SIZE`, which returns the size in bytes. The minimum supported number for any implementation is 16 KB.

If you violate any of these limits, the program will fail to link.

The following example shows how to set up a uniform buffer object with the named uniform block `LightTransform` described earlier:

```
GLuint blockId, bufferId;
GLint blockSize;
GLuint bindingPoint = 1;
GLfloat lightData[] =
{
   // lightDirection (padded to vec4 based on std140 rule)
   1.0f, 0.0f, 0.0f, 0.0f,

   // lightPosition
   0.0f, 0.0f, 0.0f, 1.0f
};

// Retrieve the uniform block index
blockId = glGetUniformBlockIndex ( program, "LightBlock" );

// Associate the uniform block index with a binding point
glUniformBlockBinding ( program, blockId, bindingPoint );

// Get the size of lightData; alternatively,
// we can calculate it using sizeof(lightData) in this example
glGetActiveUniformBlockiv ( program, blockId,
                            GL_UNIFORM_BLOCK_DATA_SIZE,
                            &blockSize );

// Create and fill a buffer object
glGenBuffers ( 1, &bufferId );
glBindBuffer ( GL_UNIFORM_BUFFER, bufferId );
glBufferData ( GL_UNIFORM_BUFFER, blockSize, lightData,
               GL_DYNAMIC_DRAW);

// Bind the buffer object to the uniform block binding point
glBindBufferBase ( GL_UNIFORM_BUFFER, bindingPoint, buffer );
```

Getting and Setting Attributes

In addition to querying for uniform information on the program object, you will need to use the program object to set up vertex attributes. The queries for vertex attributes are very similar to the uniform queries. You can find the list of active attributes using the `GL_ACTIVE_ATTRIBUTES` query. You can find the properties of an attribute using `glGetActiveAttrib`. A set of routines are then available for setting up vertex arrays to load the vertex attributes with values.

However, setting up vertex attributes really requires a bit more understanding of primitives and the vertex shader than we are ready to delve into right now. Instead, we dedicate an entire chapter (Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects") to vertex attributes and vertex arrays. If you want to find out how to query for vertex attribute info, jump to Chapter 6 and the section *Declaring Vertex Attribute Variables in a Vertex Shader*.

Shader Compiler

When you ask OpenGL ES to compile and link a shader, take a minute to think about what the implementation has to do. The shader code is typically parsed into some sort of intermediate representation, as most compiled languages are (e.g., an Abstract Syntax Tree). A compiler must then convert the abstract representation into machine instructions for the hardware. Ideally, this compiler should also do a great deal of optimization, such as dead-code removal, constant propagation, and more. Performing all this work comes at a price—and this price is primarily CPU time and memory.

OpenGL ES 3.0 implementations must support online shader compilation (the value of `GL_SHADER_COMPILER` retrieved using `glGetBooleanv` must be `GL_TRUE`). You can specify your shaders using `glShaderSource`, as we have done so far in our examples. You can also try to mitigate the resource impact of shader compilation. That is, once you have finished compiling any shaders for your application, you can call `glReleaseShaderCompiler`. This function provides a hint to the implementation that you are done with the shader compiler, so it can free its resources. Note that this function is only a hint; if you decide to compile more shaders using `glCompileShader`, the implementation will need to reallocate its resources for the compiler.

```
void   glReleaseShaderCompiler (void)
```

Provides a hint to the implementation that it can release resources used by the shader compiler. Because this function is only a hint, some implementations may ignore a call to this function.

Program Binaries

Program binaries are the binary representation of a complete compiled and linked program. They are useful because they can be saved to the file system to be reused later, thereby avoiding the cost of online compilation. You may also use program binaries so that you do not have to distribute the shader source codes in your implementation.

You can retrieve the program binary using `glGetProgramBinary` after you have compiled and linked the program successfully.

```
void   glGetProgramBinary(GLuint program, GLsizei bufSize,
                          GLsizei *length, GLenum binaryFormat,
                          GLvoid *binary)
```

program	handle to the program object
bufSize	the maximum number of bytes that may be written into the *binary*
length	the number of bytes in the binary data
binaryFormat	the vendor-specific binary format token
binary	pointer to the binary data generated by the shader compiler

After you have retrieved the program binary, you can save it to the file system or load the program binary back into the implementation using `glProgramBinary`.

```
void   glProgramBinary(GLuint program, GLenum binaryFormat,
                       const GLvoid *binary, GLsizei length)
```

program	handle to the program object
binaryFormat	the vendor-specific binary format token
binary	pointer to the binary data generated by the shader compiler
length	the number of bytes in the binary data

The OpenGL ES specification does not mandate any particular binary format; instead, the binary format is left completely up to the vendor. This obviously means that programs have less portability, but it also means the vendor can create a less burdensome implementation of OpenGL ES 3.0. In fact, the binary format may change from one driver version to another implemented by the same vendor. To ensure that the stored program binary is still compatible, after calling `glProgramBinary`, you can query the `GL_LINK_STATUS` through `glGetProgramiv`. If it is no longer compatible, then you will need to recompile the shader source code.

Summary

In this chapter, you learned how to create, compile, and link shaders into a program. Shader objects and program objects form the most fundamental objects in OpenGL ES 3.0. We discussed how to query the program object for information and how to load uniforms. In addition, you learned how source shaders and program binaries differ and how to use each. Next, you will learn how to write a shader using the OpenGL ES Shading Language.

Chapter 5

OpenGL ES Shading Language

As you saw in earlier chapters, shaders are a fundamental concept that lies at the heart of the OpenGL ES 3.0 API. Every OpenGL ES 3.0 program requires both a vertex shader and a fragment shader to render a meaningful picture. Given the centrality of the concept of shaders to the API, we want to make sure you are grounded in the fundamentals of writing shaders before diving into more details of the graphics API.

This chapter's goal is to make sure you understand the following concepts in the shading language:

- Variables and variable types
- Vector and matrix construction and selection
- Constants
- Structures and arrays
- Operators, control flow, and functions
- Input/output variables, uniforms, uniform blocks, and layout qualifiers
- Preprocessor and directives
- Uniform and interpolator packing
- Precision qualifiers and invariance

You were introduced to some of these concepts in a small amount of detail with the example in Chapter 2, "Hello Triangle: An OpenGL ES 3.0 Example." Now we will fill in the concepts with a lot more detail to make sure you understand how to write and read shaders.

OpenGL ES Shading Language Basics

As you read through this book, you will look at a lot of shaders. If you ever start developing your own OpenGL ES 3.0 application, chances are that you will write a lot of shaders. By now, you should understand the fundamental concepts of what a shader does and how it fits in the pipeline. If not, please go back and review Chapter 1, "Introduction to OpenGL ES 3.0," where we covered the pipeline and described where vertex and fragment shaders fit within it.

What we want to look at now is what exactly makes up a shader. As you have probably already observed, the syntax bears great similarity to that seen in the C programming language. If you can understand C code, you likely will not have much difficulty understanding the syntax of shaders. However, there are certainly some major differences between the two languages, beginning with the version specification and the native data types that are supported.

Shader Version Specification

The first line of your OpenGL ES 3.0 vertex and fragment shaders will always declare a shader version. Declaring the shader version informs the shader compiler which syntax and constructs it can expect to be present in the shader. The compiler checks the shader syntax against the declared version of the shading language used. To declare that your shader uses version 3.00 of the OpenGL ES Shading Language, use the following syntax:

```
#version 300 es
```

Shaders that do not declare a version number are assumed to use revision 1.00 of the OpenGL ES Shading Language. Revision 1.00 of the shading language is the version that was used in OpenGL ES 2.0. For OpenGL ES 3.0, the specification authors decided to match the version numbers for the API and Shading Language, which explains why the number jumped from 1.00 to 3.00 for OpenGL ES 3.0. As described in Chapter 1, "Introduction to OpenGL ES 3.0," the OpenGL ES Shading Language 3.0 adds many new features, including non-square matrices, full integer support, interpolation qualifiers, uniform blocks, layout qualifiers, new built-in functions, full looping, full branching support, and unlimited shader instruction length.

Variables and Variable Types

In computer graphics, two fundamental data types form the basis of transformations: vectors and matrices. These two data types are central to the OpenGL ES Shading Language as well. Specifically, Table 5-1 describes the scalar-, vector-, and matrix-based data types that exist in the shading language.

Table 5-1 Data Types in the OpenGL ES Shading Language

Variable Class	Types	Description
Scalars	`float, int, uint, bool`	Scalar-based data types for floating-point, integer, unsigned integer, and boolean values
Floating-point vectors	`float, vec2, vec3, vec4`	Floating-point–based vector types of one, two, three, or four components
Integer vector	`int, ivec2, ivec3, ivec4`	Integer-based vector types of one, two, three, or four components
Unsigned integer vector	`uint, uvec2, uvec3, uvec4`	Unsigned integer-based vector types of one, two, three, or four components
Boolean vector	`bool, bvec2, bvec3, bvec4`	Boolean-based vector types of one, two, three, or four components
Matrices	`mat2` (or `mat2x2`), `mat2x3`, `mat2x4`, `mat3x2`, `mat3` (or `mat3x3`), `mat3x4`, `mat4x2`, `mat4x3`, `mat4` (or `mat4x4`)	Floating-point based matrices of size 2 × 2, 2 × 3, 2 × 4, 3 × 2, 3 × 3, 3 × 4, 4 × 2, 4 × 3, or 4 × 4

Variables in the shading language must be declared with a type. For example, the following declarations illustrate how to declare a scalar, a vector, and a matrix:

```
float specularAtten;     // A floating-point-based scalar
vec4 vPosition;          // A floating-point-based 4-tuple vector
```

```
mat4 mViewProjection;   // A 4 x 4 matrix variable declaration
ivec2 vOffset;          // An integer-based 2-tuple vector
```

Variables can be initialized either at declaration time or later. Initialization is done through the use of constructors, which are also used for doing type conversions.

Variable Constructors

The OpenGL ES Shading Language has very strict rules regarding type conversion. That is, variables can only be assigned to or operated on other variables of the same type. The reasoning behind not allowing implicit type conversion in the language is that it avoids shader authors encountering unintended conversion that can lead to difficult-to-track-down bugs. To cope with type conversions, a number of constructors are available in the language. You can use constructors for initializing variables and as a way of type-casting between variables of different types. Variables can be initialized at declaration (or later in the shader) through the use of constructors. Each of the built-in variable types has a set of associated constructors.

Let's first look at how constructors can be used to initialize and type-cast between scalar values.

```
float myFloat = 1.0;
float myFloat2 = 1; // ERROR: invalid type conversion
bool  myBool = true;
int   myInt = 0;
int   myInt2 = 0.0; // ERROR: invalid type conversion
myFloat = float(myBool); // Convert from bool -> float
myFloat = float(myInt);  // Convert from int  -> float
myBool  = bool(myInt);   // Convert from int  -> bool
```

Similarly, constructors can be used to convert to and initialize vector data types. The arguments to a vector constructor will be converted to the same basic type as the vector being constructed (`float`, `int`, or `bool`). There are two basic ways to pass arguments to vector constructors:

- If only one scalar argument is provided to a vector constructor, that value is used to set all values of the vector.
- If multiple scalar or vector arguments are provided, the values of the vector are set from left to right using those arguments. If multiple scalar arguments are provided, there must be at least as many components in the arguments as in the vector.

The following shows some examples of constructing vectors:

```
vec4 myVec4 = vec4(1.0);          // myVec4 = {1.0, 1.0, 1.0,
                                  //           1.0}
vec3 myVec3 = vec3(1.0,0.0,0.5);  // myVec3 = {1.0, 0.0, 0.5}
vec3 temp   = vec3(myVec3);       // temp = myVec3
vec2 myVec2 = vec2(myVec3);       // myVec2 = {myVec3.x,
                                  //           myVec3.y}

myVec4 = vec4(myVec2, temp);      // myVec4 = {myVec2.x,
                                  //           myVec2.y,
                                  //           temp.x, temp.y}
```

For matrix construction, the language is flexible. These basic rules describe how matrices can be constructed:

- If only one scalar argument is provided to a matrix constructor, that value is placed in the diagonal of the matrix. For example, `mat4 (1.0)` will create a 4 × 4 identity matrix.
- A matrix can be constructed from multiple vector arguments. For example, a `mat2` can be constructed from two `vec2`s.
- A matrix can be constructed from multiple scalar arguments—one for each value in the matrix, consumed from left to right.

The matrix construction is even more flexible than the basic rules just stated, in that a matrix can basically be constructed from any combination of scalars and vectors as long as enough components are provided to initialize the matrix. Matrices in OpenGL ES are stored in column major order. When using a matrix constructor, the arguments will be consumed to fill the matrix by column. The comments in the following example show how the matrix constructor arguments map into columns.

```
mat3 myMat3 = mat3(1.0, 0.0, 0.0,  // First column
                   0.0, 1.0, 0.0,  // Second column
                   0.0, 1.0, 1.0); // Third column
```

Vector and Matrix Components

The individual components of a vector can be accessed in two ways: by using the "." operator or through array subscripting. Depending on the number of components that make up a given vector, each of the components can be accessed through the use of the swizzles {*x*, *y*, *z*, *w*}, {*r*, *g*, *b*, *a*}, or {*s*, *t*, *p*, *q*}. The reason for the three different naming schemes is that vectors are used interchangeably to represent mathematical vectors, colors, and texture coordinates. The *x*, *r*, or *s* component will always refer to the first element of a vector. The different naming conventions are just provided as a convenience. That said, you cannot mix naming conventions when accessing a vector (in other words, you cannot do something like `.xgr`, as you can use only one naming convention at a time). When using the "." operator, it is also possible to reorder components of a vector in an operation. The following examples show how this can be done.

```
vec3 myVec3 = vec3(0.0, 1.0, 2.0);  // myVec3 = {0.0, 1.0, 2.0}
vec3 temp;

temp = myVec3.xyz;                  // temp = {0.0, 1.0, 2.0}
temp = myVec3.xxx;                  // temp = {0.0, 0.0, 0.0}
temp = myVec3.zyx;                  // temp = {2.0, 1.0, 0.0}
```

In addition to the "." operator, vectors can be accessed using the array subscript "`[]`" operator. In array subscripting, element `[0]` corresponds to *x*, element `[1]` corresponds to *y*, and so forth. Matrices are treated as being composed of a number of vectors. For example, a `mat2` can be thought of as two `vec2`s, a `mat3` as three `vec3`s, and so forth. For matrices, the individual column is selected using the array subscript operator "`[]`", and then each vector can be accessed using the vector access behavior. The following shows some examples of accessing matrices:

```
mat4 myMat4 = mat4(1.0);    // Initialize diagonal to 1.0
                               (identity)

vec4 col0 = myMat4[0];      // Get col0 vector out of the matrix
float m1_1 = myMat4[1][1]; // Get element at [1][1] in matrix
float m2_2 = myMat4[2].z;  // Get element at [2][2] in matrix
```

Constants

It is possible to declare any of the basic types as being constant variables. Constant variables are those whose values do not change within the shader. To declare a constant, you add the `const` qualifier to the declaration. Constant variables must be initialized at declaration time. Some examples of `const` declarations follow:

```
const float zero = 0.0;
const float pi = 3.14159;
const vec4 red = vec4(1.0, 0.0, 0.0, 1.0);
const mat4 identity = mat4(1.0);
```

Just as in C or C++, a variable that is declared as `const` is read-only and cannot be modified within the source.

Structures

In addition to using the basic types provided in the language, it is possible to aggregate variables into structures much like in C. The declaration syntax for a structure in the OpenGL ES Shading Language is shown in the following example:

```
struct fogStruct
{
   vec4 color;
   float start;
   float end;
} fogVar;
```

The preceding definition will result in a new user type named `fogStruct` and a new variable named `fogVar`.

Structures can be initialized using constructors. After a new structure type is defined, a new structure constructor is also defined with the same name as the type. There must be a one-to-one correspondence between types in the structure and those in the constructor. For example, the preceding structure could be initialized using the following construction syntax:

```
struct fogStruct
{
   vec4 color;
   float start;
   float end;
} fogVar;

fogVar = fogStruct(vec4(0.0, 1.0, 0.0, 0.0), // color
                   0.5,                       // start
                   2.0);                      // end
```

The constructor for the structure is based on the name of the type and takes as arguments each of the components. Accessing the elements of a structure is done just as you would with a structure in C, as shown in the following example:

```
vec4 color  = fogVar.color;
float start = fogVar.start;
float end   = fogVar.end;
```

Arrays

In addition to structures, the OpenGL ES Shading Language supports arrays. The syntax is very similar to C, with the arrays being based on a 0 index. The following block of code shows some examples of creating arrays:

```
float floatArray[4];
vec4  vecArray[2];
```

Arrays can be initialized using the array initializer constructor, as shown in the following code:

```
float a[4] = float[](1.0, 2.0, 3.0, 4.0);
float b[4] = float[4](1.0, 2.0, 3.0, 4.0);
vec2 c[2] = vec2[2](vec2(1.0), vec2(1.0));
```

Providing a size to the array constructor is optional. The number of arguments in the array constructor must be equal to the size of the array.

Operators

Table 5-2 lists the operators that are offered in the OpenGL ES Shading Language.

Table 5-2 OpenGL ES Shading Language Operators

Operator Type	**Description**
`*`	Multiply
`/`	Divide
`%`	Modulus
`+`	Add
`-`	Subtract
`++`	Increment (prefix and postfix)
`--`	Decrement (prefix and postfix)
`=`	Assignment
`+=, -=, *=, /=`	Arithmetic assignment

Table 5-2 OpenGL ES Shading Language Operators *(continued)*

Operator Type	Description
`==, !=, <, >, <=, >=`	Comparison operators
`&&`	Logical and
`^^`	Logical exclusive or
`||`	Logical inclusive or
`<<, >>`	Bit-wise shift
`&, ^, |`	Bit-wise and, xor, or
`?:`	Selection
`,`	Sequence

Most of these operators behave just as they do in C. As mentioned in the constructor section, the OpenGL ES Shading Language has strict type rules that govern operators. That is, the operators must occur between variables that have the same basic type. For the binary operators (`*`, `/`, `+`, `-`), the basic types of the variables must be floating point or integer. Furthermore, operators such as multiply can operate between combinations of floats, vectors, and matrices. Some examples are provided here:

```
float   myFloat;
vec4    myVec4;
mat4    myMat4;

myVec4 = myVec4 * myFloat; // Multiplies each component of
                           // myVec4 by a scalar myFloat
myVec4 = myVec4 * myVec4;  // Multiplies each component of
                           // myVec4 together (e.g.,
                           // myVec4 ^ 2)
myVec4 = myMat4 * myVec4;  // Does a matrix * vector multiply of
                           // myMat4 * myVec4
myMat4 = myMat4 * myMat4;  // Does a matrix * matrix multiply of
                           // myMat4 * myMat4
myMat4 = myMat4 * myFloat; // Multiplies each matrix component
                           // by the scalar myFloat
```

The comparison operators, aside from == and != (`<`, `<=`, `>`, `>=`), can be used only with scalar values. To compare vectors, special built-in functions allow you to perform comparisons on a component-by-component basis (more on that later).

Functions

Functions are declared in much the same way as in C. If a function will be used prior to its definition, then a prototype declaration must be provided. The most significant difference between functions in the OpenGL ES Shading Language and C is the way in which parameters are passed to functions. The OpenGL ES Shading Language provides special qualifiers to define whether a variable argument can be modified by the function; these qualifiers are shown in Table 5-3.

Table 5-3 OpenGL ES Shading Language Qualifiers

Qualifier	Description
`in`	(Default if none specified) This qualifier specifies that the parameter is passed by value and will not be modified by the function.
`inout`	This qualifier specifies that the variable is passed by reference into the function and if its value is modified, it will be changed after function exit.
`out`	This qualifier says that the variable's value is not passed into the function, but it will be modified on return from the function.

An example function declaration is provided here. This example shows the use of parameter qualifiers.

```
vec4 myFunc(inout float myFloat, // inout parameter
            out vec4 myVec4,     // out parameter
            mat4 myMat4);        // in parameter (default)
```

An example function definition is given here for a simple function that computes basic diffuse lighting:

```
vec4 diffuse(vec3 normal,
             vec3 light,
             vec4 baseColor)
{
   return baseColor * dot(normal, light);
}
```

One note about functions in the OpenGL ES Shading Language: functions cannot be recursive. The reason for this limitation is that some implementations will implement function calls by actually placing the function code inline in the final generated program for the GPU. The shading language was purposely structured to allow this sort of inline implementation to support GPUs that do not have a stack.

Built-In Functions

The preceding section described how a shader author creates a function. One of the most powerful features of the OpenGL ES Shading Language is the built-in functions that are provided in the language. As an example, here is some shader code for computing basic specular lighting in a fragment shader:

```
float nDotL = dot(normal, light);
float rDotV = dot(viewDir, (2.0 * normal) * nDotL - light);
float specular = specularColor * pow(rDotV, specularPower);
```

As you can see, this block of shader code uses the `dot` built-in function to compute the dot product of two vectors and the `pow` built-in function to raise a scalar to a power. These are just two simple examples; a wide array of built-in functions are available in the OpenGL ES Shading Language to handle the various computational tasks that one typically has to do in a shader. Appendix B of this text provides a complete reference to the built-in functions provided in the OpenGL ES Shading Language. For now, we just want to make you aware that there are a lot of built-in functions in the language. To become proficient in writing shaders, you will need to familiarize yourself with the most common ones.

Control Flow Statements

The syntax for control flow statements in the OpenGL ES Shading Language is similar to that used in C. Simple if-then-else logical tests can be done using the same syntax as C. For example:

```
if(color.a < 0.25)
{
   color *= color.a;
}
else
{
   color = vec4(0.0);
}
```

The expression that is being tested in the conditional statement must evaluate to a boolean value. That is, the test must be based on either a boolean value or some expression that evaluates to a boolean value (e.g., a comparison operator). This is the basic concept underlying how conditionals are expressed in the OpenGL ES Shading Language.

In addition to basic if-then-else statements, it is possible to write for, while, and do-while loops. In OpenGL ES 2.0, very strict rules governed the usage of loops. Essentially, only loops that could be unrolled by the compiler were supported. These restrictions no longer exist in OpenGL ES 3.0. The GPU hardware is expected to provide support for looping and flow control; thus loops are fully supported.

That is not to say that loops don't come with some performance implications. On most GPU architectures, vertices or fragments are executed in parallel in batches. The GPU typically requires that all fragments or vertices in a batch evaluate all branches (or loop iterations) of flow control statements. If vertices or fragments in a batch execute different paths, then, usually all of the other vertices/fragments in a batch will need to execute that path as well. The size of a batch is GPU dependent and will often require profiling to determine the performance implications of the use of flow control on a particular architecture. However, a good rule of thumb is to try to limit the use of divergent flow control or loop iterations across vertices/fragments.

Uniforms

One of the variable type modifiers in the OpenGL ES Shading Language is the uniform variable. Uniform variables store read-only values that are passed in by the application through the OpenGL ES 3.0 API to the shader. Uniforms are useful for storing all kinds of data that shaders need, such as transformation matrices, light parameters, and colors. Basically, any parameter to a shader that is constant across either all vertices or fragments should be passed in as a uniform. Variables whose value is known at compile-time should be constants rather than uniforms for efficiency.

Uniform variables are declared at the global scope and simply require the uniform qualifier. Some examples of uniform variables are shown here:

```
uniform mat4 viewProjMatrix;
uniform mat4 viewMatrix;
uniform vec3 lightPosition;
```

In Chapter 4, "Shaders and Programs," we described how an application loads uniform variables to a shader. Note also that the namespace for uniform variables is shared across both a vertex shader and a fragment shader. That is, if vertex and fragment shaders are linked together into a program object, they share the same set of uniform variables. Therefore, if a uniform variable is declared in the vertex shader and also in the fragment shader, both of those declarations must match. When the application loads the uniform variable through the API, its value will be available in both the vertex and fragment shaders.

Uniform variables generally are stored in hardware into what is known as the "constant store." This special space is allocated in the hardware for the storage of constant values. Because it is typically of a fixed size, the number of uniforms that can be used in a program is limited. This limitation can be determined by reading the value of the `gl_MaxVertexUniformVectors` and `gl_MaxFragmentUniformVectors` built-in variables (or by querying `GL_MAX_VERTEX_UNIFORM_VECTORS` or `GL_MAX_FRAGMENT_UNIFORM_VECTORS` using `glGetintegerv`). An implementation of OpenGL ES 3.0 must provide at least 256 vertex uniform vectors and 224 fragment uniform vectors, although it is free to provide more. We cover the full set of limitations and queries available for the vertex and fragment shaders in Chapter 8, "Vertex Shaders," and Chapter 10, "Fragment Shaders."

Uniform Blocks

In Chapter 4, "Shaders and Programs," we introduced the concept of uniform buffer objects. To review, uniform buffer objects allow the storage of uniform data to be backed by a buffer object. Uniform buffer objects offer several advantages over individual uniform variables in certain situations. For example, with uniform buffer objects, uniform buffer data can be shared across multiple programs but need to be set only once. Further, uniform buffer objects typically allow for storage of larger amounts of uniform data. Finally, it can be more efficient to switch between uniform buffer objects than to individually load one uniform at a time.

Uniform buffer objects can be used in the OpenGL ES Shading Language through application of uniform blocks. An example uniform block follows:

```
uniform TransformBlock
{
    mat4 matViewProj;
    mat3 matNormal;
    mat3 matTexGen;
};
```

This code declares a uniform block with the name `TransformBlock` containing three matrices. The name `TransformBlock` will be used by the application as the `blockName` parameter to `glGetUniformBlockIndex` as described in Chapter 4, "Shaders and Programs," for uniform buffer objects. The variables in the uniform block declaration are then accessed throughout the shader just as if they were declared as a regular uniform. For example, the `matViewProj` matrix declared in `TransformBlock` would be accessed as follows:

```
#version 300 es
uniform TransformBlock
{
    mat4 matViewProj;
    mat3 matNormal;
    mat3 matTexGen;
};
layout(location = 0) in vec4 a_position;
void main()
{
    gl_Position = matViewProj * a_position;
}
```

A number of optional layout qualifiers can be used to specify how the uniform buffer object that backs the uniform block will be laid out in memory. Layout qualifiers can be provided either for individual uniform blocks or globally for all uniform blocks. At the global scope, setting the default layout for all uniform blocks would look as follows:

```
layout(shared, column_major) uniform;  // default if not
                                       // specified
layout(packed, row_major) uniform;
```

Individual uniform blocks can also set the layout by overriding the default set at the global scope. In addition, individual uniforms within a uniform block can specify a layout qualifier as shown here:

```
layout(std140) uniform TransformBlock
{
    mat4 matViewProj;
    layout(row_major) mat3 matNormal;
    mat3 matTexGen;
};
```

Table 5-4 lists all of the layout qualifiers that can be provided for uniform blocks.

Table 5-4 Uniform Block Layout Qualifiers

Qualifier	Description
`shared`	The `shared` qualifier specifies that the layout in memory of the uniform block across multiple shaders or multiple programs will be the same. To use this qualifier, the `row_major/column_major` values must be identical across definitions. Overrides `std140` and `packed`. (default)
`packed`	The `packed` layout qualifier specifies that the compiler can optimize the memory layout of the uniform block. The location of the offsets must be queried when using this qualifier, and the uniform blocks cannot be shared across vertex/fragment shader or programs. Overrides `std140` and `shared`.
`std140`	The `std140` layout qualifier specifies that the layout of the uniform block is based on a set of standard rules defined in the "Standard Uniform Block Layout" section of the OpenGL ES 3.0 Specification. We detail these layout rules in the *Uniform Buffer Objects* section of Chapter 4. Overrides `shared` and `packed`.
`row_major`	Matrices are laid out in row-major order in memory.
`column_major`	Matrices are laid out in column-major order in memory. (default)

Vertex and Fragment Shader Inputs/Outputs

Another special variable type in the OpenGL ES Shading Language is the vertex input (or attribute) variable. Vertex input variables are used to specify the per-vertex inputs to the vertex shader and are specified with the `in` keyword. They typically store data such as positions, normals, texture coordinates, and colors. The key here to understand is that vertex inputs are data that are specified for each vertex being drawn. Example 5-1 is a sample vertex shader that has a position and color vertex input.

The two vertex inputs in this shader, `a_position` and `a_color`, will be loaded with data by the application. Essentially, the application will create a vertex array that contains a position and a color for each vertex. Notice that the vertex inputs in Example 5-1 are preceded by the `layout` qualifier. The layout qualifier in this case is used to specify the index of the vertex attribute. The layout qualifier is optional; if it is not specified, the linker will automatically assign locations for the vertex inputs. We explain this entire process in full detail in Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects."

Example 5-1 Sample Vertex Shader

```
#version 300 es

uniform mat4 u_matViewProjection;
layout(location = 0) in vec4 a_position;
layout(location = 1) in vec3 a_color;
out vec3 v_color;
void main(void)
{
    gl_Position = u_matViewProjection * a_position;
    v_color = a_color;
}
```

As with uniform variables, the underlying hardware typically places limits on the number of attribute variables that can be input to a vertex shader. The maximum number of attributes that an implementation supports is given by the `gl_MaxVertexAttribs` built-in variable (it can also be found by querying for `GL_MAX_VERTEX_ATTRIBS` using `glGetIntegerv`). The minimum number of attributes that an OpenGL ES 3.0 implementation can support is 16. Implementations are free to support more, but if you want to write shaders that are guaranteed to run on any OpenGL ES 3.0 implementation, you should restrict yourself to using no more than 16 attributes. We cover attribute limitations in more detail in Chapter 8, "Vertex Shaders."

The output variables from the vertex shader are specified with the `out` keyword. In Example 5-1, the `v_color` variable is declared as an output and its contents are copied from the `a_color` input variable. Each vertex shader will output the data it needs to pass the fragment shader into one or more output variables. These variables will then also be declared in the fragment shader as `in` variables (with matching types) and will be linearly interpolated across the primitive during rasterization (if you want more details on how this interpolation occurs during rasterization, jump to Chapter 7, "Primitive Assembly and Rasterization").

For example, the matching input declaration in the fragment shader for the `v_color` vertex output in Example 5-1 follows:

```
in vec3 v_color;
```

Note that unlike the vertex shader input, the vertex shader output/fragment shader input variables cannot have layout qualifiers. The implementation automatically chooses locations. As with uniforms and vertex input attributes, the underlying hardware typically limits the number of vertex shader outputs/fragment shader inputs (on the hardware, these are usually referred to as interpolators). The number of vertex shader outputs supported by an implementation is given by the `gl_MaxVertexOutputVectors` built-in variable (querying for `GL_MAX_VERTEX_OUTPUT_COMPONENTS` using `glGetIntegerv` will provide the number of total component values rather than the number of vectors). The minimum number of vertex output vectors that an implementation of OpenGL ES 3.0 can support is 16. Likewise, the number of fragment shader inputs supported by an implementation is given by `gl_MaxFragmentInputVectors` (querying for `GL_MAX_FRAGMENT_INPUT_COMPONENTS` using `glGetIntegerv` will provide the number of total component values rather than the number of vectors). The minimum number of fragment input vectors that an implementation of OpenGL ES 3.0 can support is 15.

Example 5-2 is an example of a vertex shader and a fragment shader with matching output/input declarations.

Example 5-2 Vertex and Fragment Shaders with Matching Output/Input Declarations

```
// Vertex shader
#version 300 es

uniform mat4 u_matViewProjection;

// Vertex shader inputs
layout(location = 0) in vec4 a_position;
layout(location = 1) in vec3 a_color;

// Vertex shader output
out vec3 v_color;

void main(void)
{
  gl_Position = u_matViewProjection * a_position;
  v_color = a_color;
}

// Fragment shader
#version 300 es
precision mediump float;

// Input from vertex shader
in vec3 v_color;

// Output of fragment shader
layout(location = 0) out vec4 o_fragColor;
```

(continues)

Example 5-2 Vertex and Fragment Shaders with Matching Output/Input Declarations *(continued)*

```
void main()
{
    o_fragColor = vec4(v_color, 1.0);
}
```

In Example 5-2, the fragment shader contains the definition for the output variable `o_fragColor`:

```
layout(location = 0) out vec4 o_fragColor;
```

The fragment shader can output one or more colors. In the typical case, we will render just to a single color buffer, in which case the layout qualifier is optional (the output variable is assumed to go to location 0). However, when rendering to multiple render targets (MRTs), we can use the layout qualifier to specify which render target each output goes to. MRTs are covered in detail in Chapter 11, "Fragment Operations." For the typical case, you will have one output variable in your fragment shader, and that value will be the output color that is passed to the per-fragment operations portions of the pipeline.

Interpolation Qualifiers

In Example 5-2, we declared our vertex shader output and fragment shader input without any qualifiers. The default behavior for interpolation when no qualifiers are present is to perform smooth shading. That is, the output variables from the vertex shader are linearly interpolated across the primitive, and the fragment shader receives that linearly interpolated value as its input. We could have explicitly requested smooth shading rather than relying on the default behavior in Example 5-2, in which case our output/inputs would be as follows:

```
// ...Vertex shader...
// Vertex shader output
smooth out vec3 v_color;

// ...Fragment shader...
// Input from vertex shader
smooth in vec3 v_color;
```

OpenGL ES 3.0 also introduces another type of interpolation known as flat shading. In flat shading, the value is not interpolated across the primitive. Rather, one of the vertices is considered the provoking vertex (dependent on the primitive type; we describe this in the Chapter 7 section, *Provoking Vertex*), and that vertex value is used for all fragments in the primitive. We can declare the output/inputs as flat shaded as follows:

```
// ...Vertex shader...
// Vertex shader output
flat out vec3 v_color;

// ...Fragment shader...
// Input from vertex shader
flat in vec3 v_color;
```

Finally, another qualifier can be added to interpolators with the `centroid` keyword. The definition of centroid sampling is provided in Chapter 11 in the section *Multisampled Anti-Aliasing*. Essentially, when rendering with multisampling, the `centroid` keyword can be used to force interpolation to occur inside the primitive being rendered (otherwise, artifacts can occur at the edges of primitives). See Chapter 11, "Fragment Operations," for a full definition of centroid sampling. For now, we simply show how you can declare an output/input variable with centroid sampling:

```
// ...Vertex shader...
// Vertex shader output
smooth centroid out vec3 v_color;

// ...Fragment shader...
// Input from vertex shader
smooth centroid in vec3 v_color;
```

Preprocessor and Directives

One feature of the OpenGL ES Shading Language we have not mentioned yet is the preprocessor. The OpenGL ES Shading Language features a preprocessor that follows many of the conventions of a standard C++ preprocessor. Macros can be defined and conditional tests can be performed using the following directives:

```
#define
#undef
#if
#ifdef
#ifndef
#else
#elif
#endif
```

Note that macros cannot be defined with parameters (as they can be in C++ macros). The #if, #else, and #elif directives can use the defined test to see whether a macro is defined. The following macros are predefined and their description is given next:

```
__LINE__     // Replaced with the current line number in a shader
__FILE__     // Always 0 in OpenGL ES 3.0
__VERSION__  // The OpenGL ES shading language version
             // (e.g., 300)
GL_ES        // This will be defined for ES shaders to a value
             // of 1
```

The #error directive will cause a compilation error to occur during shader compilation, with a corresponding message being placed in the info log. The #pragma directive is used to specify implementation-specific directives to the compiler.

Another important directive in the preprocessor is #extension, which is used to enable and set the behavior of extensions. When vendors (or groups of vendors) extend the OpenGL ES Shading Language, they will create a language extension specification (e.g., GL_NV_shadow_samplers_cube). The shader must instruct the compiler as to whether to allow extensions to be used, and if not, which behavior should occur. This is done using the #extension directive. The general format of #extension usage is shown in the following code:

```
// Set behavior for an extension
#extension extension_name : behavior
// Set behavior for ALL extensions
#extension all : behavior
```

The first argument will be either the name of the extension (e.g., GL_NV_shadow_samplers_cube) or all, which means that the behavior applies to all extensions. The behavior has four possible options, as shown in Table 5-5.

Table 5-5 Extension Behaviors

Extension Behavior	**Description**
require	The extension is required, so the preprocessor will throw an error if the extension is not supported. If all is specified, this will always throw an error.
enable	The extension is enabled, so the preprocessor will warn if the extension is not supported. The language will be processed as if the extension is enabled. If all is specified, this will always throw an error.

Table 5-5 Extension Behaviors *(continued)*

Extension Behavior	Description
`warn`	Warn on any use of the extension, unless that use is required by another enabled extension. If `all` is specified, a warning will be thrown whenever the extension is used. Also, a warning will be thrown if the extension is not supported.
`disable`	The extension is disabled, so errors will be thrown if the extension is used. If `all` is specified (this is specified by default), no extensions are enabled.

As an example, suppose you want the preprocessor to produce a warning if the NVIDIA shadow samplers cube extension is not supported (and you want the shader to be processed as if it is supported). To do so, you would add the following at the top of your shader:

```
#extension GL_NV_shadow_samplers_cube : enable
```

Uniform and Interpolator Packing

As noted in the preceding sections on uniforms and vertex shader outputs/fragment shader inputs, a fixed number of underlying hardware resources are available for the storage of each variable. Uniforms are typically stored in the so-called constant store, which can be thought of as a physical array of vectors. Vertex shader outputs/fragment shader inputs are typically stored in interpolators, which again are usually stored as an array of vectors. As you have probably noticed, shaders can declare uniforms and shader input/outputs of various types, including scalars, various vector components, and matrices. But how do these variable declarations map to the physical space that's available on the hardware? In other words, if an OpenGL ES 3.0 implementation says it supports 16 vertex shader output vectors, how does the physical storage actually get used?

In OpenGL ES 3.0, this issue is handled through packing rules that define how the interpolators and uniforms will map to physical storage space. The rules for packing are based on the notion that the physical storage space is organized into a grid with four columns (one column for each vector component) and a row for each storage location. The packing rules seek to pack variables such that the complexity of the generated code remains constant. In other words, the packing rules will not do reordering that requires the compiler to generate extra instructions to merge unpacked data. Rather, the packing rules seek to optimize the use of the physical address space without negatively impacting runtime performance.

Let's look at an example group of uniform declarations and see how these would be packed:

```
uniform mat3 m;
uniform float f[6];
uniform vec3 v;
```

If no packing were done at all, you can see that a lot of constant storage space would be wasted. The matrix `m` would take up three rows, the array `f` would take up six rows, and the vector `v` would take up one row. This would use a total of 10 rows to store the variables. Table 5-6 shows what the results would be without any packing. With the packing rules, the variables will get organized such that they pack into the grid as shown in Table 5-7.

Table 5-6 Uniform Storage without Packing

Location	X	Y	Z	W
0	`m[0].x`	`m[0].y`	`m[0].z`	—
1	`m[1].x`	`m[1].y`	`m[1].z`	—
2	`m[2].x`	`m[2].y`	`m[2].z`	—
3	`f[0]`	—	—	—
4	`f[1]`	—	—	—
5	`f[2]`	—	—	—
6	`f[3]`	—	—	—
7	`f[4]`	—	—	—
8	`f[5]`	—	—	—
9	`v.x`	`v.y`	`v.z`	`-6`

Table 5-7 Uniform Storage with Packing

Location	X	Y	Z	W
0	`m[0].x`	`m[0].y`	`m[0].z`	`f[0]`
1	`m[1].x`	`m[1].y`	`m[1].z`	`f[1]`
2	`m[2].x`	`m[2].y`	`m[2].z`	`f[2]`
3	`v.x`	`v.y`	`v.z`	`f[3]`
4	—	—	—	`f[4]`
5	—	—	—	`f[5]`

With the packing rules, only six physical constant locations need to be used. You will notice that the array `f` needs to keep its elements spanning across row boundaries. The reason for this is that typically GPUs index the constant store by vector location index. The packing must keep the arrays spanning across row boundaries so that indexing will still work.

All of the packing that is done is completely transparent to the user of the OpenGL ES Shading Language, except for one detail: The packing impacts the way in which uniforms and vertex shader outputs/fragment shader inputs are counted. If you want to write shaders that are guaranteed to run on all implementations of OpenGL ES 3.0, you should not use more uniforms or interpolators than would exceed the minimum allowed storage sizes after packing. For this reason, it's important to be aware of packing so that you can write portable shaders that will not exceed the minimum allowed storage on any implementation of OpenGL ES 3.0.

Precision Qualifiers

Precision qualifiers enable the shader author to specify the precision with which computations for a shader variable are performed. Variables can be declared to have either low, medium, or high precision. These qualifiers are used as hints to the compiler to allow it to perform computations with variables at a potentially lower range and precision. It is possible that at lower precisions, some implementations of OpenGL ES might be able to run the shaders either faster or with better power efficiency.

Of course, that efficiency savings comes at the cost of precision, which can result in artifacts if precision qualifiers are not used properly. Note that nothing in the OpenGL ES specification says that multiple precisions must be supported in the underlying hardware, so it is perfectly valid for an implementation of OpenGL ES to perform all calculations at the highest precision and simply ignore the qualifiers. However, on some implementations, using a lower precision might offer an advantage.

Precision qualifiers can be used to specify the precision of any floating-point or integer-based variable. The keywords for specifying the precision are `lowp`, `mediump`, and `highp`. Some examples of declarations with precision qualifiers are shown here:

```
highp vec4 position;
varying lowp vec4 color;
mediump float specularExp;
```

In addition to precision qualifiers, the notion of default precision is available. That is, if a variable is declared without having a precision qualifier, it will have the default precision for that type. The default precision qualifier is specified at the top of a vertex or fragment shader using the following syntax:

```
precision highp float;
precision mediump int;
```

The precision specified for `float` will be used as the default precision for all variables based on a floating-point value. Likewise, the precision specified for `int` will be used as the default precision for all integer-based variables.

In the vertex shader, if no default precision is specified, then the default precision for both `int` and `float` is `highp`. That is, all variables declared without a precision qualifier in a vertex shader will have the highest precision. The rules for the fragment shader are different. In the fragment shader, there is no default precision given for floating-point values: Every shader must declare a default `float` precision or specify the precision for every `float` variable.

One final note is that the precision specified by a precision qualifier has an implementation-dependent range and precision. There is an associated API call for determining the range and precision for a given implementation, which is covered in Chapter 15, “State Queries.” As an example, on the PowerVR SGX GPU, a `lowp float` variable is represented in a 10-bit fixed point format, a `mediump float` variable is a 16-bit floating-point value, and a `highp float` is a 32-bit floating-point value.

Invariance

The keyword `invariant` that was introduced in the OpenGL ES Shading Language can be applied to any varying output of a vertex shader. What do we mean by invariance, and why is this necessary? The issue is that shaders are compiled and the compiler might perform optimizations that cause instructions to be reordered. This instruction reordering means that equivalent calculations between two shaders are not guaranteed to produce exactly identical results. This disparity can be an issue in particular for multipass shader effects, where the same object is being drawn on top of itself using alpha blending. If the precision of the values used to compute the output position is not exactly identical, then artifacts can arise due to the precision differences. This issue usually manifests itself as "Z fighting," when small Z precision differences per pixel cause the different passes to shimmer against each other.

The following example demonstrates visually why invariance is important to get right when doing multipass shading. The following torus object is drawn in two passes: The fragment shader computes specular lighting in the first pass and ambient and diffuse lighting in the second pass. The vertex shaders do not use invariance so small precision differences cause the Z fighting, as shown in Figure 5-1.

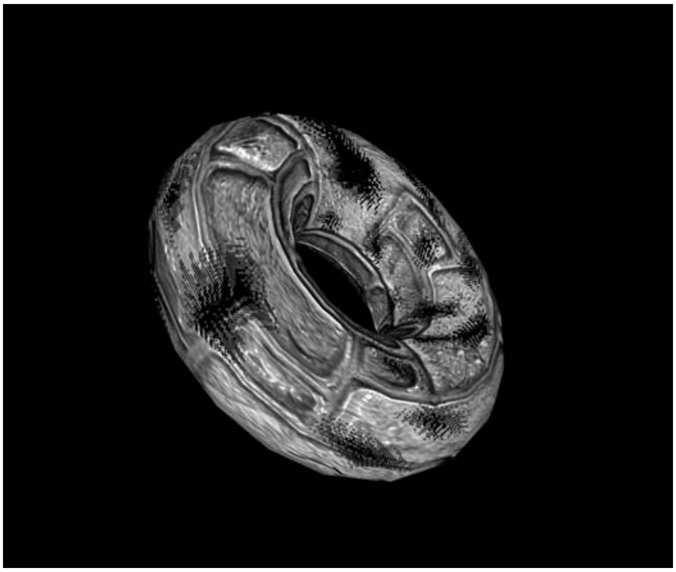


Figure 5-1 Z Fighting Artifacts Due to Not Using Invariance

The same multipass vertex shaders using invariance for position produce the correct image in Figure 5-2.

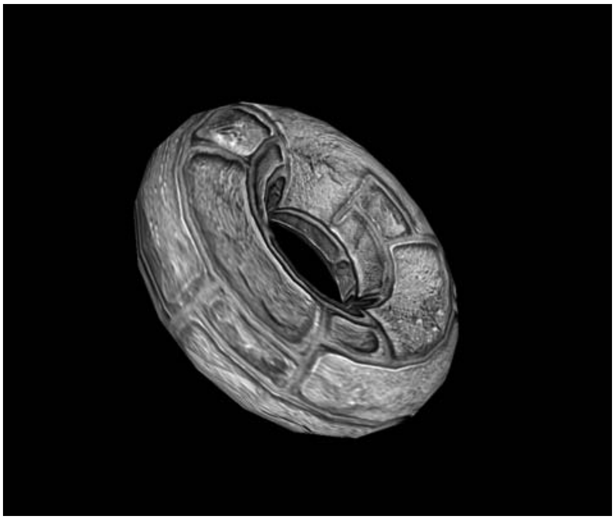


Figure 5-2 Z Fighting Avoided Using Invariance

The introduction of invariance gives the shader writer a way to specify that if the same computations are used to compute an output, its value must be *exactly* the same (or invariant). The `invariant` keyword can be used either on varying declarations or for varyings that have already been declared. Some examples follow:

```
invariant gl_Position;
invariant texCoord;
```

Once invariance is declared for an output, the compiler guarantees that the results will be the same given the same computations and inputs into the shader. For example, given two vertex shaders that compute output position by multiplying the view projection matrix by the input position, you are guaranteed that those positions will be invariant.

```
#version 300 es
uniform mat4 u_viewProjMatrix;
layout(location = 0) in vec4 a_vertex;
invariant gl_Position;
```

```
void main()
{
   // Will be the same value in all shaders with the
   // same viewProjMatrix and vertex
   gl_Position = u_viewProjMatrix * a_vertex;
}
```

It is also possible to make all variables globally invariant using a `#pragma` directive:

```
#pragma STDGL invariant(all)
```

A word of caution: Because the compiler needs to guarantee invariance, it might have to limit the optimizations it does. Therefore, the `invariant` qualifier should be used only when necessary; otherwise, it might result in performance degradation. For this reason, the `#pragma` directive to globally enable invariance should be used only when invariance is really required for all variables. Note also that while invariance does imply that the calculation will have the same results on a given GPU, it does not mean that the computation will be invariant across any implementation of OpenGL ES.

Summary

This chapter introduced the following features of the OpenGL ES Shading Language:

- Shader version specification with `#version`
- Scalar, vector, and matrix data types and constructors
- Declaration of constants using the `const` qualifier
- Creation and initialization of structures and arrays
- Operators, control flow, and functions
- Vertex shader inputs/output and fragment shader inputs/outputs using the `in` and `out` keywords and layout qualifier
- Smooth, flat, and centroid interpolation qualifiers
- Uniforms, uniform blocks, and uniform block layout qualifiers
- Preprocessor and directives
- Uniform and interpolator packing
- Precision qualifiers and invariance

In the next chapter, we focus on how to load vertex input variables with data from vertex arrays and vertex buffer objects. We will expand your knowledge of the OpenGL ES Shading Language throughout the book. For example, in Chapter 8, “Vertex Shaders,” we describe how to perform transformation, lighting, and skinning in a vertex shader. In Chapter 9, “Texturing,” we explain how to load textures and how to use them in a fragment shader. In Chapter 10, “Fragment Shaders,” we cover how to compute fog, perform alpha testing, and evaluate user clip planes in a fragment shader. In Chapter 14, “Advanced Programming with OpenGL ES 3.0,” we go deep into writing shaders that perform advanced effects such as environment mapping, projective texturing, and per-fragment lighting. With the grounding in the OpenGL ES Shading Language from this chapter, we can show you how to use shaders to achieve a variety of rendering techniques.

Chapter 6

Vertex Attributes, Vertex Arrays, and Buffer Objects

This chapter describes how vertex attributes and data are specified in OpenGL ES 3.0. We discuss what vertex attributes are, how to specify them and their supported data formats, and how to bind vertex attributes for use in a vertex shader. After reading this chapter, you will have a good grasp of what vertex attributes are and how to draw primitives with vertex attributes in OpenGL ES 3.0.

Vertex data, also referred to as vertex attributes, specify per-vertex data. This per-vertex data can be specified for each vertex, or a constant value can be used for all vertices. For example, if you want to draw a triangle that has a solid color (for the sake of this example, suppose the color is black, as shown in Figure 6-1), you would specify a constant value that will be used by all three vertices of the triangle. However, the position of the three vertices that make up the triangle will not be the same, so we will need to specify a vertex array that stores three position values.

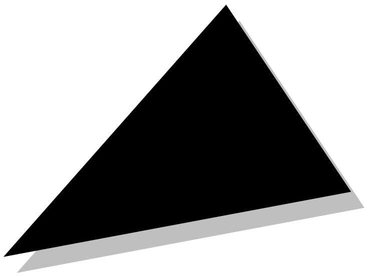


Figure 6-1 Triangle with a Constant Color Vertex and Per-Vertex Position Attributes

Specifying Vertex Attribute Data

Vertex attribute data can be specified for each vertex using a vertex array, or a constant value can be used for all vertices of a primitive.

All OpenGL ES 3.0 implementations must support a minimum of 16 vertex attributes. An application can query the exact number of vertex attributes that are supported by a particular implementation. The following code shows how an application can query the number of vertex attributes an implementation actually supports:

```
GLint maxVertexAttribs;   // n will be >= 16
glGetIntegerv(GL_MAX_VERTEX_ATTRIBS, &maxVertexAttribs);
```

Constant Vertex Attribute

A constant vertex attribute is the same for all vertices of a primitive, so only one value needs to be specified for all the vertices of a primitive. It is specified using any of the following functions:

```
void glVertexAttrib1f(GLuint index, GLfloat x);
void glVertexAttrib2f(GLuint index, GLfloat x, GLfloat y);
void glVertexAttrib3f(GLuint index, GLfloat x, GLfloat y,
                      GLfloat z);
void glVertexAttrib4f(GLuint index, GLfloat x, GLfloat y,
                      GLfloat z, GLfloat w);
void glVertexAttrib1fv(GLuint index, const GLfloat *values);
void glVertexAttrib2fv(GLuint index, const GLfloat *values);
void glVertexAttrib3fv(GLuint index, const GLfloat *values);
void glVertexAttrib4fv(GLuint index, const GLfloat *values);
```

The `glVertexAttrib*` commands are used to load the generic vertex attribute specified by `index`. The functions `glVertexAttrib1f` and `glVertexAttrib1fv` load (*x*, 0.0, 0.0, 1.0) into the generic vertex attribute. `glVertexAttrib2f` and `glVertexAttrib2fv` load (*x*, *y*, 0.0, 1.0) into the generic vertex attribute. `glVertexAttrib3f` and `glVertexAttrib3fv` load (*x*, *y*, *z*, 1.0) into the generic vertex attribute. `glVertexAttrib4f` and `glVertexAttrib4fv` load (*x*, *y*, *z*, *w*) into the generic vertex attribute. In practice, constant vertex attributes provide equivalent functionality to using a scalar/vector uniform, and using either is an acceptable choice.

Vertex Arrays

Vertex arrays specify attribute data per vertex and are buffers stored in the application's address space (what OpenGL ES calls the *client* space). They serve as the basis for vertex buffer objects that provide an efficient and flexible way for specifying vertex attribute data. Vertex arrays are specified using the `glVertexAttribPointer` or `glVertexAttribIPointer` function.

```
void   glVertexAttribPointer(GLuint index, GLint size,
                             GLenum type,
                             GLboolean normalized,
                             GLsizei stride,
                             const void *ptr)
void   glVertexAttribIPointer(GLuint index, GLint size,
                              GLenum type,
                              GLsizei stride,
                              const void *ptr)
```

index	specifies the generic vertex attribute index. This value can range from 0 to the maximum vertex attributes supported minus 1.
size	number of components specified in the vertex array for the vertex attribute referenced by the index. Valid values are 1–4.

type	data format. Valid values for both functions are
	`GL_BYTE`
	`GL_UNSIGNED_BYTE`
	`GL_SHORT`
	`GL_UNSIGNED_SHORT`
	`GL_INT`
	`GL_UNSIGNED_INT`
	Valid values for `glVertexAttribPointer` also include
	`GL_HALF_FLOAT`
	`GL_FLOAT`
	`GL_FIXED`
	`GL_INT_2_10_10_10_REV`
	`GL_UNSIGNED_INT_2_10_10_10_REV`

normalized	(`glVertexAttribPointer` only) is used to indicate whether the non-floating data format type should be normalized when converted to floating-point values. For `glVertexAttribIPointer`, the values are treated as integers.
stride	the components of vertex attribute specified by size are stored sequentially for each vertex. *stride* specifies the delta between data for vertex index I and vertex (I + 1). If *stride* is 0, attribute data for all vertices are stored

(continues)

(continued)

	sequentially. If *`stride`* is greater than 0, then we use the stride value as the pitch to get vertex data for next index.
`ptr`	pointer to the buffer holding vertex attribute data if using a client-side vertex array. If using a vertex buffer object, specifies an offset into that buffer.

Next, we present a few examples that illustrate how to specify vertex attributes with `glVertexAttribPointer`. Two methods are commonly used for allocating and storing vertex attribute data:

- Store vertex attributes together in a single buffer—a method called an *array of structures*. The structure represents all attributes of a vertex, and we have an array of these attributes per vertex.
- Store each vertex attribute in a separate buffer—a method called a *structure of arrays*.

Suppose each vertex has four vertex attributes—position, normal, and two texture coordinates—and these attributes are stored together in one buffer that is allocated for all vertices. The vertex position attribute is specified as a vector of three floats (*x*, *y*, z), the vertex normal is also specified as a vector of three floats, and each texture coordinate is specified as a vector of two floats. Figure 6-2 gives the memory layout of this buffer. In this case, the stride of the buffer is the combined size of all attributes that make up the vertex (one vertex is equal to 10 floats or 40 bytes – 12 bytes for Position, 12 bytes for Normal, 8 bytes for Tex0, and 8 bytes for Tex1).

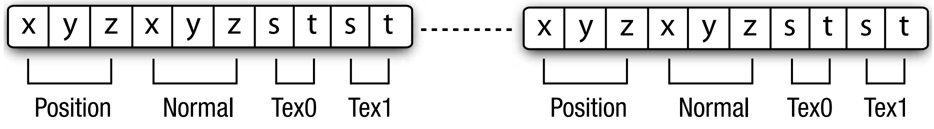


Figure 6-2 Position, Normal, and Two Texture Coordinates Stored as an Array

Example 6-1 describes how these four vertex attributes are specified with `glVertexAttribPointer`. Note that we are illustrating how to use client-side vertex arrays here so that we can explain the concept of specifying per-vertex data. We recommend that applications use vertex buffer objects (described later in the chapter) and avoid client-side vertex arrays to achieve best performance. Client-side vertex arrays are supported in OpenGL ES 3.0 only for backward compatibility with OpenGL ES 2.0. In OpenGL ES 3.0, vertex buffer objects are always recommended.

Example 6-1 Array of Structures

```
#define VERTEX_POS_SIZE             3  // x, y, and z
#define VERTEX_NORMAL_SIZE          3  // x, y, and z
#define VERTEX_TEXCOORD0_SIZE       2  // s and t
#define VERTEX_TEXCOORD1_SIZE       2  // s and t

#define VERTEX_POS_INDX             0
#define VERTEX_NORMAL_INDX          1
#define VERTEX_TEXCOORD0_INDX       2
#define VERTEX_TEXCOORD1_INDX       3

// the following 4 defines are used to determine the locations
// of various attributes if vertex data are stored as an array
// of structures
#define VERTEX_POS_OFFSET           0
#define VERTEX_NORMAL_OFFSET        3
#define VERTEX_TEXCOORD0_OFFSET     6
#define VERTEX_TEXCOORD1_OFFSET     8

#define VERTEX_ATTRIB_SIZE   (VERTEX_POS_SIZE + \
                              VERTEX_NORMAL_SIZE + \
                              VERTEX_TEXCOORD0_SIZE + \
                              VERTEX_TEXCOORD1_SIZE)

float *p  = (float*) malloc(numVertices * VERTEX_ATTRIB_SIZE
                  * sizeof(float));

// position is vertex attribute 0
glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_ATTRIB_SIZE * sizeof(float),
                      p);

// normal is vertex attribute 1
glVertexAttribPointer(VERTEX_NORMAL_INDX, VERTEX_NORMAL_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_ATTRIB_SIZE * sizeof(float),
                     (p +  VERTEX_NORMAL_OFFSET));

// texture coordinate 0 is vertex attribute 2
glVertexAttribPointer(VERTEX_TEXCOORD0_INDX,
                      VERTEX_TEXCOORD0_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_ATTRIB_SIZE * sizeof(float),
                     (p +  VERTEX_TEXCOORD0_OFFSET));

// texture coordinate 1 is vertex attribute 3
glVertexAttribPointer(VERTEX_TEXCOORD1_INDX,
```

(continues)

Example 6-1 Array of Structures *(continued)*

```
                          VERTEX_TEXC00RD1_SIZE,
                          GL_FLOAT, GL_FALSE,
                          VERTEX_ATTRIB_SIZE * sizeof(float),
                            (p + VERTEX_TEXC00RD1_0FFSET));
```

In Example 6-2, `position`, `normal`, and texture coordinates 0 and 1 are stored in separate buffers.

Example 6-2 Structure of Arrays

```
float *position  = (float*) malloc(numVertices *
   VERTEX_POS_SIZE * sizeof(float));
float *normal    = (float*) malloc(numVertices *
   VERTEX_NORMAL_SIZE * sizeof(float));
float *texcoordO = (float*) malloc(numVertices *
   VERTEX_TEXCOORD0_SIZE * sizeof(float));
float *texcoordl = (float*) malloc(numVertices *
   VERTEX_TEXC00RD1_SIZE * sizeof(float));

// position is vertex attribute 0
glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_POS_SIZE * sizeof(float),
                      position);

// normal is vertex attribute 1
glVertexAttribPointer(VERTEX_NORMAL_INDX, VERTEX_NORMAL_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_NORMAL_SIZE * sizeof(float),
                      normal);

// texture coordinate 0 is vertex attribute 2
glVertexAttribPointer(VERTEX_TEXCOORDO_INDX,
                      VERTEX_TEXCOORD0_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_TEXCOORD0_SIZE *
                      sizeof(float), texcoordO);

// texture coordinate 1 is vertex attribute 3
glVertexAttribPointer(VERTEX_TEXCOORDl_INDX,
                      VERTEX_TEXC00RD1_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_TEXC00RD1_SIZE * sizeof(float),
                      texcoordl);
```

Performance Hints

How to Store Different Attributes of a Vertex

We described the two most common ways of storing vertex attributes: an *array of structures* and a *structure of arrays*. The question to ask is which allocation method would be the most efficient for OpenGL ES 3.0 hardware implementations. In most cases, the answer is an *array of structures*. The reason is that the attribute data for each vertex can be read in sequential fashion, which will most likely result in an efficient memory access pattern. A disadvantage of using an array of structures becomes apparent when an application wants to modify specific attributes. If a subset of vertex attribute data needs to be modified (e.g., texture coordinates), this will result in strided updates to the vertex buffer. When the vertex buffer is supplied as a buffer object, the entire vertex attribute buffer will need to be reloaded. You can avoid this inefficiency by storing vertex attributes that are dynamic in nature in a separate buffer.

Which Data Format to Use for Vertex Attributes

The vertex attribute data format specified by the `type` argument in `glVertexAttribPointer` can affect not only the graphics memory storage requirements for vertex attribute data, but also the overall performance, which is a function of the memory bandwidth required to render the frame(s). The smaller the data footprint, the lower the memory bandwidth required. OpenGL ES 3.0 supports a 16-bit floating-point vertex format named `GL_HALF_FLOAT` (described in detail in Appendix A). Our recommendation is that applications use `GL_HALF_FLOAT` wherever possible. Texture coordinates, normals, binormals, tangent vectors, and so on are good candidates to be stored using `GL_HALF_FLOAT` for each component. Color could be stored as `GL_UNSIGNED_BYTE` with four components per vertex color. We also recommend `GL_HALF_FLOAT` for vertex position, but recognize that this choice might not be feasible for quite a few cases. For such cases, the vertex position could be stored as `GL_FLOAT`.

How the Normalized Flag in glVertexAttribPointer Works

Vertex attributes are internally stored as a single-precision floating-point number before being used in a vertex shader. If the data *type* indicates that the vertex attribute is not a float, then the vertex attribute will be converted to a single-precision floating-point number before it is used in a vertex shader. The *normalized* flag controls the conversion of the non-float vertex attribute data to a single precision floating-point value. If the *normalized* flag is false, the vertex data are converted directly to a floating-point value. This would be similar to casting the variable that is not a float type to float. The following code gives an example:

```
GLfloat  f;
GLbyte b;
f = (GLfloat)b;  // f represents values in the range [-128.0,
                 // 127.0]
```

If the *normalized* flag is true, the vertex data is mapped to the [–1.0, 1.0] range if the data *type* is `GL_BYTE`, `GL_SHORT`, or `GL_FIXED`, or to the [0.0, 1.0] range if the data *type* is `GL_UNSIGNED_BYTE` or `GL_UNSIGNED_SHORT`.

Table 6-1 describes conversion of non-floating-point data types with the normalized flag set. The value *c* in the second column of Table 6-1 refers to a value of the format specified in the first column.

Table 6-1 Data Conversions

Vertex Data Format	Conversion to Floating Point
`GL_BYTE`	$\max(c / (2^7 - 1), -1.0)$
`GL_UNSIGNED_BYTE`	$c / (2^8 - 1)$
`GL_SHORT`	$\max(c / (2^{16} - 1), -1.0)$
`GL_UNSIGNED_SHORT`	$c / (2^{16} - 1)$
`GL_FIXED`	$c/2^{16}$
`GL_FLOAT`	c
`GL_HALF_FLOAT_OES`	c

It is also possible to access integer vertex attribute data as integers in the vertex shader rather than having them be converted to floats. In this case, the `glVertexAttribIPointer` function should be used and the vertex attribute should be declared to be of an integer type in the vertex shader.

Selecting Between a Constant Vertex Attribute or a Vertex Array

The application can enable OpenGL ES to use either the constant data or data from vertex array. Figure 6-3 describes how this works in OpenGL ES 3.0.

The commands `glEnableVertexAttribArray` and `glDisableVertex-AttribArray` are used to enable and disable a generic vertex attribute array, respectively. If the vertex attribute array is disabled for a generic attribute index, the constant vertex attribute data specified for that index will be used.

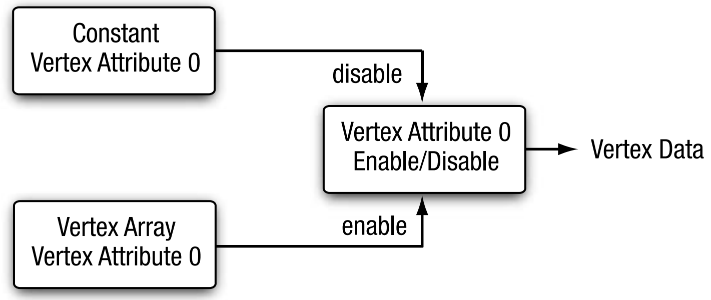


Figure 6-3 Selecting Constant or Vertex Array Vertex Attribute

```
void    glEnableVertexAttribArray(GLuint index);
void    glDisableVertexAttribArray(GLuint index);
```

index	specifies the generic vertex attribute index. This value ranges from 0 to the maximum vertex attributes supported minus 1.

Example 6-3 illustrates how to draw a triangle where one of the vertex attributes is constant and the other is specified using a vertex array.

Example 6-3 Using Constant and Vertex Array Attributes

```
int Init ( ESContext *esContext )
{
   UserData *userData = (UserData*) esContext->userData;
   const char vShaderStr[] =
      "#version 300 es                            \n"
      "layout(location = 0) in vec4 a_color;      \n"
      "layout(location = 1) in vec4 a_position;   \n"
      "out vec4 v_color;                          \n"
      "void main()                                \n"
      "{                                          \n"
      "    v_color = a_color;                     \n"
      "    gl_Position = a_position;              \n"
      "}";


   const char fShaderStr[] =
      "#version 300 es            \n"
      "precision mediump float;   \n"
      "in vec4 v_color;           \n"
      "out vec4 o_fragColor;      \n"
```

(continues)

Example 6-3 Using Constant and Vertex Array Attributes *(continued)*

```
      "void main()                 \n"
      "{                           \n"
      "    o_fragColor = v_color; \n"
      "}" ;

   GLuint programObject;

   // Create the program object
   programObject = esLoadProgram ( vShaderStr, fShaderStr );

   if ( programObject == 0 )
      return GL_FALSE;

   // Store the program object
   userData->programObject = programObject;

   glClearColor ( 0.0f, 0.0f, 0.0f, 0.0f );
   return GL_TRUE;
}

void Draw ( ESContext *esContext )
{
   UserData *userData = (UserData*) esContext->userData;
   GLfloat color[4] = { 1.0f, 0.0f, 0.0f, 1.0f };
   // 3 vertices, with (x, y, z) per-vertex
   GLfloat vertexPos[3 * 3] =
   {
       0.0f,  0.5f, 0.0f, // v0
      -0.5f, -0.5f, 0.0f, // v1
       0.5f, -0.5f, 0.0f  // v2
   };

   glViewport ( 0, 0, esContext->width, esContext->height );

   glClear ( GL_COLOR_BUFFER_BIT );

   glUseProgram ( userData->programObject );

   glVertexAttrib4fv ( 0, color );
   glVertexAttribPointer ( 1, 3, GL_FLOAT, GL_FALSE, 0,
                           vertexPos );
   glEnableVertexAttribArray ( 1 );

   glDrawArrays ( GL_TRIANGLES, 0, 3 );

   glDisableVertexAttribArray ( 1 );
}
```

The vertex attribute color used in the code example is a constant value specified with glVertexAttrib4fv without enabling the vertex attribute array 0. The vertexPos attribute is specified by using a vertex array with glVertexAttribPointer and enabling the array with glEnableVertexAttribArray. The value of color will be the same for all vertices of the triangle(s) drawn, whereas the vertexPos attribute could vary for vertices of the triangle(s) drawn.

Declaring Vertex Attribute Variables in a Vertex Shader

We have looked at what a vertex attribute is, and considered how to specify vertex attributes in OpenGL ES. We now discuss how to declare vertex attribute variables in a vertex shader.

In a vertex shader, a variable is declared as a vertex attribute by using the in qualifier. Optionally, the attribute variable can also include a layout qualifier that provides the attribute index. A few example declarations of vertex attributes are given here:

```
layout(location = 0) in vec4   a_position;
layout(location = 1) in vec2   a_texcoord;
layout(location = 2) in vec3   a_normal;
```

The in qualifier can be used only with the data types float, vec2, vec3, vec4, int, ivec2, ivec3, ivec4, uint, uvec2, uvec3, uvec4, mat2, mat2x2, mat2x3, mat2x4, mat3, mat3x3, mat3x4, mat4, mat4x2, and mat4x3. Attribute variables cannot be declared as arrays or structures. The following example declarations of vertex attributes are invalid and should result in a compilation error:

```
in foo_t  a_A;   // foo_t is a structure
in vec4   a_B[10];
```

An OpenGL ES 3.0 implementation supports GL_MAX_VERTEX_ATTRIBS four-component vector vertex attributes. A vertex attribute that is declared as a scalar, two-component vector, or three-component vector will count as a single four-component vector attribute. Vertex attributes declared as two-dimensional, three-dimensional, or four-dimensional matrices will count as two, three, or four 4-component vector attributes, respectively. Unlike uniform and vertex shader output/fragment shader input variables, which are packed automatically by the compiler, attributes do not get packed. Please consider your choices carefully when declaring vertex attributes with sizes less than a four-component vector, as the maximum number of vertex attributes available is a limited resource. It might be better to pack them together into a single four-component attribute instead of declaring them as individual vertex attributes in the vertex shader.

Variables declared as vertex attributes in a vertex shader are *read-only* variables and cannot be modified. The following code should cause a compilation error:

```
in        vec4   a_pos;
uniform   vec4   u_v;

void main()
{
   a_pos = u_v; <--- cannot assign to a_pos as it is read-only
}
```

An attribute can be declared inside a vertex shader—but if it is not used, then it is not considered active and does not count against the limit. If the number of attributes used in a vertex shader is greater than `GL_MAX_VERTEX_ATTRIBS`, the vertex shader will fail to link.

Once a program has been successfully linked, we may need to find out the number of active vertex attributes used by the vertex shader attached to this program. Note that this step is necessary only if you are *not* using input layout qualifiers for attributes. In OpenGL ES 3.0, it is recommended that you use layout qualifiers; thus you will not need to query this information after the fact. However, for completeness, the following line of code shows how to get the number of active vertex attributes:

```
glGetProgramiv(program, GL_ACTIVE_ATTRIBUTES, &numActiveAttribs);
```

A detailed description of `glGetProgramiv` is given in Chapter 4, "Shaders and Programs."

The list of active vertex attributes used by a program and their data types can be queried using the `glGetActiveAttrib` command.

```
void   glGetActiveAttrib(GLuint program, GLuint index,
                         GLsizei bufsize, GLsizei *length,
                         GLenum *type, GLint *size,
                         GLchar *name)
```

program	name of a program object that was successfully linked previously.

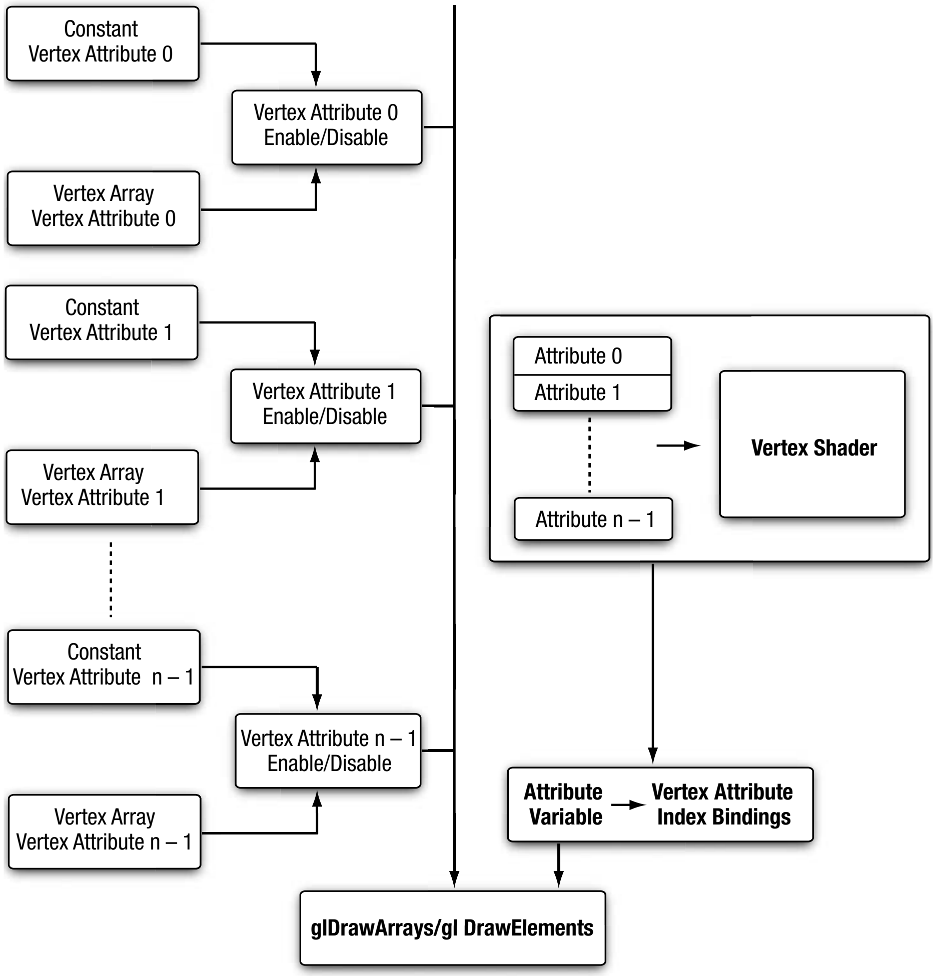
`index`	specifies the vertex attribute to query and will be a value between 0 and `GL_ACTIVE_ATTRIBUTES` – 1. The value of `GL_ACTIVE_ATTRIBUTES` is determined with `glGetProgramiv`.
`bufsize`	specifies the maximum number of characters that may be written into *`name`*, including the null terminator.
`length`	returns the number of characters written into *`name`*, excluding the null terminator, if *`length`* is not `NULL`.
`type`	returns the type of the attribute. Valid values are `GL_FLOAT, GL_FLOAT_VEC2, GL_FLOAT_VEC3, GL_FLOAT_VEC4, GL_FLOAT_MAT2, GL_FLOAT_MAT3, GL_FLOAT_MAT4, GL_FLOAT_MAT2x3, GL_FLOAT_MAT2x4, GL_FLOAT_MAT3x2, GL_FLOAT_MAT3x4, GL_FLOAT_MAT4x2, GL_FLOAT_MAT_4x3, GL_INT, GL_INT_VEC2, GL_INT_VEC3, GL_INT_VEC4, GL_UNSIGNED_INT, GL_UNSIGNED_INT_VEC2, GL_UNSIGNED_INT_VEC3, GL_UNSIGNED_INT_VEC4`
`size`	returns the size of the attribute. This is specified in units of the type returned by *`type`*. If the variable is not an array, *`size`* will always be 1. If the variable is an array, then *`size`* returns the size of the array.
`name`	name of the attribute variable as declared in the vertex shader.

The `glGetActiveAttrib` call provides information about the attribute selected by *`index`*. As detailed in the description of `glGetActiveAttrib`, *`index`* must be a value between 0 and `GL_ACTIVE_ATTRIBUTES` – l. The value of `GL_ACTIVE_ATTRIBUTES` is queried using `glGetProgramiv`. An *`index`* of `0` selects the first active attributes, and an *`index`* of `GL_ACTIVE_ATTRIBUTES - 1` selects the last vertex attribute.

Binding Vertex Attributes to Attribute Variables in a Vertex Shader

We discussed earlier that in a vertex shader, vertex attribute variables are specified by the `in` qualifier, the number of active attributes can be queried using `glGetProgramiv`, and the list of active attributes in a program can be queried using `glGetActiveAttrib`. We also described how generic attribute indices that range from 0 to (`GL_MAX_VERTEX_ATTRIBS` – 1) are used to enable a generic vertex attribute and specify a constant or per-vertex (i.e., vertex array) value using the `glVertexAttrib*` and `glVertexAttribPointer` commands. Now we consider how to map this generic attribute index to the appropriate attribute variable declared in the vertex shader. This mapping will allow appropriate vertex data to be read into the correct vertex attribute variable in the vertex shader.

Figure 6-4 describes how generic vertex attributes are specified and bound to attribute names in a vertex shader.



Constant Vertex Attribute 0
Vertex Attribute 0 Enable/Disable
Vertex Array Vertex Attribute 0
Constant Vertex Attribute 1
Vertex Attribute 1 Enable/Disable
Vertex Array Vertex Attribute 1
Constant Vertex Attribute n – 1
Vertex Attribute n – 1 Enable/Disable
Vertex Array Vertex Attribute n – 1
Attribute 0
Attribute 1
Attribute n – 1
Vertex Shader
Attribute Variable
Vertex Attribute Index Bindings
glDrawArrays/gl DrawElements

Figure 6-4 Specifying and Binding Vertex Attributes for Drawing One or More Primitives

In OpenGL ES 3.0, three approaches may be used to map a generic vertex attribute index to an attribute variable name in the vertex shader. These approaches can be categorized as follows:

- The index can be specified in the vertex shader source code using the `layout(location = N)` qualifier (recommended).
- OpenGL ES 3.0 will bind the generic vertex attribute index to the attribute name.
- The application can bind the vertex attribute index to an attribute name.

The easiest way to bind attributes to a location is to simply use the `layout(location = N)` qualifier; this approach requires the least amount of code. However, in some cases, the other two options might be more desirable. The `glBindAttribLocation` command can be used to bind a generic vertex attribute index to an attribute variable in a vertex shader. This binding takes effect when the program is linked the next time—it does not change the bindings used by the currently linked program.

```
void   glBindAttribLocation(GLuint program,  GLuint index,
                            const GLchar *name)
```

program	name of a program object
index	generic vertex attribute index
name	name of the attribute variable

If *name* was bound previously, its assigned binding is replaced with an index. `glBindAttribLocation` can be called even before a vertex shader is attached to a program object. As a consequence, this call can be used to bind any attribute name. Attribute names that do not exist or are not active in a vertex shader attached to the program object are ignored.

Another option is to let OpenGL ES 3.0 bind the attribute variable name to a generic vertex attribute index. This binding is performed when the program is linked. In the linking phase, the OpenGL ES 3.0 implementation performs the following operation for each attribute variable:

> For each attribute variable, check whether a binding has been specified via `glBindAttribLocation`. If a binding is specified, the appropriate attribute index specified is used. If not, the implementation will assign a generic vertex attribute index.

This assignment is implementation specific; that is, it can vary from one OpenGL ES 3.0 implementation to another. An application can query the assigned binding by using the `glGetAttribLocation` command.

```
GLint     glGetAttribLocation(GLuint program,
                              const GLchar *name)
```

program	program object
name	name of attribute variable

`glGetAttribLocation` returns the generic attribute index that was bound to the attribute variable *name* when the program object defined by *program* was last linked. If *name* is not an active attribute variable, or if *program* is not a valid program object or was not linked successfully, then `-1` is returned, indicating an invalid attribute index.

Vertex Buffer Objects

The vertex data specified using vertex arrays are stored in client memory. This data must be copied from client memory to graphics memory when a draw call such as `glDrawArrays` or `glDrawElements` is made. These two commands are described in detail in Chapter 7, "Primitive Assembly and Rasterization." It would, however, be much better if we did not have to copy the vertex data on every draw call, but instead could cache the data in graphics memory. This approach can significantly improve the rendering performance and also reduce the memory bandwidth and power consumption requirements, both of which are quite important for handheld devices. This is where vertex buffer objects can help. Vertex buffer objects allow OpenGL ES 3.0 applications to allocate and cache vertex data in high-performance graphics memory and render from this memory, thereby avoiding resending data every time a primitive is drawn. Not only the vertex data, but also the element indices that describe the vertex indices of the primitive and are passed as an argument to `glDrawElements`, can be cached.

OpenGL ES 3.0 supports two types of buffer objects that are used for specifying vertex and primitive data: *array buffer objects* and *element array buffer objects*. The array buffer objects specified by the `GL_ARRAY_BUFFER` token are used to create buffer objects that will store vertex data. The element array buffer objects specified by the `GL_ELEMENT_ARRAY_BUFFER` token are used to create buffer objects that will store indices of a primitive. Other buffer object types in OpenGL ES 3.0 are described elsewhere in this book: uniform buffers (Chapter 4), transform feedback buffers (Chapter 8), pixel unpack buffers (Chapter 9), pixel pack buffers (Chapter 11), and copy buffers (the *Copying Buffer Objects* section later in this chapter). For now, we will focus on the buffer objects used for specifying vertex attributes and element arrays.

Note: To get best performance, we recommend that OpenGL ES 3.0 applications use vertex buffer objects for vertex attribute data and element indices.

Before we can render using buffer objects, we need to allocate the buffer objects and upload the vertex data and element indices into appropriate buffer objects. This is demonstrated by the sample code in Example 6-4.

Example 6-4 Creating and Binding Vertex Buffer Objects

```
void       initVertexBufferObjects(vertex_t *vertexBuffer,
                                   GLushort *indices,
                                   GLuint numVertices,
                                   GLuint numlndices,
                                   GLuint *vboIds)

{
    glGenBuffers(2, vboIds);

    glBindBuffer(GL_ARRAY_BUFFER, vboIds[0]);
    glBufferData(GL_ARRAY_BUFFER, numVertices *
                 sizeof(vertex_t), vertexBuffer,
                 GL_STATIC_DRAW);

    // bind buffer object for element indices
    glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, vboIds[1]);
    glBufferData(GL_ELEMENT_ARRAY_BUFFER,
                 numIndices * sizeof(GLushort),
                 indices, GL_STATIC_DRAW);
}
```

The code in Example 6-4 creates two buffer objects: a buffer object to store the actual vertex attribute data, and a buffer object to store the element indices that make up the primitive. In this example, the `glGenBuffers` command is called to get two unused buffer object names in `vboIds`. The unused buffer object names returned in `vboIds` are then used to create an array buffer object and an element array buffer object. The array buffer object is used to store vertex attribute data for vertices of one or more primitives. The element array buffer object stores the indices of one or more primitives. The actual array or element data are specified using `glBufferData`. Note that `GL_STATIC_DRAW` is passed as an argument to `glBufferData`. This value is used to describe how the buffer is accessed by the application and will be described later in this section.

```
void   glGenBuffers(GLsizei n,   GLuint *buffers)
```

n	number of buffer object names to return
buffers	pointer to an array of *n* entries, where allocated buffer objects are returned

`glGenBuffers` assigns *n* buffer object names and returns them in *buffers*. The buffer object names returned by `glGenBuffers` are unsigned integer numbers other than `0`. The value `0` is reserved by OpenGL ES and does not refer to a buffer object. Attempts to modify or query the buffer object state for buffer object `0` will generate an error.

The `glBindBuffer` command is used to make a buffer object current. The first time a buffer object name is bound by calling `glBindBuffer`, the buffer object is allocated with the default state; if the allocation is successful, this allocated object is bound as the current buffer object for the target.

```
void   glBindBuffer(GLenum target,   GLuint buffer)
```

target	can be set to any of the following targets:
	`GL_ARRAY_BUFFER`
	`GL_ELEMENT_ARRAY_BUFFER`
	`GL_COPY_READ_BUFFER`
	`GL_COPY_WRITE_BUFFER`
	`GL_PIXEL_PACK_BUFFER`
	`GL_PIXEL_UNPACK_BUFFER`
	`GL_TRANSFORM_FEEDBACK_BUFFER`
	`GL_UNIFORM_BUFFER`

buffer	buffer object to be assigned as the current object to target

Note that glGenBuffers is not required to assign a buffer object name before it is bound using glBindBuffer. Alternatively, an application can specify an unused buffer object name with glBindBuffer. However, we recommend that OpenGL ES applications call glGenBuffers and use buffer object names returned by glGenBuffers instead of specifying their own buffer object names.

The state associated with a buffer object can be categorized as follows:

- GL_BUFFER_SIZE. This refers to the size of the buffer object data that is specified by glBufferData. The initial value when the buffer object is first bound using glBindBuffer is 0.
- GL_BUFFER_USAGE. This is a hint as to how the application will use the data stored in the buffer object. It is described in detail in Table 6-2. The initial value is GL_STATIC_DRAW.

Table 6-2 Buffer Usage

Buffer Usage Enum	**Description**
GL_STATIC_DRAW	The buffer object data will be modified once and used many times to draw primitives or specify images.
GL_STATIC_READ	The buffer object data will be modified once and used many times to read data back from OpenGL ES. The data read back from OpenGL ES will be queried for from the application.
GL_STATIC_COPY	The buffer object data will be modified once and used many times to read data back from OpenGL ES. The data read back from OpenGL ES will be used directly as a source to draw primitives or specify images.
GL_DYNAMIC_DRAW	The buffer object data will be modified repeatedly and used many times to draw primitives or specify images.
GL_DYNAMIC_READ	The buffer object will be modified repeatedly and used many times to read data back from OpenGL ES. The data read back from OpenGL ES will be queried for from the application.
GL_DYNAMIC_COPY	The buffer object data will be modified repeatedly and used many times to read data back from OpenGL ES. The data read back from OpenGL ES will be used directly as a source to draw primitives or specify images.

(continues)

Table 6-2 Buffer Usage *(continued)*

Buffer Usage Enum	Description
`GL_STREAM_DRAW`	The buffer object data will be modified once and used only a few times to draw primitives or specify images.
`GL_STREAM_READ`	The buffer object data will be modified once and used only a few times to read data back from OpenGL ES. The data read back from OpenGL ES will be queried for from the application.
`GL_STREAM_COPY`	The buffer object data will be modified once and used only a few times to read data back from OpenGL ES. The data read back from OpenGL ES will be used directly as a source to draw primitives or specify images.

As mentioned earlier, `GL_BUFFER_USAGE` is a hint to OpenGL ES—not a guarantee. Therefore, an application could allocate a buffer object data store with usage set to `GL_STATIC_DRAW` and frequently modify it.

The vertex array data or element array data storage is created and initialized using the `glBufferData` command.

```
void   glBufferData(GLenum target,   GLsizeiptr size,
                    const void *data,   GLenum usage)
```

target	can be set to any of the following targets:
	`GL_ARRAY_BUFFER`
	`GL_ELEMENT_ARRAY_BUFFER`
	`GL_COPY_READ_BUFFER`
	`GL_COPY_WRITE_BUFFER`
	`GL_PIXEL_PACK_BUFFER`
	`GL_PIXEL_UNPACK_BUFFER`
	`GL_TRANSFORM_FEEDBACK_BUFFER`
	`GL_UNIFORM_BUFFER`

size	size of buffer data store in bytes
data	pointer to the buffer data supplied by the application
usage	a hint on how the application will use the data stored in the buffer object (refer to Table 6-2 for details)

`glBufferData` will reserve appropriate data storage based on the value of *`size`*. The *`data`* argument can be a `NULL` value, indicating that the reserved data store remains uninitialized. If *`data`* is a valid pointer, then the contents of *`data`* are copied to the allocated data store. The contents of the buffer object data store can be initialized or updated using the `glBufferSubData` command.

```
void   glBufferSubData(GLenum target,   GLintptr offset,
                       GLsizeiptr size,    const void *data)
```

`target`	can be set to any of the following targets:
	`GL_ARRAY_BUFFER`
	`GL_ELEMENT_ARRAY_BUFFER`
	`GL_COPY_READ_BUFFER`
	`GL_COPY_WRITE_BUFFER`
	`GL_PIXEL_PACK_BUFFER`
	`GL_PIXEL_UNPACK_BUFFER`
	`GL_TRANSFORM_FEEDBACK_BUFFER`
	`GL_UNIFORM_BUFFER`

`offset`	offset into the buffer data store and number of bytes of the
`size`	data store that is being modified
`data`	pointer to the client data that need to be copied into the buffer object data storage

After the buffer object data store has been initialized or updated using `glBufferData` or `glBufferSubData`, the client data store is no longer needed and can be released. For static geometry, applications can free the client data store and reduce the overall system memory consumed by the application. This might not be possible for dynamic geometry.

We now look at drawing primitives with and without buffer objects. Example 6-5 describes drawing primitives with and without vertex buffer objects. Notice that the code to set up the vertex attributes is very similar. In this example, we use the same buffer object for all attributes of a vertex. When a `GL_ARRAY_BUFFER` buffer object is used, the `pointer` argument in `glVertexAttribPointer` changes from being a pointer to the actual data to being an offset in bytes into the vertex buffer store allocated using `glBufferData`. Similarly, if a valid `GL_ELEMENT_ARRAY_BUFFER` object is used, the `indices` argument in `glDrawElements` changes from being a pointer to the actual element indices to being an offset in bytes to the element index buffer store allocated using `glBufferData`.

Example 6-5 Drawing with and without Vertex Buffer Objects

```
#define VERTEX_POS_SIZE       3 // x, y, and z
#define VERTEX_COLOR_SIZE     4 // r, g, b, and a

#define VERTEX_POS_INDX       0
#define VERTEX_COLOR_INDX     1
//
// vertices   - pointer to a buffer that contains vertex
//              attribute data
// vtxStride  - stride of attribute data / vertex in bytes
// numIndices - number of indices that make up primitives
//              drawn as triangles
// indices    - pointer to element index buffer
//
void DrawPrimitiveWithoutVBOs(GLfloat *vertices,
                              GLint vtxStride,
                              GLint numIndices,
                              GLushort *indices)
{
   GLfloat   *vtxBuf = vertices;

   glBindBuffer(GL_ARRAY_BUFFER, 0);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, 0);

   glEnableVertexAttribArray(VERTEX_POS_INDX);
   glEnableVertexAttribArray(VERTEX_COLOR_INDX);

   glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                         GL_FLOAT, GL_FALSE, vtxStride,
                         vtxBuf);
   vtxBuf += VERTEX_POS_SIZE;

   glVertexAttribPointer(VERTEX_COLOR_INDX,
                         VERTEX_COLOR_SIZE, GL_FLOAT,
                         GL_FALSE, vtxStride, vtxBuf);

   glDrawElements(GL_TRIANGLES, numIndices, GL_UNSIGNED_SHORT,
                  indices);

   glDisableVertexAttribArray(VERTEX_POS_INDX);
   glDisableVertexAttribArray(VERTEX_COLOR_INDX);
}

void DrawPrimitiveWithVBOs(ESContext *esContext,
                           GLint numVertices, GLfloat *vtxBuf,
                           GLint vtxStride, GLint numIndices,
                           GLushort *indices)
```

Example 6-5 Drawing with and without Vertex Buffer Objects *(continued)*

```
{
   UserData *userData = (UserData*) esContext->userData;
   GLuint   offset = 0;
   // vboIds[0] - used to store vertex attribute data
   // vboIds[l] - used to store element indices
   if ( userData->vboIds[0] == 0 && userData->vboIds[1] == 0 )
   {
      // Only allocate on the first draw
      glGenBuffers(2, userData->vboIds);

      glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
      glBufferData(GL_ARRAY_BUFFER, vtxStride * numVertices,
                   vtxBuf, GL_STATIC_DRAW);
      glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,
                    userData->vboIds[1]);
      glBufferData(GL_ELEMENT_ARRAY_BUFFER,
                   sizeof(GLushort) * numIndices,
                   indices, GL_STATIC_DRAW);
   }

   glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, userData->vboIds[1]);

   glEnableVertexAttribArray(VERTEX_POS_INDX);
   glEnableVertexAttribArray(VERTEX_COLOR_INDX);

   glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                         GL_FLOAT, GL_FALSE, vtxStride,
                         (const void*)offset);

   offset += VERTEX_POS_SIZE * sizeof(GLfloat);
   glVertexAttribPointer(VERTEX_COLOR_INDX,
                         VERTEX_COLOR_SIZE,
                         GL_FLOAT, GL_FALSE, vtxStride,
                         (const void*)offset);

   glDrawElements(GL_TRIANGLES, numIndices, GL_UNSIGNED_SHORT,
                  0);

   glDisableVertexAttribArray(VERTEX_POS_INDX);
   glDisableVertexAttribArray(VERTEX_COLOR_INDX);

   glBindBuffer(GL_ARRAY_BUFFER, 0);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, 0);
}
```

(continues)

Example 6-5 Drawing with and without Vertex Buffer Objects *(continued)*

```
void Draw ( ESContext *esContext )
{
   UserData *userData = (UserData*) esContext->userData;

   // 3 vertices, with (x, y, z),(r, g, b, a) per-vertex
   GLfloat vertices[3 * (VERTEX_POS_SIZE + VERTEX_COLOR_SIZE)] =
   {
      -0.5f,  0.5f, 0.0f,        // v0
       1.0f,  0.0f, 0.0f, 1.0f,  // c0
      -1.0f, -0.5f, 0.0f,        // v1
       0.0f,  1.0f, 0.0f, 1.0f,  // c1
       0.0f, -0.5f, 0.0f,        // v2
       0.0f,  0.0f, 1.0f, 1.0f,  // c2
   };
   // index buffer data
   GLushort indices[3] = { 0, 1, 2 };

   glViewport ( 0, 0, esContext->width, esContext->height );
   glClear ( GL_COLOR_BUFFER_BIT );
   glUseProgram ( userData->programObject );
   glUniform1f ( userData->offsetLoc, 0.0f );

   DrawPrimitiveWithoutVBOs ( vertices,
      sizeof(GLfloat) * (VERTEX_POS_SIZE + VERTEX_COLOR_SIZE),
      3, indices );

   // offset the vertex positions so both can be seen
   glUniform1f ( userData->offsetLoc, 1.0f );

   DrawPrimitiveWithVBOs ( esContext, 3, vertices,
      sizeof(GLfloat) * (VERTEX_POS_SIZE + VERTEX_COLOR_SIZE),
      3, indices );
}
```

In Example 6-5, we used one buffer object to store all the vertex data. This demonstrates the array of structures method of storing vertex attributes described in Example 6-1. It is also possible to have a buffer object for each vertex attribute—that is, the structure of arrays method of storing vertex attributes described in Example 6-2. Example 6-6 illustrates how `drawPrimitiveWithVBOs` would look with a separate buffer object for each vertex attribute.

Example 6-6 Drawing with a Buffer Object per Attribute

```
#define VERTEX_POS_SIZE       3 // x, y, and z
#define VERTEX_COLOR_SIZE     4 // r, g, b, and a

#define VERTEX_POS_INDX       0
#define VERTEX_COLOR_INDX     1


void DrawPrimitiveWithVBOs(ESContext *esContext,
                           GLint numVertices, GLfloat **vtxBuf,
                           GLint *vtxStrides, GLint numIndices,
                           GLushort *indices)
{
   UserData *userData = (UserData*) esContext->userData;
   // vboIds[0] - used to store vertex position
   // vboIds[1] - used to store vertex color
   // vboIds[2] - used to store element indices
   if ( userData->vboIds[0] == 0 && userData->vboIds[1] == 0 &&
        userData->vboIds[2] == 0)
   {
      // allocate only on the first draw
      glGenBuffers(3, userData->vboIds);

      glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
      glBufferData(GL_ARRAY_BUFFER, vtxStrides[0] * numVertices,
                   vtxBuf[0], GL_STATIC_DRAW);
      glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[1]);
      glBufferData(GL_ARRAY_BUFFER, vtxStrides[1] * numVertices,
                   vtxBuf[1], GL_STATIC_DRAW);
      glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,
                   userData->vboIds[2]);
      glBufferData(GL_ELEMENT_ARRAY_BUFFER,
                   sizeof(GLushort) * numIndices,
                   indices, GL_STATIC_DRAW);
   }

   glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
   glEnableVertexAttribArray(VERTEX_POS_INDX);
   glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                         GL_FLOAT, GL_FALSE, vtxStrides[0], 0);

   glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[1]);
   glEnableVertexAttribArray(VERTEX_COLOR_INDX);
   glVertexAttribPointer(VERTEX_COLOR_INDX,
                         VERTEX_COLOR_SIZE,
                         GL_FLOAT, GL_FALSE, vtxStrides[1], 0);
```

(continues)

Example 6-6 Drawing with a Buffer Object per Attribute *(continued)*

```
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, userData->vboIds[2]);

   glDrawElements(GL_TRIANGLES, numIndices,
                  GL_UNSIGNED_SHORT, 0);

   glDisableVertexAttribArray(VERTEX_POS_INDX);
   glDisableVertexAttribArray(VERTEX_COLOR_INDX);

   glBindBuffer(GL_ARRAY_BUFFER, 0);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, 0);
}
```

After the application has finished using the buffer objects, they can be deleted using the `glDeleteBuffers` command.

`void` **`glDeleteBuffers`**`(GLsizei` *`n`*`, const GLuint *`*`buffers`*`)`

n	number of buffer objects to be deleted
buffers	array of *n* entries that contain the buffer objects to be deleted

`glDeleteBuffers` deletes the buffer objects specified in buffers. Once a buffer object has been deleted, it can be reused as a new buffer object that stores vertex attributes or element indices for a different primitive.

As you can see from these examples, using vertex buffer objects is very easy and requires very little extra work to implement over vertex arrays. The minimal extra work involved in supporting vertex buffer objects is well worth it, considering the performance gain this feature provides. In the next chapter, we discuss how to draw primitives using commands such as `glDrawArrays` and `glDrawElements`, and how the primitive assembly and rasterization pipeline stages in OpenGL ES 3.0 work.

Vertex Array Objects

So far, we have covered how to load vertex attributes in two different ways: using client vertex arrays and using vertex buffer objects. Vertex buffer objects are preferred to client vertex arrays because they can reduce the amount of data copied between the CPU and GPU and, therefore, have better performance. In OpenGL ES 3.0, a new feature was introduced to make using vertex arrays even more efficient: vertex array objects (VAOs). As we have seen, setting up drawing using vertex buffer objects can require many calls to `glBindBuffer`, `glVertexAttribPointer`, and `glEnableVertexAttribArray`. To make it faster to switch between vertex array configurations, OpenGL ES 3.0 introduced vertex array objects. VAOs provide a single object that contains all of the state required to switch between vertex array/vertex buffer object configurations.

In fact, there is always a vertex array object that is active in OpenGL ES 3.0. All of the examples so far in this chapter have operated on the default vertex array object (the default VAO has the ID of 0). To create a new vertex array object, you use the `glGenVertexArrays` function.

```
void   glGenVertexArrays(GLsizei n,   GLuint *arrays)
```

n	number of vertex array object names to return
arrays	pointer to an array of *n* entries, where allocated vertex array objects are returned

Once created, the vertex array object can be bound for use using `glBindVertexArray`.

```
void   glBindVertexArray(GLuint array)
```

array	object to be assigned as the current vertex array object

Each VAO contains a full state vector that describes all of the vertex buffer bindings and vertex client state enables. When the VAO is bound, its state vector provides the current settings of the vertex buffer state. After binding the vertex array object using `glBindVertexArray`, subsequent calls that change the vertex array state (`glBindBuffer, glVertexAttribPointer, glEnableVertexAttribArray`, and `glDisableVertexAttribArray`) will affect the new VAO.

In this way, an application can quickly switch between vertex array configurations by binding a vertex array object that has been set with state. Rather than having to make many calls to change the vertex array state, all of the changes can be made in a single function call. Example 6-7 demonstrates the use of a vertex array object at initialization time to set up the vertex array state. The vertex array state is then set in a single function call at draw time using `glBindVertexArray`.

Example 6-7 Drawing with a Vertex Array Object

```
#define VERTEX_POS_SIZE       3 // x, y, and z
#define VERTEX_COLOR_SIZE     4 // r, g, b, and a

#define VERTEX_POS_INDX       0
#define VERTEX_COLOR_INDX     1

#define VERTEX_STRIDE         ( sizeof(GLfloat) *     \
                               ( VERTEX_POS_SIZE +    \
                                 VERTEX_COLOR_SIZE ) )


int Init ( ESContext *esContext )
{
   UserData *userData = (UserData*) esContext->userData;
   const char vShaderStr[] =
      "#version 300 es                            \n"
      "layout(location = 0) in vec4 a_position;   \n"
      "layout(location = 1) in vec4 a_color;      \n"
      "out vec4 v_color;                          \n"
      "void main()                                \n"
      "{                                          \n"
      "    v_color = a_color;                     \n"
      "    gl_Position = a_position;              \n"
      "}";


   const char fShaderStr[] =
      "#version 300 es             \n"
      "precision mediump float;    \n"
      "in vec4 v_color;            \n"
      "out vec4 o_fragColor;       \n"
      "void main()                 \n"
      "{                           \n"
      "    o_fragColor = v_color; \n"
      "}" ;

   GLuint programObject;

   // 3 vertices, with (x, y, z),(r, g, b, a) per-vertex
   GLfloat vertices[3 * (VERTEX_POS_SIZE + VERTEX_COLOR_SIZE)] =
   {
       0.0f,  0.5f, 0.0f,        // v0
       1.0f,  0.0f, 0.0f, 1.0f,  // c0
      -0.5f, -0.5f, 0.0f,        // v1
       0.0f,  1.0f, 0.0f, 1.0f,  // c1
       0.5f, -0.5f, 0.0f,        // v2
       0.0f,  0.0f, 1.0f, 1.0f,  // c2
   };
```

Example 6-7 Drawing with a Vertex Array Object *(continued)*

```
   // Index buffer data
   GLushort indices[3] = { 0, 1, 2 };

   // Create the program object
   programObject = esLoadProgram ( vShaderStr, fShaderStr );

   if ( programObject == 0 )
      return GL_FALSE;

   // Store the program object
   userData->programObject = programObject;

   // Generate VBO Ids and load the VBOs with data
   glGenBuffers ( 2, userData->vboIds );

   glBindBuffer ( GL_ARRAY_BUFFER, userData->vboIds[0] );
   glBufferData ( GL_ARRAY_BUFFER, sizeof(vertices),
                  vertices, GL_STATIC_DRAW);
   glBindBuffer ( GL_ELEMENT_ARRAY_BUFFER, userData->vboIds[1]);
   glBufferData ( GL_ELEMENT_ARRAY_BUFFER, sizeof ( indices ),
                  indices, GL_STATIC_DRAW );

   // Generate VAO ID
   glGenVertexArrays ( 1, &userData->vaoId );

   // Bind the VAO and then set up the vertex
   // attributes
   glBindVertexArray ( userData->vaoId );

   glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, userData->vboIds[1]);

   glEnableVertexAttribArray(VERTEX_POS_INDX);
   glEnableVertexAttribArray(VERTEX_COLOR_INDX);

   glVertexAttribPointer ( VERTEX_POS_INDX, VERTEX_POS_SIZE,
      GL_FLOAT, GL_FALSE, VERTEX_STRIDE, (const void*) 0 );

   glVertexAttribPointer ( VERTEX_COLOR_INDX, VERTEX_COLOR_SIZE,
      GL_FLOAT, GL_FALSE, VERTEX_STRIDE,
      (const void*) ( VERTEX_POS_SIZE * sizeof(GLfloat) ) );

   // Reset to the default VAO
   glBindVertexArray ( 0 );

   glClearColor ( 0.0f, 0.0f, 0.0f, 0.0f );
   return GL_TRUE;
}
```

(continues)

Example 6-7 Drawing with a Vertex Array Object *(continued)*

```
void Draw ( ESContext *esContext )
{
   UserData *userData = (UserData*) esContext->userData;

   glViewport ( 0, 0, esContext->width, esContext->height );
   glClear ( GL_COLOR_BUFFER_BIT );
   glUseProgram ( userData->programObject );

   // Bind the VAO
   glBindVertexArray ( userData->vaoId );

   // Draw with the VAO settings
   glDrawElements ( GL_TRIANGLES, 3, GL_UNSIGNED_SHORT,
                    (const void*) 0 );

   // Return to the default VAO
   glBindVertexArray ( 0 );
}
```

When an application is finished with one or more vertex array objects, they can be deleted using `glDeleteVertexArrays`.

`void` **`glDeleteVertexArrays`**`(GLsizei` *`n`*`, GLuint *`*`arrays`*`)`

n	number of vertex array objects to be deleted
arrays	array of *n* entries that contain the vertex array objects to be deleted

Mapping Buffer Objects

So far, we have shown how to load data into buffer objects using `glBufferData` or `glBufferSubData`. It is also possible for applications to map and unmap a buffer object's data storage into the application's address space. There are several reasons why an application might prefer to map a buffer rather than load its data using `glBufferData` or `glBufferSubData`:

- Mapping the buffer can reduce the memory utilization of the application because potentially only a single copy of the data needs to be stored.
- On architectures with shared memory, mapping the buffer returns a direct pointer into the address space where the buffer will be stored for the GPU. By mapping the buffer, the application can avoid the copy step, thereby realizing better performance on updates.

The `glMapBufferRange` command returns a pointer to all of or a portion (range) of the data storage for the buffer object. This pointer can be used by the application to read or update the contents of the buffer object. The `glUnmapBuffer` command is used to indicate that the updates have been completed and to release the mapped pointer.

```
void   *glMapBufferRange(GLenum target,  GLintptr offset,
                         GLsizeiptr length, GLbitfield
                         access)
```

`target`	can be set to any of the following targets:
	`GL_ARRAY_BUFFER`
	`GL_ELEMENT_ARRAY_BUFFER`
	`GL_COPY_READ_BUFFER`
	`GL_COPY_WRITE_BUFFER`
	`GL_PIXEL_PACK_BUFFER`
	`GL_PIXEL_UNPACK_BUFFER`
	`GL_TRANSFORM_FEEDBACK_BUFFER`
	`GL_UNIFORM_BUFFER`

`offset`	offset in bytes into the buffer data store
`length`	number of bytes of the buffer data to map
`access`	a bitfield combination of access flags. The application must specify at least one of the following flags:

`GL_MAP_READ_BIT`	The application will read from the returned pointer.
`GL_MAP_WRITE_BIT`	The application will write to the returned pointer.

Additionally, the application may include the following optional access flags:

`GL_MAP_INVALIDATE_RANGE_BIT`	Indicates that the contents of the buffer within the specified range can be discarded by the driver before returning the pointer. This flag cannot be used in combination with `GL_MAP_READ_BIT`.

(continues)

(continued)

`GL_MAP_INVALIDATE_BUFFER_BIT`	Indicates that the contents of the entire buffer can be discarded by the driver before returning the pointer. This flag can only be used in combination with `GL_MAP_READ_BIT`.
`GL_MAP_FLUSH_EXPLICIT_BIT`	Indicates that the application will explicitly flush operations to subranges of the mapped range using `glFlushMappedBufferRange`. This flag cannot be used in combination with `GL_MAP_WRITE_BIT`.
`GL_MAP_UNSYNCHRONIZED_BIT`	Indicates that the driver does not need to wait for pending operations on the buffer object before returning a pointer to the buffer range. If there are pending operations, the results of outstanding operations and any future operations on the buffer object become undefined.

`glMapBufferRange` returns a pointer to the buffer data storage range requested. If an error occurs or an invalid request is made, the function will return `NULL`. The `glUnmapBuffer` command unmaps a previously mapped buffer.

```
GLboolean   glUnmapBuffer(GLenum target)
```

`target`	must be set to `GL_ARRAY_BUFFER`

`glUnmapBuffer` returns `GL_TRUE` if the unmap operation is successful. The pointer returned by `glMapBufferRange` can no longer be used after a successful unmap has been performed. `glUnmapBuffer` returns `GL_FALSE` if the data in the vertex buffer object's data storage have become corrupted after the buffer has been mapped. This can occur due to a change in the screen resolution, multiple screens being used by OpenGL ES context, or an out-of-memory event that causes the mapped memory to be discarded.[1]

The code in Example 6-8 demonstrates the use of `glMapBufferRange` and `glUnmapBuffer` to write the contents of vertex buffer objects.

Example 6-8 Mapping a Buffer Object for Writing

```
GLfloat *vtxMappedBuf;
GLushort *idxMappedBuf;

glGenBuffers ( 2, userData->vboIds );

glBindBuffer ( GL_ARRAY_BUFFER, userData->vboIds[0] );
glBufferData ( GL_ARRAY_BUFFER, vtxStride * numVertices,
               NULL, GL_STATIC_DRAW );

vtxMappedBuf = (GLfloat*)
   glMapBufferRange ( GL_ARRAY_BUFFER, 0,
                      vtxStride * numVertices,
                      GL_MAP_WRITE_BIT |
                      GL_MAP_INVALIDATE_BUFFER_BIT );
if ( vtxMappedBuf == NULL )
{
   esLogMessage( "Error mapping vertex buffer object." );
   return;
}

// Copy the data into the mapped buffer
memcpy ( vtxMappedBuf, vtxBuf, vtxStride * numVertices );

// Unmap the buffer
if ( glUnmapBuffer( GL_ARRAY_BUFFER ) == GL_FALSE )
{
   esLogMessage( "Error unmapping array buffer object." );
   return;
}

// Map the index buffer
glBindBuffer ( GL_ELEMENT_ARRAY_BUFFER,
               userData->vboIds[1] );
glBufferData ( GL_ELEMENT_ARRAY_BUFFER,
               sizeof(GLushort) * numIndices,
            NULL, GL_STATIC_DRAW );
```

(continues)

1. If the screen resolution changes to a larger width, height, and bits per pixel at runtime, the mapped memory may have to be released. Note that this is not a very common issue on handheld devices. A backing store is rarely implemented on most handheld and embedded devices. Therefore, an out-of-memory event will result in memory being freed and becoming available for reuse for critical needs.

Example 6-8 Mapping a Buffer Object for Writing *(continued)*

```
idxMappedBuf = (GLushort*)
   glMapBufferRange ( GL_ELEMENT_ARRAY_BUFFER, 0,
                      sizeof(GLushort) * numIndices,
                      GL_MAP_WRITE_BIT |
                      GL_MAP_INVALIDATE_BUFFER_BIT );
if ( idxMappedBuf == NULL )
{
   esLogMessage( "Error mapping element buffer object." );
   return;
}

// Copy the data into the mapped buffer
memcpy ( idxMappedBuf, indices,
         sizeof(GLushort) * numIndices );

// Unmap the buffer
if ( glUnmapBuffer( GL_ELEMENT_ARRAY_BUFFER ) == GL_FALSE )
{
   esLogMessage( "Error unmapping element buffer object." );
   return;
}
```

Flushing a Mapped Buffer

An application may wish to map a range (or all) of a buffer object using `glMapBufferRange`, but update only discrete subregions of the mapped range. To avoid the potential performance penalty for flushing the entire mapped range when calling `glUnmapBuffer`, the application can map with the `GL_MAP_FLUSH_EXPLICIT_BIT` access flag (along with `GL_MAP_WRITE_BIT`). When the application has finished updating a portion of the mapped range, it can indicate this fact using `glFlushMappedBufferRange`.

```
void *glFlushMappedBufferRange(GLenum target,
                               GLintptr offset,
                               GLsizeiptr length)
```

target	can be set to any of the following targets:
	`GL_ARRAY_BUFFER`
	`GL_ELEMENT_ARRAY_BUFFER`
	`GL_COPY_READ_BUFFER`
	`GL_COPY_WRITE_BUFFER`
	`GL_PIXEL_PACK_BUFFER`
	`GL_PIXEL_UNPACK_BUFFER`

	GL_TRANSFORM_FEEDBACK_BUFFER GL_UNIFORM_BUFFER
offset	offset in bytes from the beginning of the mapped buffer
length	number of bytes of the buffer from offset to flush

If an application maps with `GL_MAP_FLUSH_EXPLICIT_BIT` but does not explicitly flush a modified region with `glFlushMappedBufferRange`, its contents will be undefined.

Copying Buffer Objects

So far, we have shown how to load buffer objects with data using `glBufferData`, `glBufferSubData`, and `glMapBufferRange`. All of these techniques involve transferring data from the application to the device. It is also possible with OpenGL ES 3.0 to copy data from one buffer object to another entirely on the device. This can be done using the function `glCopyBufferSubData`.

```
void   glCopyBufferSubData(GLenum readtarget,
                           GLenum writetarget,
                           GLintptr readoffset,
                           GLintptr writeoffset,
                           GLsizeiptr size)
```

readtarget	the buffer object target to read from.
writetarget	the buffer object target to write to. Both `readtarget` and `writetarget` can be set to any of the following targets (although they must not be the same target): GL_ARRAY_BUFFER GL_ELEMENT_ARRAY_BUFFER GL_COPY_READ_BUFFER GL_COPY_WRITE_BUFFER GL_PIXEL_PACK_BUFFER GL_PIXEL_UNPACK_BUFFER GL_TRANSFORM_FEEDBACK_BUFFER GL_UNIFORM_BUFFER

(continues)

(continued)

readoffset	offset in bytes into the read buffer data to copy from.
writeoffset	offset in bytes into the write buffer data to copy to.
size	the number of bytes to copy from the read buffer data to the write buffer data.

Calling `glCopyBufferSubData` will copy the specified bytes from the buffer bound to the `readtarget` to the `writetarget`. The buffer binding is determined based on the last call to `glBindBuffer` for each target. Any type of buffer object (array, element array, transform feedback, and so on) can be bound to the `GL_COPY_READ_BUFFER` or `GL_COPY_WRITE_BUFFER` target. These two targets are provided as a convenience so that the application doesn't have to change any of the true buffer bindings to perform a copy between buffers.

Summary

This chapter explored how vertex attributes and data are specified in OpenGL ES 3.0. Specifically, it covered the following topics:

- How to specify constant vertex attributes using the `glVertexAttrib*` functions and vertex arrays using the `glVertexAttrib[I]Pointer` functions
- How to create and store vertex attribute and element data in vertex buffer objects
- How vertex array state is encapsulated in vertex array objects and how to use VAOs to improve performance
- The variety of methods for loading buffer objects with data: `glBuffer[Sub]Data`, `glMapBufferRange`, and `glCopyBufferSubData`

Now that we know how vertex data are specified, the next chapter covers all of the primitives that can be drawn in OpenGL ES using vertex data.

Chapter 7

Primitive Assembly and Rasterization

This chapter describes the types of primitives and geometric objects that are supported by OpenGL ES, and explains how to draw them. It then describes the primitive assembly stage, which occurs after the vertices of a primitive are processed by the vertex shader. In the primitive assembly stage, clipping, perspective divide, and viewport transformation operations are performed. These operations are discussed in detail. The chapter concludes with a description of the rasterization stage. Rasterization is the process that converts primitives into a set of two-dimensional fragments, which are processed by the fragment shader. These two-dimensional fragments represent pixels that may be drawn on the screen.

Refer to Chapter 8, “Vertex Shaders,” for a detailed description of vertex shaders. Chapter 9, “Texturing,” and Chapter 10, “Fragment Shaders,” describe processing that is applied to fragments generated by the rasterization stage.

Primitives

A primitive is a geometric object that can be drawn using the `glDrawArrays`, `glDrawElements`, `glDrawRangeElements`, `glDrawArraysInstanced`, and `glDrawElementsInstanced` commands in OpenGL ES. The primitive is described by a set of vertices that indicate the vertex position. Other information, such as color, texture coordinates, and geometric normal can also be associated with each vertex as generic attributes.

The following primitives can be drawn in OpenGL ES 3.0:

- Triangles
- Lines
- Point sprites

Triangles

Triangles represent the most common method used to describe a geometry object rendered by a 3D application. The triangle primitives supported by OpenGL ES are `GL_TRIANGLES`, `GL_TRIANGLE_STRIP`, and `GL_TRIANGLE_FAN`. Figure 7-1 shows examples of supported triangle primitive types.

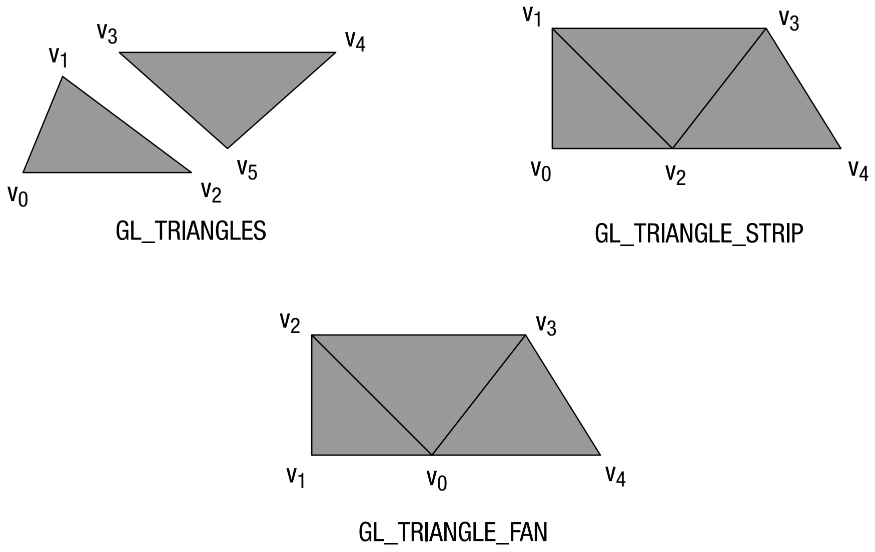


Figure 7-1 Triangle Primitive Types

`GL_TRIANGLES` draws a series of separate triangles. In Figure 7-1, two triangles given by vertices (v_0, v_1, v_2) and (v_3, v_4, v_5) are drawn. A total of `n/3` triangles are drawn, where `n` is the number of indices specified as `count` in `glDraw***` APIs mentioned previously.

`GL_TRIANGLE_STRIP` draws a series of connected triangles. In the example shown in Figure 7-1, three triangles are drawn given by (v_0, v_1, v_2), (v_2, v_1, v_3) (note the order), and (v_2, v_3, v_4). A total of `(n-2)` triangles are drawn, where `n` is the number of indices specified as `count` in `glDraw***` APIs.

GL_TRIANGLE_FAN also draws a series of connected triangles. In the example shown in Figure 7-1, the triangles drawn are (v_0, v_1, v_2), (v_0, v_2, v_3), and (v_0, v_3, v_4). A total of (n-2) triangles are drawn, where n is the number of indices specified as count in glDraw*** APIs.

Lines

The line primitives supported by OpenGL ES are GL_LINES, GL_LINE_STRIP, and GL_LINE_LOOP. Figure 7-2 shows examples of supported line primitive types.

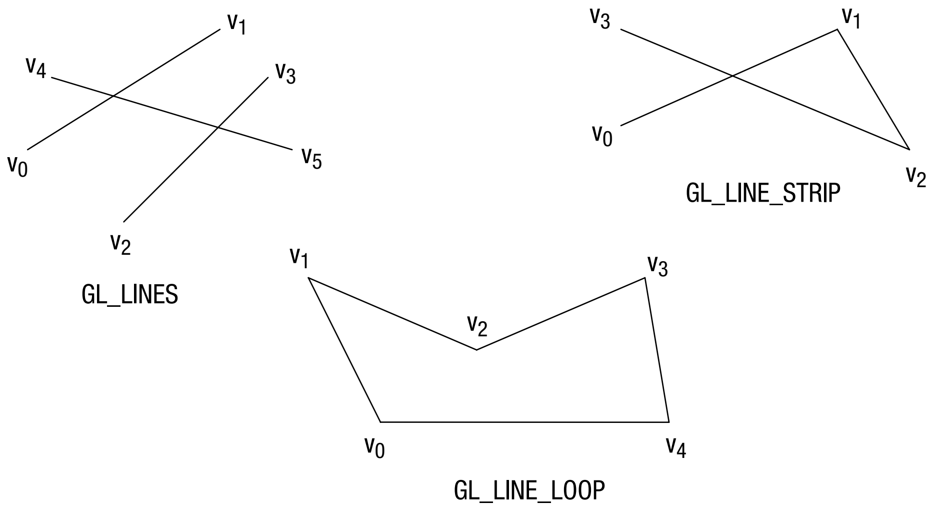


Figure 7-2 Line Primitive Types

GL_LINES draws a series of unconnected line segments. In the example shown in Figure 7-2, three individual lines are drawn given by (v_0, v_1), (v_2, v_3), and (v_4, v_5). A total of n/2 segments are drawn, where n is the number of indices specified as count in glDraw*** APIs.

GL_LINE_STRIP draws a series of connected line segments. In the example shown in Figure 7-2, three line segments are drawn given by (v_0, v_1), (v_1, v_2), and (v_2, v_3). A total of (n-1) line segments are drawn, where n is the number of indices specified as count in glDraw*** APIs.

GL_LINE_LOOP works similar to GL_LINE_STRIP, except that a final line segment is drawn from v_{n-1} to v_0. In the example shown in Figure 7-2, the line segments drawn are (v_0, v_1), (v_1, v_2), (v_2, v_3), (v_3, v_4), and (v_4, v_0). A total of n line segments are drawn, where n is the number of indices specified as count in glDraw*** APIs.

The width of a line can be specified using the `glLineWidth` API call.

`void`	**`glLineWidth`**`(GLfloat` *`width`*`)`
`width`	specifies the width of the line in pixels; the default width is 1.0

The width specified by `glLineWidth` will be clamped to the line width range supported by the OpenGL ES 3.0 implementation. In addition, the width specified will be remembered by OpenGL until updated by the application. The supported line width range can be queried using the following command. There is no requirement for lines with widths greater than 1 to be supported.

```
GLfloat   lineWidthRange[2];
glGetFloatv ( GL_ALIASED_LINE_WIDTH_RANGE, lineWidthRange );
```

Point Sprites

The point sprite primitive supported by OpenGL ES is `GL_POINTS`. A point sprite is drawn for each vertex specified. Point sprites are typically used for rendering particle effects efficiently by drawing them as points instead of quads. A point sprite is a screen-aligned quad specified as a *position* and a *radius*. The position describes the center of the square, and the radius is then used to calculate the four coordinates of the quad that describes the point sprite.

`gl_PointSize` is the built-in variable that can be used to output the point radius (or point size) in the vertex shader. It is important that a vertex shader associated with the point primitive output `gl_PointSize`; otherwise, the value of the point size is considered undefined and will most likely result in drawing errors. The `gl_PointSize` value output by a vertex shader will be clamped to the aliased point size range supported by the OpenGL ES 3.0 implementation. This range can be queried using the following command:

```
GLfloat   pointSizeRange[2];
glGetFloatv ( GL_ALIASED_POINT_SIZE_RANGE, pointSizeRange );
```

By default, OpenGL ES 3.0 describes the window origin (0, 0) to be the (left, bottom) region. However, for point sprites, the point coordinate origin is (left, top).

`gl_PointCoord` is a built-in variable available only inside a fragment shader when the primitive being rendered is a point sprite. It is declared as a vec2 variable using the mediump precision qualifier. The values assigned to gl_PointCoord go from 0.0 to 1.0 as we move from left to right or from top to bottom, as illustrated in Figure 7-3.

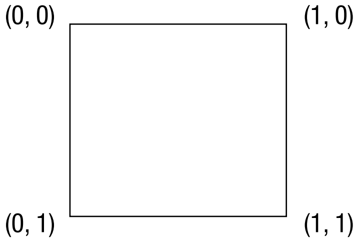


Figure 7-3 gl_PointCoord Values

The following fragment shader code illustrates how gl_PointCoord can be used as a texture coordinate to draw a textured point sprite:

```
#version 300 es
precision mediump float;
uniform sampler2D s_texSprite;
layout(location = 0) out vec4 outColor;

void main()
{
   outColor = texture(s_texSprite, gl_PointCoord);
}
```

Drawing Primitives

There are five API calls in OpenGL ES to draw primitives: glDrawArrays, glDrawElements, glDrawRangeElements, glDrawArraysInstanced, and glDrawElementsInstanced. We will describe the first three regular non-instanced draw call APIs in this section and the remaining two instanced draw call APIs in the next section.

glDrawArrays draws primitives specified by mode using vertices given by element index first to first + count - 1. A call to glDrawArrays (GL_TRIANGLES, 0, 6) will draw two triangles: a triangle given by element indices (0, 1, 2) and another triangle given by element indices (3, 4, 5). Similarly, a call to glDrawArrays(GL_TRIANGLE_STRIP, 0, 5) will draw three triangles: a triangle given by element indices (0, 1, 2), the second triangle given by element indices (2, 1, 3), and the final triangle given by element indices (2, 3, 4).

```
void   glDrawArrays(GLenum mode, GLint first,
                    GLsizei count)
```

mode	specifies the primitive to render; valid values are
	`GL_POINTS`
	`GL_LINES`
	`GL_LINE_STRIP`
	`GL_LINE_LOOP`
	`GL_TRIANGLES`
	`GL_TRIANGLE_STRIP`
	`GL_TRIANGLE_FAN`

first	specifies the starting vertex index in the enabled vertex arrays
count	specifies the number of vertices to be drawn

```
void  glDrawElements(GLenum mode, GLsizei count,
                     GLenum type, const GLvoid *indices)
void  glDrawRangeElements(GLenum mode, GLuint start,
                          GLuint end, GLsizei count,
                          GLenum type, const GLvoid *indices)
```

mode	specifies the primitive to render; valid values are
	`GL_POINTS`
	`GL_LINES`
	`GL_LINE_STRIP`
	`GL_LINE_LOOP`
	`GL_TRIANGLES`
	`GL_TRIANGLE_STRIP`
	`GL_TRIANGLE_FAN`

start	specifies the minimum array index in *indices* (`glDrawRangeElements` only)
end	specifies the maximum array index in *indices* (`glDrawRangeElements` only)
count	specifies the number of indices to be drawn

type	specifies the type of element indices stored in *indices*; valid values are
	`GL_UNSIGNED_BYTE`
	`GL_UNSIGNED_SHORT`
	`GL_UNSIGNED_INT`

indices	specifies a pointer to location where element indices are stored

glDrawArrays is great if you have a primitive described by a sequence of element indices and if vertices of geometry are not shared. However, typical objects used by games or other 3D applications are made up of multiple triangle meshes where element indices may not necessarily be in sequence and vertices will typically be shared between triangles of a mesh.

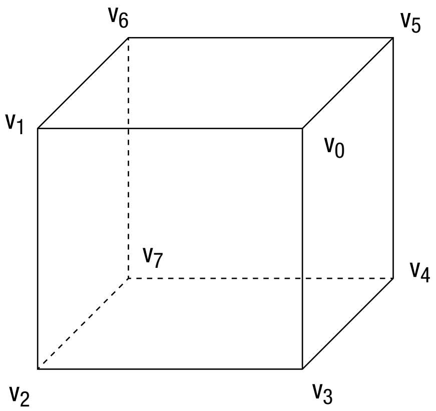


Figure 7-4 Cube

Consider the cube shown in Figure 7-4. If we were to draw this using glDrawArrays, the code would be as follows:

```
#define VERTEX_POS_INDX 0
#define NUM_FACES       6

GLfloat vertices[] = { … }; // (x, y, z) per vertex
glEnableVertexAttribArray ( VERTEX_POS_INDX );
glVertexAttribPointer ( VERTEX_POS_INDX, 3, GL_FLOAT,
                        GL_FALSE, 0, vertices );

for (int i=0; i<NUM_FACES; i++)
{
   glDrawArrays ( GL_TRIANGLE_FAN, i*4, 4 );
}

   Or

glDrawArrays ( GL_TRIANGLES, 0, 36 );
```

To draw this cube with glDrawArrays, we would call glDrawArrays for each face of the cube. Vertices that are shared would need to be replicated, which means that instead of having 8 vertices, we would now need to allocate 24 vertices (if we draw each face as a GL_TRIANGLE_FAN) or 36 vertices (if we use GL_TRIANGLES). This is not an efficient approach.

This is how the same cube would be drawn using `glDrawElements`:

```
#define VERTEX_POS_INDX 0
GLfloat vertices[] = { … };// (x, y, z) per vertex
GLubyte indices[36] = {0, 1, 2, 0, 2, 3,
                       0, 3, 4, 0, 4, 5,
                       0, 5, 6, 0, 6, 1,
                       7, 1, 6, 7, 2, 1,
                       7, 5, 4, 7, 6, 5,
                       7, 3, 2, 7, 4, 3 };

glEnableVertexAttribArray ( VERTEX_POS_INDX );
glVertexAttribPointer ( VERTEX_POS_INDX, 3, GL_FLOAT,
                        GL_FALSE, 0, vertices );
glDrawElements ( GL_TRIANGLES,
                 sizeof(indices)/sizeof(GLubyte),
                 GL_UNSIGNED_BYTE, indices );
```

Even though we are drawing triangles with `glDrawElements` and a triangle fan with `glDrawArrays` and `glDrawElements`, our application will run faster than `glDrawArrays` on a GPU for many reasons. For example, the size of vertex attribute data will be smaller with `glDrawElements` as vertices are reused (we will discuss the GPU post-transform vertex cache in a later section). This also leads to a smaller memory footprint and memory bandwidth requirement.

Primitive Restart

Using primitive restart, you can render multiple disconnected primitives (such as triangle fans or strips) using a single draw call. This is beneficial to reduce the overhead of the draw API calls. A less elegant alternative to using primitive restart is generating degenerate triangles (with some caveats), which we will discuss in a later section.

Using primitive restart, you can restart a primitive for indexed draw calls (such as `glDrawElements`, `glDrawElementsInstanced`, or `glDrawRangeElements`) by inserting a special index into the indices list. The special index is the largest possible index for the type of the indices (such as 255 or 65535 when the index type is `GL_UNSIGNED_BYTE` or `GL_UNSIGNED_SHORT`, respectively).

For example, suppose two triangle strips have element indices of (0, 1, 2, 3) and (8, 9, 10, 11), respectively. The combined element index list if we were to draw both strips using one call to `glDrawElements*` with primitive restart would be (0, 1, 2, 3, **255**, 8, 9, 10, 11) if the index type is `GL_UNSIGNED_BYTE`.

You can enable and disable primitive restart as follows:

```
glEnable ( GL_PRIMITIVE_RESTART_FIXED_INDEX );
// Draw primitives
…
glDisable ( GL_PRIMITIVE_RESTART_FIXED_INDEX );
```

Provoking Vertex

Without qualifiers, output values of the vertex shader are linearly interpolated across the primitive. However, with the use of flat shading (described in the *Interpolation Qualifiers* section in Chapter 5), no interpolation occurs. Because no interpolation occurs, only one of the vertex values can be used in the fragment shader. For a given primitive instance, the provoking vertex determines which of the vertices output from the vertex shader are used, as only one can be used. Table 7-1 shows the rule for the provoking vertex selection.

Table 7-1 Provoking Vertex Selection for the `i`th Primitive Instance Where Vertices Are Numbered from 1 to `n`, and `n` Is the Number of Vertices Drawn

Type of Primitive i	Provoking Vertex
`GL_POINTS`	`i`
`GL_LINES`	`2i`
`GL_LINE_LOOP`	`i` + 1, if `i` < `n` 1, if `i` = `n`
`GL_LINE_STRIP`	`i` + 1
`GL_TRIANGLES`	`3i`
`GL_TRIANGLE_STRIP`	`i` + 2
`GL_TRIANGLE_FAN`	`i` + 2

Geometry Instancing

Geometry instancing allows for efficiently rendering an object multiple times with different attributes (such as a different transformation matrix, color, or size) using a single API call. This feature is useful in rendering large quantities of similar objects, such as in crowd rendering. Geometry instancing reduces the overhead of CPU processing to send many API calls to the OpenGL ES engine. To render using an instanced draw call, use the following commands:

```
void   glDrawArraysInstanced(GLenum mode, GLint first,
                      GLsizei count, GLsizei instanceCount)
void   glDrawElementsInstanced (GLenum mode, GLsizei count,
                      GLenum type, const GLvoid *indices,
                      GLsizei instanceCount)
```

mode	specifies the primitive to render; valid values are
	`GL_POINTS`
	`GL_LINES`
	`GL_LINE_STRIP`
	`GL_LINE_LOOP`
	`GL_TRIANGLES`
	`GL_TRIANGLE_STRIP`
	`GL_TRIANGLE_FAN`

first	specifies the starting vertex index in the enabled vertex arrays (`glDrawArraysInstanced` only)
count	specifies the number of indices to be drawn

type	specifies the type of element indices stored in *indices* (`glDrawElementsInstanced` only);
	valid values are
	`GL_UNSIGNED_BYTE`
	`GL_UNSIGNED_SHORT`
	`GL_UNSIGNED_INT`

indices	specifies a pointer to the location where element indices are stored (`glDrawElementsInstanced` only)
instanceCount	specifies the number of instances of the primitive to be drawn

Two methods may be used to access per-instance data. The first method is to instruct OpenGL ES to read vertex attributes once or multiple times per instance using the following command:

```
void   glVertexAttribDivisor(GLuint index, GLuint divisor)
```

index	specifies the index of the generic vertex attribute
divisor	specifies the number of instances that will pass between updates of the generic attribute at slot *index*

By default, if `glVertexAttribDivisor` is not specified or is specified with *`divisor`* equal to 0 for the vertex attributes, then the vertex attributes will be read once per vertex. If *`divisor`* equals 1, then the vertex attributes will be read once per primitive instance.

The second method is to use the built-in input variable `gl_InstanceID` as an index to a buffer in the vertex shader to access the per-instance data. `gl_InstanceID` will hold the index of the current primitive instance when the previously mentioned geometry instancing API calls are used. When a non-instanced draw call is used, `gl_InstanceID` will return `0`.

The next two code fragments illustrate how to draw many geometry (i.e., cubes) using a single instanced draw call where each cube instance will be colored uniquely. Note that the complete source code is available in `Chapter_7/Instancing` example.

First, we create a color buffer to store many color data to be used later for the instanced draw call (one color per instance).

```
// Random color for each instance
{
   GLubyte colors[NUM_INSTANCES][4];
   int instance;

   srandom ( 0 );

   for ( instance = 0; instance < NUM_INSTANCES; instance++ )
   {
      colors[instance][0] = random() % 255;
      colors[instance][1] = random() % 255;
      colors[instance][2] = random() % 255;
      colors[instance][3] = 0;
   }

   glGenBuffers ( 1, &userData->colorVBO );
   glBindBuffer ( GL_ARRAY_BUFFER, userData->colorVBO );
   glBufferData ( GL_ARRAY_BUFFER, NUM_INSTANCES * 4, colors,
                  GL_STATIC_DRAW );
}
```

After the color buffer has been created and filled, we can bind the color buffer as one of the vertex attributes for the geometry. Then, we specify the vertex attribute divisor as 1 so that the color will be read per primitive instance. Finally, the cubes are drawn with a single instanced draw call.

```
// Load the instance color buffer
glBindBuffer ( GL_ARRAY_BUFFER, userData->colorVBO );
glVertexAttribPointer ( COLOR_LOC, 4, GL_UNSIGNED_BYTE,
                        GL_TRUE, 4 * sizeof ( GLubyte ),
                        ( const void * ) NULL );
```

```
glEnableVertexAttribArray ( COLOR_LOC );

// Set one color per instance
glVertexAttribDivisor ( COLOR_LOC, 1 );

// code skipped ...

// Bind the index buffer
glBindBuffer ( GL_ELEMENT_ARRAY_BUFFER, userData->indicesIBO );

// Draw the cubes
glDrawElementsInstanced ( GL_TRIANGLES, userData->numIndices,
                          GL_UNSIGNED_INT,
                          (const void *) NULL, NUM_INSTANCES );
```

Performance Tips

Applications should make sure that `glDrawElements` and `glDrawElementsInstanced` are called with as large a primitive size as possible. This is very easy to do if we are drawing `GL_TRIANGLES`. However, if we have meshes of triangle strips or fans, instead of making individual calls to `glDrawElements*` for each triangle strip mesh, these meshes could be connected together by using primitive restart (see the earlier section discussing this feature).

If you cannot use the primitive restart mechanism to connect meshes together (to maintain compatibility with an older OpenGL ES version), you can add element indices that result in degenerate triangles at the expense of using more indices and some caveats that we will discuss here. A degenerate triangle is a triangle where two or more vertices of the triangle are coincident. GPUs can detect and reject degenerate triangles very easily, so this is a good performance enhancement that allows us to queue a big primitive to be rendered by the GPU.

The number of element indices (or degenerate triangles) we need to add to connect distinct meshes will depend on whether each mesh is a triangle fan or a triangle strip and the number of indices defined in each strip. The number of indices in a mesh that is a triangle strip matters, as we need to preserve the winding order as we go from one triangle to the next triangle of the strip across the distinct meshes that are being connected.

When connecting separate triangle strips, we need to check the order of the last triangle and the first triangle of the two strips being connected. As seen in Figure 7-5, the ordering of vertices that describe even-numbered triangles of a triangle strip differs from the ordering of vertices that describe odd-numbered triangles of the same strip.

Two cases need to be handled:

- The odd-numbered triangle of the first triangle strip is being connected to the first (and therefore even-numbered) triangle of the second triangle strip.
- The even-numbered triangle of the first triangle strip is being connected to the first (and therefore even-numbered) triangle of the second triangle strip.

Figure 7-5 shows two separate triangle strips that represent these two cases, where the strips need to be connected to allow us to draw both of them using a single call to `glDrawElements*`.

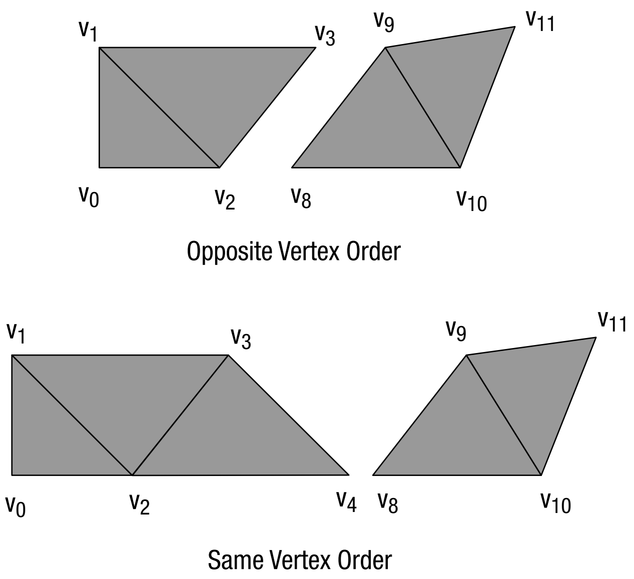


Figure 7-5 Connecting Triangle Strips

For the triangle strips in Figure 7-5 with opposite vertex order for the last and first triangles of the two strips being connected, the element indices for each triangle strip are (0, 1, 2, 3) and (8, 9, 10, 11), respectively. The combined element index list if we were to draw both strips using one call to `glDrawElements*` would be (0, 1, 2, 3, **3**, **8**, 8, 9, 10, 11). This new element index results in the following triangles drawn: (0, 1, 2), (2, 1, 3), **(2, 3, 3)**, **(3, 3, 8)**, **(3, 8, 8)**, **(8, 8, 9)**, (8, 9, 10), (10, 9, 11). The triangles in boldface type are the degenerate triangles. The element indices in boldface type represent the new indices added to the combined element index list.

For triangle strips in Figure 7-5 with the same vertex order for the last and first triangles of the two strips being connected, the element indices for each triangle strip are (0, 1, 2, 3, 4) and (8, 9, 10, 11), respectively. The combined element index list if we were to draw both strips using one call to `glDrawElements` would be (0, 1, 2, 3, 4, **4**, **4**, **8**, 8, 9, 10, 11). This new element index results in the following triangles drawn: (0, 1, 2), (2, 1, 3), (2, 3, 4), **(4, 3, 4)**, **(4, 4, 4)**, **(4, 4, 8)**, **(4, 8, 8)**, **(8, 8, 9)**, (8, 9, 10), (10, 9, 11). The triangles in boldface type are the degenerate triangles. The element indices in boldface type represent the new indices added to the combined element index list.

Note that the number of additional element indices required and the number of degenerate triangles generated vary depending on the number of vertices in the first strip. This is required to preserve the *winding order* of the next strip being connected.

It might also be worth investigating techniques that take the size of the *post-transform vertex cache* into consideration in determining how to arrange element indices of a primitive. Most GPUs implement a post-transform vertex cache. Before a vertex (given by its element index) is executed by the vertex shader, a check is performed to determine whether the vertex already exists in the post-transform cache. If the vertex exists in the post-transform cache, the vertex is not executed by the vertex shader. If it is not in the cache, the vertex will need to be executed by the vertex shader. Using the post-transform cache size to determine how element indices are created should help overall performance, as it will reduce the number of times a vertex that is reused gets executed by the vertex shader.

Primitive Assembly

Figure 7-6 shows the primitive assembly stage. Vertices that are supplied through `glDraw***` are executed by the vertex shader. Each vertex transformed by the vertex shader includes the vertex position that describes the (x, y, z, w) value of the vertex. The primitive type and vertex indices determine the individual primitives that will be rendered. For each individual primitive (triangle, line, and point) and its corresponding vertices, the primitive assembly stage performs the operations shown in Figure 7-6.

Before we discuss how primitives are rasterized in OpenGL ES, we need to understand the various coordinate systems used within OpenGL ES 3.0. This is needed to get a good understanding of what happens to vertex coordinates as they go through the various stages of the OpenGL ES 3.0 pipeline.

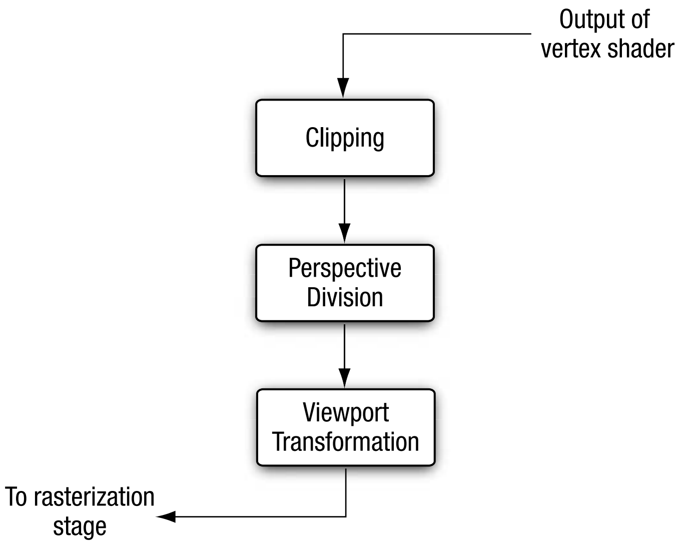


Figure 7-6 OpenGL ES Primitive Assembly Stage

Coordinate Systems

Figure 7-7 shows the coordinate systems as a vertex goes through the vertex shader and primitive assembly stages. Vertices are input to OpenGL ES in the object or local coordinate space. This is the coordinate space in which an object is most likely modeled and stored. After a vertex shader executes, the vertex position is considered to be in the clip coordinate space. The transformation of the vertex position from the local coordinate system (i.e., object coordinates) to clip coordinates is done by loading the appropriate matrices that perform this conversion in appropriate uniforms defined in

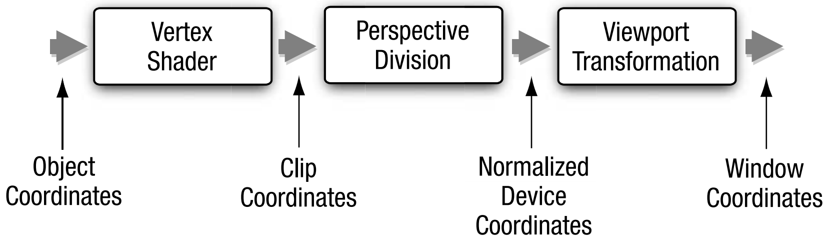


Figure 7-7 Coordinate Systems

the vertex shader. Chapter 8, "Vertex Shaders," describes how to transform the vertex position from object to clip coordinates and how to load appropriate matrices in the vertex shader to perform this transformation.

Clipping

To avoid processing of primitives outside the viewable volume, primitives are clipped to the clip space. The vertex position after the vertex shader has been executed is in the clip coordinate space. The clip coordinate is a homogeneous coordinate given by (x_c, y_c, z_c, w_c). The vertex coordinates defined in clip space (x_c, y_c, z_c, w_c) get clipped against the viewing volume (also known as the clip volume).

The clip volume, as shown in Figure 7-8, is defined by six clipping planes, referred to as the near, and far clip planes, the left and right clip planes, and the top and bottom clip planes. In clip coordinates, the clip volume is given as follows:

$$-w_c <= x_c <= w_c$$
$$-w_c <= y_c <= w_c$$
$$-w_c <= z_c <= w_c$$

The preceding six checks help determine the list of planes against which the primitive needs to be clipped.

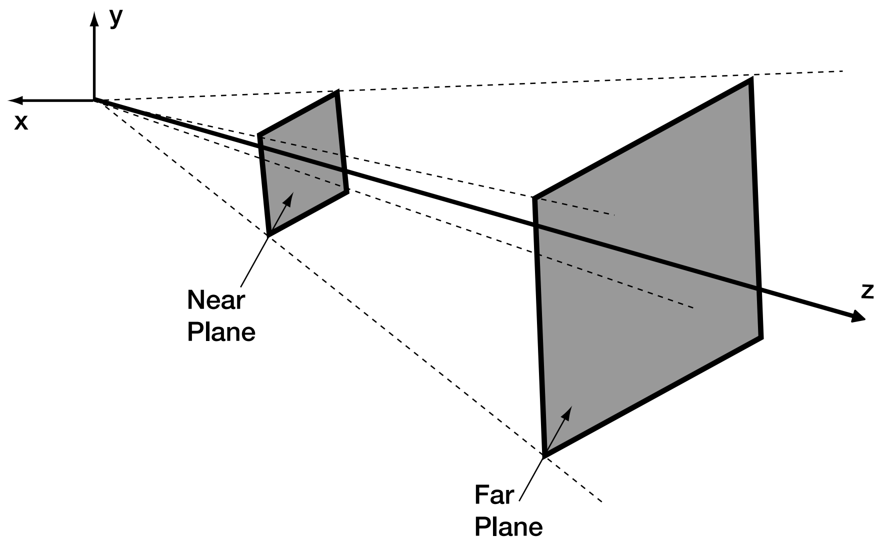


Figure 7-8 Viewing Volume

The clipping stage will clip each primitive to the clip volume shown in Figure 7-8. By "primitive," here we imply each triangle of a list of separate triangles drawn using `GL_TRIANGLES`, or a triangle of a triangle strip or a fan, or a line from a list of separate lines drawn using `GL_LINES`, or a line of a line strip or line loop, or a specific point in a list of point sprites. For each primitive type, the following operations are performed:

- Clipping triangles—If the triangle is completely inside the viewing volume, no clipping is performed. If the triangle is completely outside the viewing volume, the triangle is discarded. If the triangle lies partly inside the viewing volume, then the triangle is clipped against the appropriate planes. The clipping operation will generate new vertices that are clipped to the plane that are arranged as a triangle fan.
- Clipping lines—If the line is completely inside the viewing volume, then no clipping is performed. If the line is completely outside the viewing volume, the line is discarded. If the line lies partly inside the viewing volume, then the line is clipped and appropriate new vertices are generated.
- Clipping point sprites—The clipping stage will discard the point sprite if the point position lies outside the near or far clip plane or if the quad that represents the point sprite is outside the clip volume. Otherwise, it is passed unchanged and the point sprite will be scissored as it moves from inside the clip volume to the outside, or vice versa.

After the primitives have been clipped against the six clipping planes, the vertex coordinates undergo perspective division to become normalized device coordinates. A normalized device coordinate is in the range –1.0 to +1.0.

Note: The clipping operation (especially for lines and triangles) can be quite expensive to perform in hardware. A primitive must be clipped against six clip planes of the viewing volume, as shown in Figure 7-8. Primitives that are partly outside the near and far planes go through the clipping operations. However, primitives that are partially outside the *x* and *y* planes do not necessarily need to be clipped. By rendering into a viewport that is bigger than the dimensions of the viewport specified with `glViewport`, clipping in the *x* and *y* planes becomes a scissoring operation. Scissoring is implemented very efficiently by GPUs. This larger viewport region is called the *guard-band* region. Although OpenGL ES does not allow an application to specify a guard-band region, most—if not all—OpenGL ES implementations implement a guard-band.

Perspective Division

Perspective division takes the point given by clip coordinate (x_c, y_c, z_c, w_c) and projects it onto the screen or viewport. This projection is performed by dividing the (x_c, y_c, z_c) coordinates with w_c. After performing (x_c/w_c), (y_c/w_c), and (z_c/w_c), we get normalized device coordinates (x_d, y_d, z_d). These are called normalized device coordinates, as they will be in the [–1.0 ... 1.0] range. These normalized (x_d, y_d) coordinates will then be converted to actual screen (or window) coordinates depending on the dimensions of the viewport. The normalized (z_d) coordinate is converted to the screen z value using the `near` and `far` depth values specified by `glDepthRangef`. These conversions are performed in the viewport transformation phase.

Viewport Transformation

A viewport is a 2D rectangular window region in which all OpenGL ES rendering operations will ultimately be displayed. The viewport transformation can be set by using the following API call:

```
void  glViewport(GLint x, GLint y, GLsizei w, GLsizei h)
```

`x, y`	specifies the window coordinates of the viewport's lower-left corner in pixels
`w, h`	specifies the width and height of viewport in pixels; these values must be greater than 0

The conversion from normalized device coordinates (x_d, y_d, z_d) to window coordinates (x_w, y_w, z_w) is given by the following transformation:

$$\begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = \begin{bmatrix} (w/2)x_d + o_x \\ (h/2)y_d + o_y \\ ((f-n)/2)z_d + (n+f)/2 \end{bmatrix}$$

In the transformation $o_x = x + w/2$ and $o_y = y + h/2$, n and f represent the desired depth range.

The depth range values *n* and *f* can be set using the following API call:

```
void  glDepthRangef(GLclampf n, GLclampf f)
```

`n, f`	specify the desired depth range. Default values for `n` and `f` are 0.0 and 1.0, respectively. The values are clamped to lie within (0.0, 1.0).

The values specified by `glDepthRangef` and `glViewport` are used to transform the vertex position from normalized device coordinates into window (screen) coordinates.

The initial (or default) viewport state is set to *w* = `width` and *h* = `height` of the window created by the application in which OpenGL ES is to do its rendering. This window is given by the `EGLNativeWindowType` *`win`* argument specified in `eglCreateWindowSurface`.

Rasterization

Figure 7-9 shows the rasterization pipeline. After the vertices have been transformed and primitives have been clipped, the rasterization pipelines take an individual primitive such as a triangle, a line segment, or a point sprite and generate appropriate fragments for this primitive. Each fragment is identified by its integer location (*x*, *y*) in screen space. A fragment represents a pixel location given by (*x*, *y*) in screen space and additional fragment data that will be processed by the fragment shader to produce a fragment color. These operations are described in detail in Chapter 9, "Texturing," and Chapter 10, "Fragment Shaders."

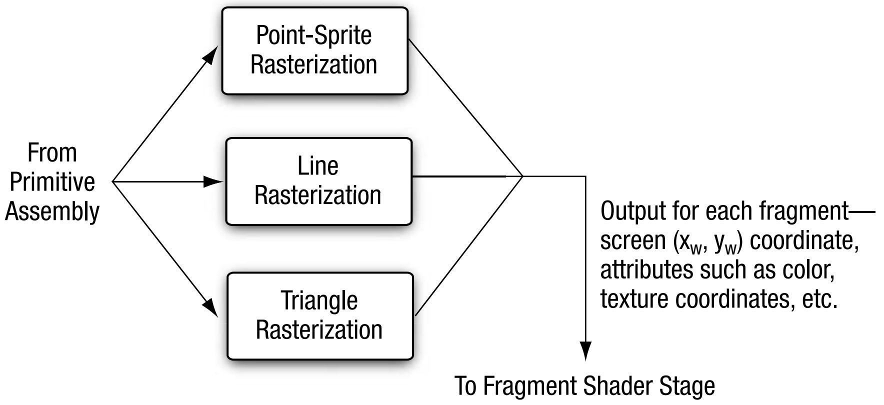

Point-Sprite Rasterization
Line Rasterization
Triangle Rasterization
From Primitive Assembly
Output for each fragment—screen (x_w, y_w) coordinate, attributes such as color, texture coordinates, etc.
To Fragment Shader Stage

Figure 7-9 OpenGL ES Rasterization Stage

In this section, we discuss the various options that an application can use to control rasterization of triangles, strips, and fans.

Culling

Before triangles are rasterized, we need to determine whether they are front-facing (i.e., facing the viewer) or back-facing (i.e., facing away from the viewer). The culling operation discards triangles that face away from the viewer. To determine whether the triangle is front-facing or back-facing we first need to know the orientation of the triangle.

The orientation of a triangle specifies the winding order of a path that begins at the first vertex, goes through the second and third vertex, and ends back at the first vertex. Figure 7-10 shows two examples of triangles with clockwise and counterclockwise winding orders.

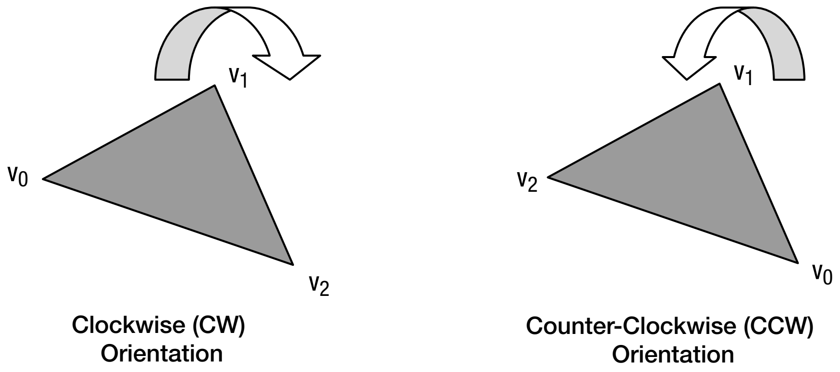

v_1
v_0
v_2
Clockwise (CW) Orientation
v_1
v_2
v_0
Counter-Clockwise (CCW) Orientation

Figure 7-10 Clockwise and Counterclockwise Triangles

The orientation of a triangle is computed by calculating the signed area of the triangle in window coordinates. We now need to translate the sign of the computed triangle area into a clockwise (CW) or counterclockwise (CCW) orientation. This mapping from the sign of triangle area to a CW or CCW orientation is specified by the application using the following API call:

`void`	**`glFrontFace`**`(GLenum` *`dir`*`)`
`dir`	specifies the orientation of front-facing triangles. Valid values are `GL_CW` or `GL_CCW`. The default value is `GL_CCW`.

We have discussed how to calculate the orientation of a triangle. To determine whether the triangle needs to be culled, we need to know the facing of triangles that are to be culled. This is specified by the application using the following API call:

```
void   glCullFace(GLenum mode)
```

mode specifies the facing of triangles that are to be culled. Valid values are `GL_FRONT`, `GL_BACK`, and `GL_FRONT_AND_BACK`. The default value is `GL_BACK`.

Last but not least, we need to know whether the culling operation should be performed. The culling operation will be performed if the `GL_CULL_FACE` state is enabled. The `GL_CULL_FACE` state can be enabled or disabled by the application using the following API calls:

```
void   glEnable(GLenum cap)
void   glDisable(GLenum cap)
```

where *cap* is set to `GL_CULL_FACE`. Initially, culling is disabled.

To recap, to cull appropriate triangles, an OpenGL ES application must first enable culling using `glEnable` (`GL_CULL_FACE`), set the appropriate cull face using `glCullFace`, and set the orientation of front-facing triangles using `glFrontFace`.

Note: Culling should always be enabled to avoid the GPU wasting time rasterizing triangles that are not visible. Enabling culling should improve the overall performance of the OpenGL ES application.

Polygon Offset

Consider the case where we are drawing two polygons that overlap each other. You will most likely notice artifacts, as shown in Figure 7-11. These artifacts, called *Z-fighting artifacts*, occur because of limited precision of triangle rasterization, which can affect the precision of the depth values generated per fragment, resulting in artifacts. The limited precision of parameters used by triangle rasterization and generated depth values per fragment will get better and better but will never be completely resolved.

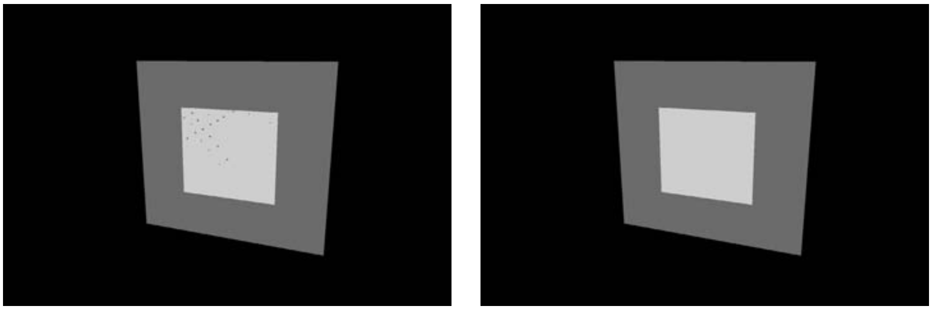


Figure 7-11 Polygon Offset

Figure 7-11 shows two coplanar polygons being drawn. The code to draw these two coplanar polygons without polygon offset is as follows:

```
glClear ( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );

// load vertex shader
// set the appropriate transformation matrices
// set the vertex attribute state

// draw the SMALLER quad
glDrawArrays ( GL_TRIANGLE_FAN, 0, 4 );

// set the depth func to <= as polygons are coplanar
glDepthFunc ( GL_LEQUAL );

// set the vertex attribute state

// draw the LARGER quad
glDrawArrays ( GL_TRIANGLE_FAN, 0, 4 );
```

To avoid the artifacts shown in Figure 7-11, we need to add a *delta* to the computed depth value before the depth test is performed and before the depth value is written to the depth buffer. If the depth test passes, the original depth value—and not the original depth value + delta—will be stored in the depth buffer.

The polygon offset is set using the following API call:

```
void   glPolygonOffset(GLfloat factor, GLfloat units)
```

The depth offset is computed as follows:

$$\text{depth offset} = m * factor + r * units$$

In this equation, *m* is maximum depth slope of the triangle and is calculated as

$$m = \sqrt{(\partial z/\partial x^2 + \partial z/\partial y^2)}$$

m can also be calculated as max $\{|\partial z/\partial x|, |\partial z/\partial y|\}$.

The slope terms $\partial z/\partial x$ and $\partial z/\partial y$ are calculated by the OpenGL ES implementation during the triangle rasterization stage.

r is an implementation-defined constant and represents the smallest value that can produce a guaranteed difference in depth value.

Polygon offset can be enabled or disabled using `glEnable(GL_POLYGON_OFFSET_FILL)` and `glDisable(GL_POLYGON_OFFSET_FILL)`, respectively.

With polygon offset enabled, the code for triangles rendered by Figure 7-11 is as follows:

```
const float polygonOffsetFactor = -1.0f;
const float polygonOffsetUnits  = -2.0f;

glClear ( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );

// load vertex shader
// set the appropriate transformation matrices
// set the vertex attribute state

// draw the SMALLER quad
glDrawArrays ( GL_TRIANGLE_FAN, 0, 4 );

// set the depth func to <= as polygons are coplanar
glDepthFunc ( GL_LEQUAL );

glEnable ( GL_POLYGON_OFFSET_FILL );
glPolygonOffset ( polygonOffsetFactor, polygonOffsetUnits );

// set the vertex attribute state

// draw the LARGER quad
glDrawArrays ( GL_TRIANGLE_FAN, 0, 4 );
```

Occlusion Queries

Occlusion queries use query objects to track any fragments or samples that pass the depth test. This approach can be used for a variety of techniques, such as visibility determination for a lens flare effect as well as optimization to avoid performing geometry processing on obscured objects whose bounding volume is obscured.

Occlusion queries can be started and ended using `glBeginQuery` and `glEndQuery`, respectively, with `GL_ANY_SAMPLES_PASSED` or `GL_ANY_SAMPLES_PASSED_CONSERVATIVE` target.

```
void   glBeginQuery(GLenum target, GLuint id)
void   glEndQuery(GLenum target)
```

target	specifies the target type of query object; valid values are `GL_ANY_SAMPLES_PASSED` `GL_ANY_SAMPLES_PASSED_CONSERVATIVE` `GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN`
id	specifies the name of the query object (`glBeginQuery` only)

Using the `GL_ANY_SAMPLES_PASSED` target will return the precise boolean state indicating whether any samples passed the depth test. The `GL_ANY_SAMPLES_PASSED_CONSERVATIVE` target can offer better performance but a less precise answer. Using `GL_ANY_SAMPLES_PASSED_CONSERVATIVE`, some implementations may return `GL_TRUE` even if no sample passed the depth test.

The *id* is created using `glGenQueries` and deleted using `glDeleteQueries`.

```
void   glGenQueries(GLsizei n, GLuint *ids)
```

n	specifies the number of query name objects to be generated
ids	specifies an array to store the list of query name objects

```
void   glDeleteQueries(GLsizei n, const GLuint *ids)
```

n	specifies the number of query name objects to be deleted
ids	specifies an array of the list of query name objects to be deleted

After you have specified the boundary of the query object using `glBeginQuery` and `glEndQuery`, you can use `glGetQueryObjectuiv` to retrieve the result of the query object.

```
void   glGetQueryObjectuiv(GLuint id, GLenum pname,
                           GLuint *params)
```

target	specifies the name of a query object
pname	specifies the query object parameter to be retrieved, and can be `GL_QUERY_RESULT` or `GL_QUERY_RESULT_AVAILABLE`
params	specifies an array of the appropriate type for storing the returned parameter values

Note: For better performance, you should wait several frames before performing a `glGetQueryObjectuiv` call to wait for the result to be available in the GPU.

The following example shows how to set up an occlusion query object and query the result:

```
glBeginQuery ( GL_ANY_SAMPLES_PASSED, queryObject );
// draw primitives here
…
glEndQuery ( GL_ANY_SAMPLES_PASSED );

…
// after several frames have elapsed, query the number of
// samples that passed the depth test
glGetQueryObjectuiv( queryObject, GL_QUERY_RESULT,
                     &numSamples );
```

Summary

In this chapter, you learned the types of primitives supported by OpenGL ES, and saw how to draw them efficiently using regular non-instanced and instanced draw calls. We also discussed how coordinate transformations are performed on vertices. In addition, you learned about the rasterization stage, in which primitives are converted into fragments representing pixels that may be drawn on the screen. Now that you have learned how to draw primitives using vertex data, in the next chapter we describe how to write a vertex shader to process the vertices in a primitive.

Chapter 8

Vertex Shaders

This chapter describes the OpenGL ES 3.0 programmable vertex pipeline. Figure 8-1 illustrates the entire OpenGL ES 3.0 programmable pipeline. The shaded boxes indicate the programmable stages in OpenGL ES 3.0. In this chapter, we discuss the **vertex shader stage**. Vertex shaders can be used to do traditional vertex-based operations such as transforming the position by a matrix, computing the lighting equation to generate a per-vertex color, and generating or transforming texture coordinates.

The previous chapters—specifically, Chapter 5, "OpenGL ES Shading Language," and Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects"—discussed how to specify the vertex attribute and uniform inputs and also gave a good description of the OpenGL ES 3.0 Shading Language. Chapter 7, "Primitive Assembly and Rasterization," discussed how the output of the vertex shader, referred to as vertex shader output variables, is used by the rasterization stage to generate per-fragment values, which are then input to the fragment shader. In this chapter, we begin with a high-level overview of a vertex shader, including its inputs and outputs. We then describe how to write vertex shaders by discussing a few examples. These examples describe common use cases such as transforming a vertex position with a model view and projection matrix, vertex lighting that generates per-vertex diffuse and specular colors, texture coordinate generation, vertex skinning, and displacement mapping. We hope that these examples help you get a good idea of how to write vertex shaders. Last but not least, we describe a vertex shader that implements the OpenGL ES 1.1 fixed-function vertex pipeline.

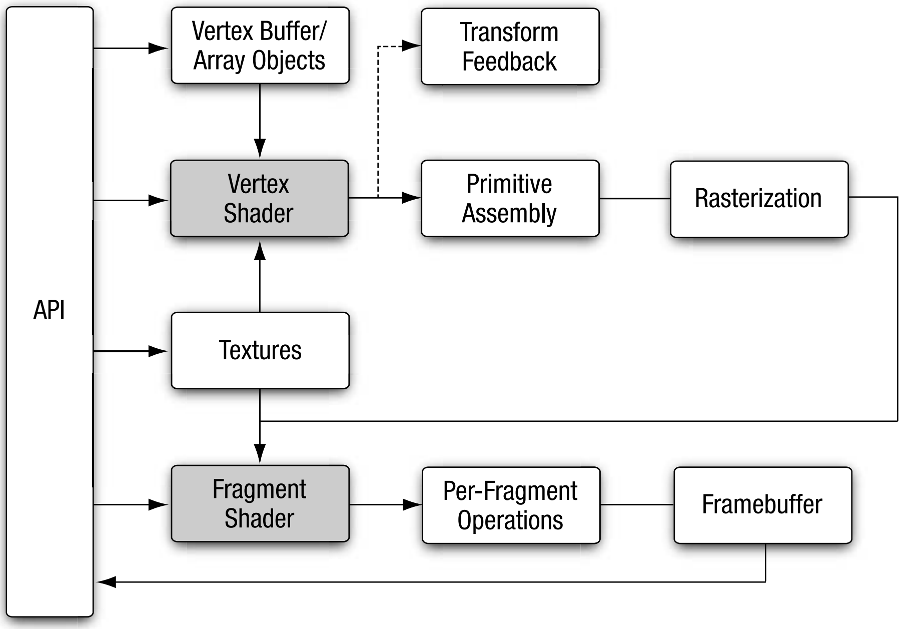


Figure 8-1 OpenGL ES 3.0 Programmable Pipeline

Vertex Shader Overview

The vertex shader provides a general-purpose programmable method for operating on vertices. Figure 8-2 shows the inputs and outputs of a vertex shader. The inputs to the vertex shader consist of the following:

- Attributes—Per-vertex data supplied using vertex arrays.
- Uniforms and uniform buffers—Constant data used by the vertex shader.
- Samplers—A specific type of uniform that represents textures used by the vertex shader.
- Shader program—Vertex shader program source code or executable that describes the operations that will be performed on the vertex.

The outputs of the vertex shader are called vertex shader output variables. In the primitive rasterization stage, these variables are computed for each generated fragment and are passed in as inputs to the fragment shader.

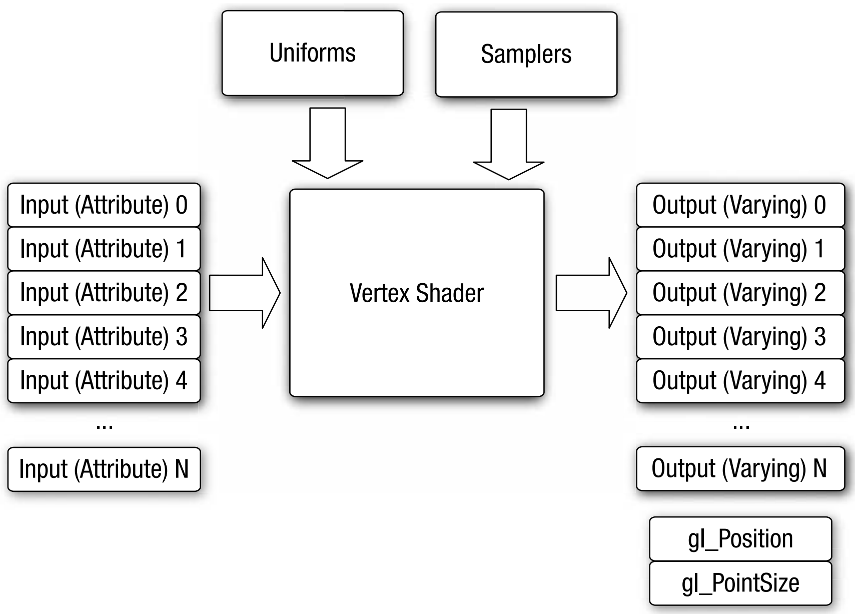


Figure 8-2 OpenGL ES 3.0 Vertex Shader

Vertex Shader Built-In Variables

The built-in variables of a vertex shader can be categorized into special variables that are input or output of the vertex shader, uniform state such as depth range, and constants that specify maximum values such as the number of attributes, number of vertex shader output variables, and number of uniforms.

Built-In Special Variables

OpenGL ES 3.0 has built-in special variables that serve as inputs to the vertex shader, or outputs by the vertex shader that then become inputs to the fragment shader, or outputs by the fragment shader. The following built-in special variables are available to the vertex shader:

- `gl_VertexID` is an input variable that holds an integer index for the vertex. This integer variable is declared using the `highp` precision qualifier.
- `gl_InstanceID` is an input variable that holds the instance number of a primitive in an instanced draw call. Its value is `0` for a regular draw call. `gl_InstanceID` is an integer variable declared using the `highp` precision qualifier.

- gl_Position is used to output the vertex position in clip coordinates. Its values are used by the clipping and viewport stages to perform appropriate clipping of primitives and to convert the vertex position from clip coordinates to screen coordinates. The value of gl_Position is undefined if the vertex shader does not write to gl_Position. gl_Position is a floating-point variable declared using the highp precision qualifier.
- gl_PointSize is used to write the size of the point sprite in pixels. It is used when point sprites are rendered. The gl_PointSize value output by a vertex shader is then clamped to the aliased point size range supported by the OpenGL ES 3.0 implementation. gl_PointSize is a floating-point variable declared using the highp precision qualifier.
- gl_FrontFacing is a special variable that, although not directly written by the vertex shader, is generated based on the position values generated by the vertex shader and primitive type being rendered. gl_FrontFacing is a boolean variable.

Built-In Uniform State

The only built-in uniform state available inside a vertex shader is the depth range in window coordinates. This is given by the built-in uniform name gl_DepthRange, which is declared as a uniform of type gl_DepthRangeParameters.

```
struct gl_DepthRangeParameters
{
   highp float near; // near Z
   highp float far;  // far Z
   highp float diff; // far - near
}

uniform gl_DepthRangeParameters gl_DepthRange;
```

Built-In Constants

The following built-in constants are also available inside the vertex shader:

```
const mediump int gl_MaxVertexAttribs             = 16;
const mediump int gl_MaxVertexUniformVectors      = 256;
const mediump int gl_MaxVertexOutputVectors       = 16;
const mediump int gl_MaxVertexTextureImageUnits   = 16;
const mediump int gl_MaxCombinedTextureImageUnits = 32;
```

The built-in constants describe the following maximum terms:

- `gl_MaxVertexAttribs` is the maximum number of vertex attributes that can be specified. The minimum value supported by all ES 3.0 implementations is 16.
- `gl_MaxVertexUniformVectors` is the maximum number of `vec4` uniform entries that can be used inside a vertex shader. The minimum value supported by all ES 3.0 implementations is 256 `vec4` entries. The number of `vec4` uniform entries that can actually be used by a developer can vary from one implementation to another and from one vertex shader to another. For example, some implementations might count user-specified literal values used in a vertex shader against the uniform limit. In other cases, implementation-specific uniforms (or constants) might need to be included depending on whether the vertex shader makes use of any built-in transcendental functions. There currently is no mechanism that an application can use to find the number of uniform entries that it can use in a particular vertex shader. The vertex shader compilation will fail and the compile log might provide specific information with regard to number of uniform entries being used. However, the information returned by the compile log is implementation specific. We provide some guidelines in this chapter to help maximize the use of vertex uniform entries available in a vertex shader.
- `gl_MaxVertexOutputVectors` is the maximum number of output vectors—that is, the number of `vec4` entries that can be output by a vertex shader. The minimum value supported by all ES 3.0 implementations is 16 `vec4` entries.
- `gl_MaxVertexTextureImageUnits` is the maximum number of texture units available in a vertex shader. The minimum value is 16.
- `gl_MaxCombinedTextureImageUnits` is the sum of the maximum number of texture units available in the vertex + fragment shaders. The minimum value is 32.

The values specified for each built-in constant are the minimum values that must be supported by all OpenGL ES 3.0 implementations. It is possible that implementations might support values greater than the minimum values described. The actual supported values can be queried using the following code:

```
GLint maxVertexAttribs, maxVertexUniforms, maxVaryings;
GLint maxVertexTextureUnits, maxCombinedTextureUnits;
```

```
glGetIntegerv ( GL_MAX_VERTEX_ATTRIBS, &maxVertexAttribs );
glGetIntegerv ( GL_MAX_VERTEX_UNIFORM_VECTORS,
                &maxVertexUniforms );
glGetIntegerv ( GL_MAX_VARYING_VECTORS,
                &maxVaryings );
glGetIntegerv ( GL_MAX_VERTEX_TEXTURE_IMAGE_UNITS,
                &maxVertexTextureUnits );
glGetIntegerv ( GL_MAX_COMBINED_TEXTURE_IMAGE_UNITS,
                &maxCombinedTextureUnits );
```

Precision Qualifiers

This section briefly reviews precision qualifiers, which are covered in depth in Chapter 5, "OpenGL ES Shading Language." Precision qualifiers can be used to specify the precision of any floating-point or integer-based variable. The keywords for specifying the precision are `lowp`, `mediump`, and `highp`. Some examples of declarations with precision qualifiers are shown here:

```
highp vec4     position;
out lowp vec4  color;
mediump float  specularExp;
highp int      oneConstant;
```

In addition to precision qualifiers, default precision may be employed. That is, if a variable is declared without having a precision qualifier, it will have the default precision for that type. The default precision qualifier is specified at the top of a vertex or fragment shader using the following syntax:

```
precision highp float;
precision mediump int;
```

The precision specified for `float` will be used as the default precision for all variables based on a floating-point value. Likewise, the precision specified for `int` will be used as the default precision for all integer-based variables. In the vertex shader, if no default precision is specified, the default precision for both `int` and `float` is `highp`.

For operations typically performed in a vertex shader, the precision qualifier that will most likely be needed is `highp`. For instance, operations that transform a position with a matrix, transform normals and texture coordinates, or generate texture coordinates will need to be done with `highp` precision. Color computations and lighting equations can most likely be done with `mediump` precision. Again, this decision will depend on the kind of color computations being performed and the range and precision required for the operations being performed. We believe that `highp` will most likely be the default precision used for most operations in a vertex shader; thus we use `highp` as the default precision qualifier in the examples that follow.

Number of Uniforms Limitations in a Vertex Shader

`gl_MaxVertexUniformVectors` describes the maximum number of uniforms that can be used in a vertex shader. The minimum value for `gl_MaxVertexUniformVectors` that must be supported by any compliant OpenGL ES 3.0 implementation is 256 `vec4` entries. The uniform storage is used to store the following variables:

- Variables declared with the uniform qualifier
- Constant variables
- Literal values
- Implementation-specific constants

The number of uniform variables used in a vertex shader along with the variables declared with the `const` qualifier, literal values, and implementation-specific constants must fit in `gl_MaxVertexUniformVectors` as per the packing rules described in Chapter 5, "OpenGL ES Shading Language." If these do not fit, then the vertex shader will fail to compile. A developer might potentially apply the packing rules and determine the amount of uniform storage needed to store uniform variables, constant variables, and literal values. It is not possible to determine the number of implementation-specific constants, however, as this value will not only vary from implementation to implementation but will also change depending on which built-in shading language functions are being used by the vertex shader. Typically, the implementation-specific constants are required when built-in transcendental functions are used.

As far as literal values are concerned, the OpenGL ES 3.0 Shading Language specification states that no constant propagation is assumed. As a consequence, multiple instances of the same literal value(s) will be counted multiple times. Understandably, it is easier to use literal values such as `0.0` or `1.0` in a vertex shader, but our recommendation is that this technique be avoided as much as possible. Instead of using literal values, appropriate constant variables should be declared. This approach avoids having to perform the same literal value count multiple times, which might cause the vertex shader to fail to compile if vertex uniform storage requirements exceed what the implementation supports.

Consider the following example, which shows a snippet of vertex shader code that transforms two texture coordinates per vertex:

```
#version 300 es
#define NUM_TEXTURES  2

uniform mat4 tex_matrix[NUM_TEXTURES];          // texture
                                                // matrices
uniform bool enable_tex[NUM_TEXTURES];          // texture
                                                // enables
uniform bool enable_tex_matrix[NUM_TEXTURES];   // texture matrix
                                                // enables

in vec4 a_texcoord0; // available if enable_tex[0] is true
in vec4 a_texcoordl; // available if enable_tex[1] is true

out vec4 v_texcoord[NUM_TEXTURES];

void main()
{
   v_texcoord[0] = vec4 ( 0.0, 0.0, 0.0, 1.0 );
   // is texture 0 enabled
   if ( enable_tex[0] )
   {
      // is texture matrix 0 enabled
      if ( enable_tex_matrix[0] )
         v_texcoord[0] = tex_matrix[0] * a_texcoord0;
      else
         v_texcoord[0] = a_texcoord0;
   }

   v_texcoord[1] = vec4 ( 0.0, 0.0, 0.0, 1.0 );
   // is texture 1 enabled
   if ( enable_tex[1] )
   {
      // is texture matrix 1 enabled
      if ( enable_tex_matrix[1] )
         v_texcoord[1] = tex_matrix[1] * a_texcoordl;
      else
         v_texcoord[1] = a_texcoordl;
   }

   // set gl_Position to make this into a valid vertex shader
}
```

This code might result in each reference to the literal values 0, 1, 0.0, and 1.0 counting against the uniform storage. To guarantee that these literal values count only once against the uniform storage, the vertex shader code snippet should be written as follows:

```
#version 300 es
#define NUM_TEXTURES  2

const int c_zero = 0;
const int c_one  = 1;

uniform mat4 tex_matrix[NUM_TEXTURES];         // texture
                                               // matrices
uniform bool enable_tex[NUM_TEXTURES];         // texture
                                               // enables
uniform bool enable_tex_matrix[NUM_TEXTURES]; // texture matrix
      // enables

in vec4 a_texcoord0; // available if enable_tex[0] is      true
in vec4 a_texcoordl; // available if enable_tex[1] is      true

out vec4 v_texcoord[NUM_TEXTURES];

void main()
{
   v_texcoord[c_zero] = vec4 ( float(c_zero), float(c_zero),
                               float(c_zero), float(c_one) );
   // is texture 0 enabled
   if ( enable_tex[c_zero] )
   {
      // is texture matrix 0 enabled
      if ( enable_tex_matrix[c_zero] )
         v_texcoord[c_zero] = tex_matrix[c_zero] * a_texcoord0;
      else
         v_texcoord[c_zero] = a_texcoord0;
   }

   v_texcoord[c_one] = vec4(float(c_zero), float(c_zero),
          float(c_zero), float(c_one));
   // is texture 1 enabled
   if ( enable_tex[c_one] )
   {
      // is texture matrix 1 enabled
      if ( enable_tex_matrix[c_one] )
         v_texcoord[c_one] = tex_matrix[c_one] * a_texcoordl;
      else
         v_texcoord[c_one] = a_texcoordl;
   }
   // set gl_Position to make this into a valid vertex shader
}
```

This section should help you better understand the limitations of the OpenGL ES 3.0 Shading Language and appreciate how to write vertex shaders that should compile and run on most OpenGL ES 3.0 implementations.

Vertex Shader Examples

We now present a few examples that demonstrate how to implement the following features in a vertex shader:

- Transforming vertex position with a matrix
- Lighting computations to generate per-vertex diffuse and specular color
- Texture coordinate generation
- Vertex skinning
- Displacing vertex position with a texture lookup value

These features represent typical use cases that OpenGL ES 3.0 applications will want to perform in a vertex shader.

Matrix Transformations

Example 8-1 describes a simple vertex shader written using the OpenGL ES Shading Language. The vertex shader takes a position and its associated

Example 8-1 Vertex Shader with Matrix Transform for the Position

```
#version 300 es

// uniforms used by the vertex shader
uniform mat4 u_mvpMatrix; // matrix to convert position from
                          // model space to clip space

// attribute inputs to the vertex shader
layout(location = 0) in vec4 a_position; // input position value
layout(location = 1) in vec4 a_color;    // input color

// vertex shader output, input to the fragment shader
out vec4 v_color;

void main()
{
   v_color = a_color;
   gl_Position = u_mvpMatrix * a_position;
}
```

color data as inputs or attributes, transforms the position by a 4 × 4 matrix, and outputs the transformed position and color.

The transformed vertex positions and primitive type are then used by the setup and rasterization stages to rasterize the primitive into fragments. For each fragment, the interpolated `v_color` will be computed and passed as input to the fragment shader.

Example 8-1 introduces the concept of the model–view–projection (MVP) matrix in the uniform `u_mvpMatrix`. As described in the *Coordinate Systems* section in Chapter 7, the positions input to the vertex shader are stored in object coordinates and the output position of the vertex shader is stored in clip coordinates. The MVP matrix is the product of three very important transformation matrices in 3D graphics that perform this transformation: the model matrix, the view matrix, and the projection matrix.

The transformations performed by each of the individual matrices that make up the MVP matrix are as follows:

- Model matrix—Transform object coordinates to world coordinates.
- View matrix—Transform world coordinates to eye coordinates.
- Projection matrix—Transform eye coordinates to clip coordinates.

Model–View Matrix

In traditional fixed-function OpenGL, the model and view matrices are combined into a single matrix known as the model–view matrix. This 4 × 4 matrix transforms the vertex position from object coordinates into eye coordinates. It is the combination of the transformation from object to world coordinates and the transformation from world to eye coordinates. In fixed-function OpenGL, the model–view matrix can be created using functions such as `glRotatef`, `glTranslatef`, and `glScalef`. Because these functions do not exist in OpenGL ES 2.0 or 3.0, it is up to the application to handle creation of the model–view matrix.

To simply this process, we have included in the sample code framework `esTransform.c`, which contains functions that perform equivalently to the fixed-function OpenGL routines for building a model–view matrix. These transformation functions (`esRotate`, `esTranslate`, `esScale`, `esMatrixLoadIdentity`, and `esMatrixMultiply`) are detailed in Appendix C. In Example 8-1, the model–view matrix is computed as follows:

```
ESMatrix modelview;

// Generate a model-view matrix to rotate/translate the cube
esMatrixLoadIdentity ( &modelview );
```

```
// Translate away from the viewer
esTranslate ( &modelview, 0.0, 0.0, -2.0 );

// Rotate the cube
esRotate ( &modelview, userData->angle, 1.0, 0.0, 1.0 );
```

First, the identity matrix is loaded into the `modelview` matrix using `esMatrixLoadIdentity`. Then the identity matrix is concatenated with a translation that moves the object away from the viewer. Finally, a rotation is concatenated to the `modelview` matrix that rotates the object around the vector (1.0, 0.0, 1.0) with an angle in degrees that is updated based on time to rotate the object continuously.

Projection Matrix

The projection matrix takes the eye coordinates (computed from applying the model–view matrix) and produces clip coordinates as described in the *Clipping* section in Chapter 7. In fixed-function OpenGL, this transformation was specified using `glFrustum` or the OpenGL utility function `gluPerspective`. In the OpenGL ES Framework API, we have provided two equivalent functions: `esFrustum` and `esPerspective`. These functions specify the clip volume detailed in Chapter 7. The `esFrustum` function describes the clip volume by specifying the coordinates of the clip volume. The `esPerspective` function is a convenience function that computes the parameters to `esFrustum` using a field-of-view and aspect ratio description of the viewing volume. The projection matrix is computed for Example 8-1 as follows:

```
ESMatrix projection;

// Compute the window aspect ratio
aspect = (GLfloat) esContext->width /
         (GLfloat) esContext->height;

// Generate a perspective matrix with a 60-degree FOV
// and near and far clip planes at 1.0 and 20.0
esMatrixLoadIdentity ( &projection);
esPerspective ( &projection, 60.0f, aspect, 1.0f, 20.0f );
```

Finally, the MVP matrix is computed as the product of the model–view and projection matrices:

```
// Compute the final MVP by multiplying the
// model-view and projection matrices together
esMatrixMultiply ( &userData->mvpMatrix, &modelview,
                   &projection );
```

The MVP matrix is loaded into the uniform for the shader using `glUniformMatrix4fv`.

```
// Get the uniform locations
userData->mvpLoc =
   glGetUniformLocation ( userData->programObject,
                          "u_mvpMatrix" );

…

// Load the MVP matrix
glUniformMatrix4fv( userData->mvpLoc, 1, GL_FALSE,
                    (GLfloat*) &userData->mvpMatrix.m[0][0] );
```

Lighting in a Vertex Shader

In this section, we look at examples that compute the lighting equation for directional lights, point lights, and spotlights. The vertex shaders described in this section use the OpenGL ES 1.1 lighting equation model to compute the lighting equation for a directional or a spot (or point) light. In the lighting examples described here, the viewer is assumed to be at infinity.

A directional light is a light source that is at an infinite distance from the objects in the scene being lit. An example of a directional light is the sun. As the light is at infinite distance, the light rays from the light source are parallel. The light direction vector is a constant and does not need to be computed per vertex. Figure 8-3 describes the terms that are needed in computing the lighting equation for a directional light. P_{eye} is

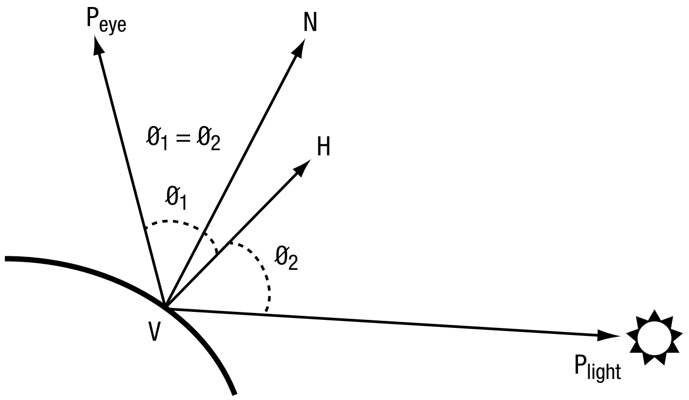


Figure 8-3 Geometric Factors in Computing Lighting Equation for a Directional Light

the position of the viewer, P_{light} is the position of the light (P_{light} . $w = 0$), N is the normal, and H is the half-plane vector. Because P_{light} . $w = 0$, the light direction vector will be P_{light} . xyz. The half-plane vector H is computed as $||VP_{light} + VP_{eye}||$. As both the light source and viewer are at infinity, the half-plane vector $H = ||P_{light} . xyz + (0, 0, 1)||$.

Example 8-2 provides the vertex shader code that computes the lighting equation for a directional light. The directional light properties are described by a `directional_light struct` that contains the following elements:

- `direction`—The normalized light direction in eye space.
- `halfplane`—The normalized half-plane vector H. This can be precomputed for a directional light, as it does not change.
- `ambient_color`—The ambient color of the light.
- `diffuse_color`—The diffuse color of the light.
- `specular_color`—The specular color of the light.

The material properties needed to compute the vertex diffuse and specular color are described by a `material_properties struct` that contains the following elements:

- `ambient_color`—The ambient color of the material.
- `diffuse_color`—The diffuse color of the material.
- `specular_color`—The specular color of the material.
- `specular_exponent`—The specular exponent that describes the shininess of the material and is used to control the shininess of the specular highlight.

Example 8-2 Directional Light

```
#version 300 es

struct  directional_light
{
   vec3  direction;          // normalized light direction in eye
                             // space
   vec3  halfplane;          // normalized half-plane vector
   vec4  ambient_color;
   vec4  diffuse_color;
   vec4  specular_color;
};
```

Example 8-2 Directional Light *(continued)*

```
struct material_properties
{
   vec4  ambient_color;
   vec4  diffuse_color;
   vec4  specular_color;
   float specular_exponent;
};

const float c_zero = 0.0;
const float c_one = 1.0;

uniform material_properties   material;
uniform directional_light     light;

// normal has been transformed into eye space and is a
// normalized vector; this function returns the computed color
vec4 directional_light_color ( vec3 normal )
{
   vec4  computed_color = vec4 ( c_zero, c_zero, c_zero,
                                 c_zero );
   float ndotl; // dot product of normal & light direction
   float ndoth; // dot product of normal & half-plane vector

   ndotl = max ( c_zero, dot ( normal, light.direction ) );
   ndoth = max ( c_zero, dot ( normal, light.halfplane ) );

   computed_color += ( light.ambient_color
                     * material.ambient_color );
   computed_color += ( ndotl * light.diffuse_color
                     * material.diffuse_color );
   if ( ndoth > c_zero )
   {
      computed_color += ( pow ( ndoth,
                          material.specular_exponent )*
                          material.specular_color *
                          light.specular_color );
   }

   return computed_color;
}

// add a main function to make this into a valid vertex shader
```

The directional light vertex shader code described in Example 8-2 combines the per-vertex diffuse and specular color into a single color (given by `computed_color`). Another option would be to compute the per-vertex diffuse and specular colors and pass them as separate output variables to the fragment shader.

Note: In Example 8-2, we multiply the material colors (ambient, diffuse, and specular) with the light colors. This is fine if we are computing the lighting equation for only one light. If we have to compute the lighting equation for multiple lights, however, we should compute the ambient, diffuse, and specular values for each light and then compute the final vertex color by multiplying the material ambient, diffuse, and specular colors with appropriate computed terms and then summing them to generate a per-vertex color.

A point light is a light source that emanates light in all directions from a position in space. A point light is given by a position vector (x, y, z, w), where $w \neq 0$. The point light shines evenly in all directions but its intensity falls off (i.e., becomes attenuated) based on the distance from the light to the object. This attenuation is computed using the following equation:

$$\textit{distance attenuation} = 1 / (K_0 + K_1 \times \| VP_{light} \| + K_2 \times \| VP_{light} \|^2)$$

where K_0, K_1, and K_2 are the constant, linear, and quadratic attenuation factors, respectively.

A spotlight is a light source with both a position and a direction that simulates a cone of light emitted from a position (P_{light}) in a direction (given by $spot_{direction}$). Figure 8-4 describes the terms that are needed in computing the lighting equation for a spotlight.

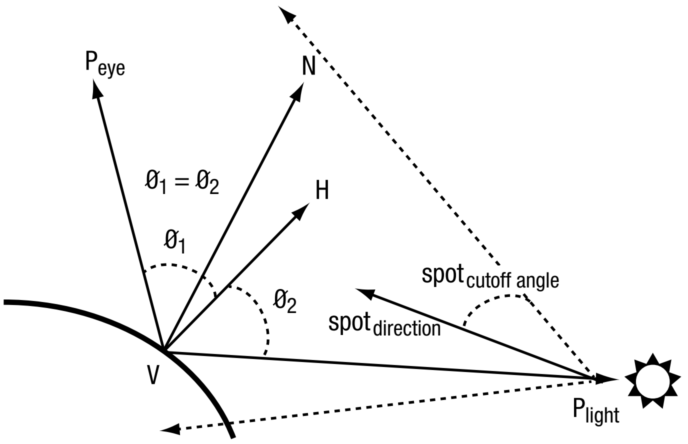


Figure 8-4 Geometric Factors in Computing Lighting Equation for a Spotlight

The intensity of the emitted light is attenuated by a spot cutoff factor based on the angle from the center of the cone. The angle away from the center axis of the cone is computed as the dot product of VP_{light} and

$spot_{direction}$. The spot cutoff factor is 1.0 in the spotlight direction given by $spot_{direction}$ and falls off exponentially to 0.0 at $spot_{cutoff\ angle}$ radians away.

Example 8-3 describes the vertex shader code that computes the lighting equation for a spot (and point) light. The spotlight properties are described by a `spot_light struct` that contains the following elements:

- `direction`—The light direction in eye space.
- `ambient_color`—The ambient color of the light.
- `diffuse_color`—The diffuse color of the light.
- `specular_color`—The specular color of the light.
- `attenuation_factors`—The distance attenuation factors K_0, K_1, and K_2.
- `compute_distance_attenuation`—A boolean term that determines whether the distance attenuation must be computed.
- `spot_direction`—The normalized spot direction vector.
- `spot_exponent`—The spotlight exponent used to compute the spot cutoff factor.
- `spot_cutoff_angle`—The spotlight cutoff angle in degrees.

Example 8-3 Spotlight

```
#version 300 es

struct spot_light

{
   vec4  position;               // light position in eye space
   vec4  ambient_color;
   vec4  diffuse_color;
   vec4  specular_color;
   vec3  spot_direction;         // normalized spot direction
   vec3  attenuation_factors;    // attenuation factors K0, K1, K2
   bool  compute_distance_attenuation;
   float spot_exponent;          // spotlight exponent term
   float spot_cutoff_angle;      // spot cutoff angle in degrees
};
struct material_properties
{
   vec4  ambient_color;
   vec4  diffuse_color;
```

(continues)

Example 8-3 Spotlight *(continued)*

```
   vec4  specular_color;
   float specular_exponent;
};

const float c_zero = 0.0;
const float c_one = 1.0;

uniform material_properties material;
uniform spot_light light;

// normal and position are normal and position values in
//   eye space.
// normal is a normalized vector.
// This function returns the computed color.

vec4 spot_light_color ( vec3 normal, vec4 position )
{
   vec4  computed_color = vec4 ( c_zero, c_zero, c_zero,
                                c_zero );
   vec3  lightdir;
   vec3  halfplane;
   float ndotl, ndoth;
   float att_factor;

   att_factor = c_one;

   // we assume "w" values for light position and
   // vertex position are the same
   lightdir = light.position.xyz - position.xyz;

   // compute distance attenuation
   if ( light.compute_distance_attenuation )
   {
      vec3     att_dist;
      att_dist.x = c_one;
      att_dist.z = dot ( lightdir, lightdir );
      att_dist.y = sqrt ( att_dist.z );
      att_factor = c_one / dot ( att_dist,
                               light.attenuation_factors );
   }

   // normalize the light direction vector
   lightdir = normalize ( lightdir );

   // compute spot cutoff factor
   if ( light.spot_cutoff_angle < 180.0 )
   {
      float spot_factor = dot ( -lightdir,
                               light.spot_direction );
```

Example 8-3 Spotlight *(continued)*

```
      if ( spot_factor >= cos ( radians (
                              light.spot_cutoff_angle ) ) )
         spot_factor = pow ( spot_factor, light.spot_exponent );
      else
         spot_factor = c_zero;

      // compute combined distance and spot attenuation factor
      att_factor *= spot_factor;
   }

   if ( att_factor > c_zero )
   {
      // process lighting equation --> compute the light color
      computed_color += ( light.ambient_color *
                        material.ambient_color );
      ndotl = max ( c_zero, dot(normal, lightdir ) );
      computed_color += ( ndotl * light.diffuse_color *
                        material.diffuse_color );
      halfplane = normalize ( lightdir + vec3 ( c_zero, c_zero,
                              c_one ) );
      ndoth = dot ( normal, halfplane );
      if ( ndoth > c_zero )
      {
         computed_color += ( pow ( ndoth,
                            material.specular_exponent )*
                            material.specular_color *
                            light.specular_color );
      }

      // multiply color with computed attenuation
      computed_color *= att_factor;
   }

   return computed_color;
}
// add a main function to make this into a valid vertex shader
```

Generating Texture Coordinates

We look at two examples that generate texture coordinates in a vertex shader. The two examples are used when rendering shiny (i.e., reflective) objects in a scene by generating a reflection vector and then using this vector to compute a texture coordinate that indexes into a latitude–longitude map (also called a sphere map) or a cubemap (represents six views or faces that capture reflected environment, assuming a single viewpoint in the middle of the shiny object). The fixed-function OpenGL specification describes the texture coordinate generation modes as `GL_SPHERE_MAP` and `GL_REFLECTION_MAP`, respectively. The `GL_SPHERE_MAP` mode generates a texture coordinate that uses a reflection vector to compute a 2D texture coordinate for lookup into a 2D texture map. The `GL_REFLECTION_MAP` mode generates a texture coordinate that is a reflection vector, which can then can be used as a 3D texture coordinate for lookup into a cubemap. Examples 8-4 and 8-5 show the vertex shader code that generates the texture coordinates that will be used by the appropriate fragment shader to calculate the reflected image on the shiny object.

Example 8-4 Sphere Map Texture Coordinate Generation

```
// position is the normalized position coordinate in eye space.
// normal is the normalized normal coordinate in eye space.
// This function returns a vec2 texture coordinate.
vec2 sphere_map ( vec3 position, vec3 normal )
{
   reflection = reflect ( position, normal );
   m = 2.0 * sqrt ( reflection.x * reflection.x +
                    reflection.y * reflection.y +
              (  reflection.z + 1.0 ) * ( reflection.z + 1.0 ) );
   return vec2(( reflection.x / m + 0.5 ),
               ( reflection.y / m + 0.5 ) );
}
```

Example 8-5 Cubemap Texture Coordinate Generation

```
// position is the normalized position coordinate in eye space.
// normal is the normalized normal coordinate in eye space.
// This function returns the reflection vector as a vec3 texture
// coordinate.
vec3 cube_map ( vec3 position, vec3 normal )
{
   return reflect ( position, normal );
}
```

The reflection vector will then be used inside a fragment shader as the texture coordinate to the appropriate cubemap.

Vertex Skinning

Vertex skinning is a commonly used technique whereby the joins between polygons are smoothed. This is implemented by applying additional transform matrices with appropriate weights to each vertex. The multiple matrices used to skin vertices are stored in a matrix palette. The matrices' indices per vertex are used to refer to appropriate matrices in the matrix palette that will be used to skin the vertex. Vertex skinning is commonly used for character models in 3D games to ensure that they appear smooth and realistic (as much as possible) without having to use additional geometry. The number of matrices used to skin a vertex is typically two to four.

The mathematics of vertex skinning is given by the following equations:

$$P' = \sum w_i \times M_i \times P$$
$$N' = \sum w_i \times M_i^{-1T} \times N$$
$$\sum w_i = 1,\ i = 1 \text{ to } n$$

where

n is the number of matrices that will be used to transform the vertex

P is the vertex position

P' is the transformed (skinned) position

N is the vertex normal

N' is the transformed (skinned) normal

M_i is the matrix associated with the *i*th matrix per vertex and is computed as

M_i = `matrix_palette [ matrix_index[i] ]`
with *n* `matrix_index` values specified per vertex

M_i^{-1T} is the inverse transpose of matrix M_i

W_i is the weight associated with the matrix

We discuss how to implement vertex skinning with a matrix palette of 32 matrices and up to four matrices per vertex to generate a skinned vertex. A matrix palette size of 32 matrices is quite common. The matrices in the matrix palette typically are 4 × 3 column major matrices (i.e., four `vec3` entries per matrix). If the matrices were to be stored in column-major order, 128 uniform entries with 3 elements of each uniform entry would be necessary to store a row. The minimum value of gl_MaxVertexUniformVectors that is supported by all OpenGL ES 3.0 implementations is 256 vec4 entries. Thus we will have only the fourth row of these 256 vec4 uniform entries available. This row of floating-point values can store only uniforms declared to be of type float (as per the uniform packing rule). There is no room, therefore, to store a vec2, vec3, or vec4 uniform. It would be better to store the matrices in the palette in row-major order using three vec4 entries per matrix. If we did this, then we would use 96 vec4 entries of uniform storage and the remaining 160 vec4 entries could be used to store other uniforms. Note that we do not have enough uniform storage to store the inverse transpose matrices needed to compute the skinned normal. This is typically not a problem, however: In most cases, the matrices used are orthonormal and, therefore, can be used to transform the vertex position and the normal.

Example 8-6 shows the vertex shader code that computes the skinned normal and position. We assume that the matrix palette contains 32 matrices, and that these matrices are stored in row-major order. The matrices are also assumed to be orthonormal (i.e., the same matrix can be used to transform position and normal) and up to four matrices are used to transform each vertex.

Example 8-6 Vertex Skinning Shader with No Check of Whether Matrix Weight = 0

```
#version 300 es

#define NUM_MATRICES 32 // 32 matrices in matrix palette

const int c_zero  = 0;
const int c_one   = 1;
const int c_two   = 2;
const int c_three = 3;

// store 32 4 x 3 matrices as an array of floats representing
// each matrix in row-major order (i.e., 3 vec4s)
uniform vec4 matrix_palette[NUM_MATRICES * 3];

// vertex position and normal attributes
in vec4 a_position;
in vec3 a_normal;

// matrix weights - 4 entries / vertex
in vec4 a_matrixweights;
// matrix palette indices
in vec4 a_matrixindices;
```

Example 8-6 Vertex Skinning Shader with No Check of Whether Matrix Weight = 0 *(continued)*

```
void skin_position ( in vec4 position, float m_wt, int m_indx,
                     out vec4 skinned_position )
{
   vec4 tmp;
   tmp.x = dot ( position, matrix_palette[m_indx] );
   tmp.y = dot ( position, matrix_palette[m_indx + c_one] );
   tmp.z = dot ( position, matrix_palette[m_indx + c_two] );
   tmp.w = position.w;

   skinned_position += m_wt * tmp;
}

void skin_normal ( in vec3 normal, float m_wt, int m_indx,
                   inout vec3 skinned_normal )
{
   vec3 tmp;

   tmp.x = dot ( normal, matrix_palette[m_indx].xyz );
   tmp.y = dot ( normal, matrix_palette[m_indx + c_one].xyz );
   tmp.z = dot ( normal, matrix_palette[m_indx + c_two].xyz );

   skinned_normal += m_wt * tmp;
}

void do_skinning ( in vec4 position, in vec3 normal,
                   out vec4 skinned_position,
                   out vec3 skinned_normal )
{
   skinned_position = vec4 ( float ( c_zero ) );
   skinned_normal = vec3 ( float ( c_zero ) );

   // transform position and normal to eye space using matrix
   // palette with four matrices used to transform a vertex

   float m_wt = a_matrixweights[0];
   int m_indx = int ( a_matrixindices[0] ) * c_three;
   skin_position ( position, m_wt, m_indx, skinned_position );
   skin_normal ( normal, m_wt, m_indx, skinned_normal );

   m_wt = a_matrixweights[1] ;
   m_indx = int ( a_matrixindices[1] ) * c_three;
   skin_position ( position, m_wt, m_indx, skinned_position );
   skin_normal ( normal, m_wt, m_indx, skinned_normal );

   m_wt = a_matrixweights[2];
   m_indx = int ( a_matrixindices[2] ) * c_three;
   skin_position ( position, m_wt, m_indx, skinned_position );
   skin_normal ( normal, m_wt, m_indx, skinned_normal );
```

(continues)

Example 8-6 Vertex Skinning Shader with No Check of Whether Matrix Weight = 0 *(continued)*

```
   m_wt = a_matrixweights[3];
   m_indx = int ( a_matrixindices[3] ) * c_three;
   skin_position ( position, m_wt, m_indx, skinned_position );
   skin_normal ( normal, m_wt, m_indx, skinned_normal );
}

// add a main function to make this into a valid vertex shader
```

In Example 8-6, the vertex skinning shader generates a skinned vertex by transforming a vertex with four matrices and appropriate matrix weights. It is possible and quite common that some of these matrix weights may be zero. In Example 8-6, the vertex is transformed using all four matrices, irrespective of their weights. It might be better, however, to use a conditional expression to check whether the matrix weight is zero before calling `skin_position` and `skin_normal`. In Example 8-7, the vertex skinning shader checks for a matrix weight of zero before applying the matrix transformation.

Example 8-7 Vertex Skinning Shader with Checks of Whether Matrix Weight = 0

```
void do_skinning ( in vec4 position, in vec3 normal,
                   out vec4 skinned_position,
                   out vec3 skinned_normal )
{
   skinned_position = vec4 ( float ( c_zero ) );
   skinned_normal = vec3 ( float( c_zero ) );

   // transform position and normal to eye space using matrix
   // palette with four matrices used to transform a vertex

   int m_indx = 0;
   float m_wt = a_matrixweights[0];
   if ( m_wt > 0.0 )
   {
      m_indx = int ( a_matrixindices[0] ) * c_three;
      skin_position( position, m_wt, m_indx, skinned_position );
      skin_normal ( normal, m_wt, m_indx, skinned_normal );
   }

   m_wt = a_matrixweights[1] ;
   if ( m_wt > 0.0 )
```

Example 8-7 Vertex Skinning Shader with Checks of Whether Matrix Weight = 0 *(continued)*

```
   {
      m_indx = int ( a_matrixindices[1] ) * c_three;
      skin_position( position, m_wt, m_indx, skinned_position );
      skin_normal ( normal, m_wt, m_indx, skinned_normal );
   }

   m_wt = a_matrixweights[2] ;
   if ( m_wt > 0.0 )
   {
      m_indx = int ( a_matrixindices[2] ) * c_three;
      skin_position( position, m_wt, m_indx, skinned_position );
      skin_normal ( normal, m_wt, m_indx, skinned_normal );
   }
   m_wt = a_matrixweights[3];
   if ( m_wt > 0.0 )
   {
      m_indx = int ( a_matrixindices[3] ) * c_three;
      skin_position( position, m_wt, m_indx, skinned_position );
      skin_normal ( normal, m_wt, m_indx, skinned_normal );
   }
}
```

At first glance, we might conclude that the vertex skinning shader in Example 8-7 offers better performance than the vertex skinning shader in Example 8-6. This is not necessarily true; indeed, the answer can vary across GPUs. Such variations occur because in the conditional expression `if (m_wt > 0.0)`, `m_wt` is a dynamic value and can be different for vertices being executed in parallel by the GPU. We now run into divergent flow control where vertices being executed in parallel may have different values for `m_wt`, which in turn can cause execution to serialize. If a GPU does not implement divergent flow control efficiently, the vertex shader in Example 8-7 might not be as efficient as the version in Example 8-6. Applications should, therefore, test performance of divergent flow control by executing a test shader on the GPU as part of the application initialization phase to determine which shaders to use.

Transform Feedback

The transform feedback mode allows for capturing the outputs of the vertex shader into buffer objects. The output buffers then can be used as sources of the vertex data in a subsequent draw call. This approach is useful for a wide range of techniques that perform animation on the GPU without any CPU intervention, such as particle animation or physics simulation using render-to-vertex-buffer.

To specify the set of vertex attributes to be captured during the transform feedback mode, use the following command:

```
void  glTransformFeedbackVaryings(GLuint program,
                                  GLsizei count,
                                  const char** varyings,
                                  GLenum bufferMode)
```

program	specifies the handle to the program object.
count	specifies the number of vertex output variables used for transform feedback.
varyings	specifies an array of *count* zero-terminated strings specifying the names of the vertex output variables to use for transform feedback.
bufferMode	specifies the mode used to capture the vertex output variables when transform feedback is active. Valid values are `GL_INTERLEAVED_ATTRIBS`, to capture the vertex output variables into a single buffer, and `GL_SEPARATE_ATTRIBS`, to capture each vertex output variable into its own buffer.

After calling `glTransformFeedbackVaryings`, it is necessary to link the program object using `glLinkProgram`. For example, to specify two vertex attributes to be captured into one transform feedback buffer, the code will be as follows:

```
const char* varyings[] = { "v_position", "v_color" };
glTransformFeedbackVarying ( programObject, 2, varyings,
                             GL_INTERLEAVED_ATTRIBS );
glLinkProgram ( programObject );
```

Then, we need to bind one or more buffer objects as the transform feedback buffers using `glBindBuffer` with `GL_TRANSFORM_FEED-BACK_BUFFER`. The buffer is allocated using `glBufferData` with `GL_TRANSFORM_FEEDBACK_BUFFER` and bound to the indexed binding points using `glBindBufferBase` or `glBindBufferRange`. These buffer APIs are described in more details in Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects."

After the transform feedback buffers are bound, we can enter and exit the transform feedback mode using the following API calls:

```
void     glBeginTransformFeedback(GLenum primitiveMode)
void     glEndTransformFeedback()
```

primitiveMode	specifies the output type of the primitives that will be captured into the buffer objects that are bound for transform feedback. Transform feedback is limited to non-indexed `GL_POINTS`, `GL_LINES`, and `GL_TRIANGLES`.

All draw calls that occur between `glBeginTransformFeedback` and `glEndTransformFeedback` will have their vertex outputs captured into the transform feedback buffers. Table 8-1 indicates the allowed draw mode corresponding to the transform feedback primitive mode.

Table 8-1 Transform Feedback Primitive Mode and Allowed Draw Mode

Primitive Mode	**Allowed Draw Mode**
GL_POINTS	GL_POINTS
GL_LINES	GL_LINES, GL_LINE_LOOP, GL_LINE_STRIP
GL_TRIANGLES	GL_TRIANGLES, GL_TRIANGLE_STRIP, GL_TRIANGLE_FAN

We can retrieve the number of primitives that were successfully written into the transform buffer objects using `glGetQueryObjectuiv` after setting up `glBeginQuery` and `glEndQuery` with `GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN`. For example, to begin and end the transform feedback mode for rendering a set of points and querying the number of points written, the code will be as follows:

```
glBeginTransformFeedback ( GL_POINTS );
   glBeginQuery ( GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN,
                  queryObject );
      glDrawArrays ( GL_POINTS, 0, 10 );
   glEndQuery ( GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN );
glEndTransformFeedback ( );

// query the number of primitives written
glGetQueryObjectuiv( queryObject, GL_QUERY_RESULT,
                     &numPoints );
```

We can disable and enable rasterization while capturing in transform feedback mode using `glEnable` and `glDisable` with `GL_RASTERIZER_DISCARD`. While `GL_RASTERIZER_DISCARD` is enabled, no fragment shader will run.

Note that we describe a full example of using transform feedback in the *Particle System Using Transform Feedback* example in Chapter 14, "Advanced Programming with OpenGL ES 3.0."

Vertex Textures

OpenGL ES 3.0 supports texture lookup operations in a vertex shader. This is useful to implement techniques such as displacement mapping, where you can displace the vertex position along the vertex normal based on the texture lookup value in the vertex shader. A typical application of the displacement mapping technique is for rendering terrain or water surfaces.

Performing texture lookup in a vertex shader has some notable limitations:

- The level of detail is not implicitly computed.
- The bias parameter in the `texture` lookup function is not accepted.
- The base texture is used for mipmapped texture.

The maximum number of texture image units supported by an implementation can be queried using `glGetIntegerv` with `GL_MAX_VERTEX_TEXTURE_UNITS`. The minimum number that an OpenGL ES 3.0 implementation can support is 16.

Example 8-8 is a sample vertex shader that performs displacement mapping. The process of loading textures on various texture units is described in more detail in Chapter 9, "Texturing."

Example 8-8 Displacement Mapping Vertex Shader

```
#version 300 es

// uniforms used by the vertex shader
uniform mat4 u_mvpMatrix; // matrix to convert P from
                          // model space to clip space

uniform sampler2D displacementMap;

// attribute inputs to the vertex shader
layout(location = 0) in vec4 a_position; // input position value
```

Example 8-8 Displacement Mapping Vertex Shader *(continued)*

```
layout(location = 1) in vec3 a_normal;   // input normal value
layout(location = 2) in vec2 a_texcoord; // input texcoord value
layout(location = 3) in vec4 a_color;    // input color

// vertex shader output, input to the fragment shader
out vec4 v_color;

void main ( )
{
   v_color = a_color;
   float displacement = texture ( displacementMap,
                                  a_texcoord ).a;

   vec4 displaced_position = a_position +
                          vec4 ( a_normal * displacement, 0.0 );
   gl_Position = u_mvpMatrix * displaced_position;
}
```

We hope that the examples discussed so far have provided a good understanding of vertex shaders, including how to write them and how to use them for a wide-ranging array of effects.

OpenGL ES 1.1 Vertex Pipeline as an ES 3.0 Vertex Shader

We now discuss a vertex shader that implements the OpenGL ES 1.1 fixed-function vertex pipeline without vertex skinning. This is also meant to be an interesting exercise in figuring out how big a vertex shader can be and still run across all OpenGL ES 3.0 implementations.

This vertex shader implements the following fixed functions of the OpenGL ES 1.1 vertex pipeline:

- Transform the normal and position to eye space, if required (typically required for lighting). Rescale or normalization of normal is also performed.
- Compute the OpenGL ES 1.1 vertex lighting equation for up to eight directional lights, point lights, or spotlights with two-sided lighting and color material per vertex.
- Transform the texture coordinates for up to two texture coordinates per vertex.

- Compute the fog factor passed to the fragment shader. The fragment shader uses the fog factor to interpolate between fog color and vertex color.
- Compute the per-vertex user clip plane factor. Only one user clip plane is supported.
- Transform the position to clip space.

Example 8-9 is the vertex shader that implements the OpenGL ES 1.1 fixed-function vertex pipeline as already described.

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline

```
#version 300 es
//**************************************************************
//
// OpenGL ES 3.0 vertex shader that implements the following
// OpenGL ES 1.1 fixed-function pipeline
//
// - compute lighting equation for up to eight
//   directional/point/spotlights
// - transform position to clip coordinates
// - texture coordinate transforms for up to two texture
//   coordinates
// - compute fog factor
// - compute user clip plane dot product (stored as
//   v_ucp_factor)
//
//**************************************************************
#define NUM_TEXTURES          2
#define GLI_FOG_MODE_LINEAR   0
#define GLI_FOG_MODE_EXP      1
#define GLI_FOG_MODE_EXP2     2

struct light
{
   vec4  position; // light position for a point/spotlight or
                   // normalized dir. for a directional light
   vec4  ambient_color;
   vec4  diffuse_color;
   vec4  specular_color;
   vec3  spot_direction;
   vec3  attenuation_factors;
   float spot_exponent;
   float spot_cutoff_angle;
   bool  compute_distance_attenuation;
};
```

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
struct material
{
   vec4  ambient_color;
   vec4  diffuse_color;
   vec4  specular_color;
   vec4  emissive_color;
   float specular_exponent;
};

const float       c_zero = 0.0;
const float       c_one = 1.0;
const int         indx_zero = 0;
const int         indx_one = 1;

uniform mat4      mvp_matrix;  // combined model-view +
                               // projection matrix

uniform mat4      modelview_matrix;  // model-view matrix
uniform mat3      inv_transpose_modelview_matrix; // inverse
                                   // model-view matrix used
                                   // to transform normal
uniform mat4      tex_matrix[NUM_TEXTURES]; // texture matrices
uniform bool      enable_tex[NUM_TEXTURES]; // texture enables
uniform bool      enable_tex_matrix[NUM_TEXTURES]; // texture
                                          // matrix enables

uniform material  material_state;
uniform vec4      ambient_scene_color;
uniform light     light_state[8];
uniform bool      light_enable_state[8]; // booleans to indicate
                                       // which of eight
                                       // lights are enabled
uniform int       num_lights; // number of lights
                              // enabled = sum of
                              // light_enable_state bools
                              // set to TRUE

uniform bool      enable_lighting;       // is lighting enabled
uniform bool      light_model_two_sided; // is two-sided
                                       // lighting enabled
uniform bool      enable_color_material; // is color material
                                       // enabled
uniform bool      enable_fog;            // is fog enabled
uniform float     fog_density;
uniform float     fog_start, fog_end;
uniform int       fog_mode;  // fog mode: linear, exp, or exp2
```

(continues)

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
uniform bool      xform_eye_p; // xform_eye_p is set if we need
                               // Peye for user clip plane,
                               // lighting, or fog
uniform bool      rescale_normal;   // is rescale normal enabled
uniform bool      normalize_normal; // is normalize normal
                                    // enabled
uniform float     rescale_normal_factor; // rescale normal
                                         // factor if
                               // glEnable(GL_RESCALE_NORMAL)

uniform vec4      ucp_eqn;  // user clip plane equation;
                            // one user clip plane specified

uniform bool      enable_ucp;  // is user clip plane enabled

//****************************************************
// vertex attributes: not all of them may be passed in
//****************************************************
in vec4    a_position;  // this attribute is always specified
in vec4    a_texcoord0; // available if enable_tex[0] is true
in vec4    a_texcoord1; // available if enable_tex[1] is true
in vec4    a_color;     // available if !enable_lighting or
                // (enable_lighting && enable_color_material)
in vec3    a_normal;    // available if xform_normal is set
                        // (required for lighting)

//************************************************
// output variables of the vertex shader
//************************************************
out vec4          v_texcoord[NUM_TEXTURES];
out vec4          v_front_color;
out vec4          v_back_color;
out float         v_fog_factor;
out float         v_ucp_factor;

//************************************************
// temporary variables used by the vertex shader
//************************************************
vec4                   p_eye;
vec3                   n;
vec4                   mat_ambient_color;
vec4                   mat_diffuse_color;
```

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
vec4 lighting_equation ( int i )
{
   vec4  computed_color = vec4( c_zero, c_zero, c_zero,
                                c_zero );
   vec3   h_vec;
   float  ndotl, ndoth;
   float  att_factor;
   vec3   VPpli;

   att_factor = c_one;
   if ( light_state[i].position.w != c_zero )
   {
      float  spot_factor;
      vec3  att_dist;

      // this is a point or spotlight
      // we assume "w" values for PPli and V are the same
      VPpli = light_state[i].position.xyz - p_eye.xyz;
      if ( light_state[i].compute_distance_attenuation )
      {
         // compute distance attenuation
         att_dist.x = c_one;
         att_dist.z = dot ( VPpli, VPpli );
         att_dist.y = sqrt ( att_dist.z ) ;
         att_factor = c_one / dot ( att_dist,
            light_state[i] .attenuation_factors );
      }
      VPpli = normalize ( VPpli );

      if ( light_state[i].spot_cutoff_angle < 180.0 )
      {
         // compute spot factor
         spot_factor = dot ( -VPpli,
                             light_state[i].spot_direction );
         if( spot_factor >= cos ( radians (
                          light_state[i].spot_cutoff_angle ) ) )
            spot_factor = pow ( spot_factor,
                                light_state[i].spot_exponent );
         else
            spot_factor = c_zero;

         att_factor *= spot_factor;
      }
   }
```

(continues)

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
   else
   {
      // directional light
      VPpli = light_state[i].position.xyz;
   }

   if( att_factor > c_zero )
   {
      // process lighting equation --> compute the light color
      computed_color += ( light_state[i].ambient_color *
                          mat_ambient_color );
      ndotl = max( c_zero, dot( n, VPpli ) );
      computed_color += ( ndotl * light_state[i].diffuse_color *
                         mat_diffuse_color );
       h_vec = normalize( VPpli + vec3(c_zero, c_zero, c_one ) );
       ndoth = dot ( n, h_vec );
       if ( ndoth > c_zero )
       {
          computed_color += ( pow ( ndoth,
                             material_state.specular_exponent ) *
                             material_state.specular_color *
                             light_state[i].specular_color );
       }
       computed_color *= att_factor; // multiply color with
                                     // computed attenuation
                                     // factor
                                     // * computed spot factor
   }
   return computed_color;
}

float compute_fog( )
{
   float  f;

   // use eye Z as approximation
   if ( fog_mode == GLI_FOG_MODE_LINEAR )
   {
      f = ( fog_end - p_eye.z ) / ( fog_end - fog_start );
   }
   else if ( fog_mode == GLI_FOG_MODE_EXP )
   {
      f = exp( - ( p_eye.z * fog_density ) );
   }
```

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
   else
   {
      f = ( p_eye.z * fog_density );
      f = exp( -( f * f ) );
   }

   f = clamp ( f, c_zero, c_one) ;
   return f;
}

vec4 do_lighting( )
{
   vec4   vtx_color;
   int    i, j ;

   vtx_color = material_state.emissive_color +
               ( mat_ambient_color * ambient_scene_color );
   j = int( c_zero );
   for ( i=int( c_zero ); i<8; i++ )
   {
      if ( j >= num_lights )
         break;

      if ( light_enable_state[i] )
      {
         j++;
         vtx_color += lighting_equation(i);
      }
   }

   vtx_color.a = mat_diffuse_color.a;

   return vtx_color;
}

void main( void )
{
   int  i, j;

   // do we need to transform P
   if ( xform_eye_p )
      p_eye = modelview_matrix * a_position;

   if ( enable_lighting )
   {
      n = inv_transpose_modelview_matrix * a_normal;
      if ( rescale_normal )
         n = rescale_normal_factor * n;
```

(continues)

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
      if ( normalize_normal )
         n = normalize(n);

      mat_ambient_color = enable_color_material ? a_color
                                  : material_state.ambient_color;
      mat_diffuse_color = enable_color_material ? a_color
                                  : material_state.diffuse_color;
      v_front_color = do_lighting( );
      v_back_color = v_front_color;

      // do two-sided lighting
      if ( light_model_two_sided )
      {
         n = -n;
         v_back_color = do_lighting( );
      }
   }
   else
   {
      // set the default output color to be the per-vertex /
      // per-primitive color
      v_front_color = a_color;
      v_back_color = a_color;
   }

   // do texture transforms
   v_texcoord[indx_zero] = vec4( c_zero, c_zero, c_zero,
                                 c_one );
   if ( enable_tex[indx_zero] )
   {
      if ( enable_tex_matrix[indx_zero] )
         v_texcoord[indx_zero] = tex_matrix[indx_zero] *
                                  a_texcoord0;
      else
         v_texcoord[indx_zero] = a_texcoord0;
   }

   v_texcoord[indx_one] = vec4( c_zero, c_zero, c_zero, c_one );
   if ( enable_tex[indx_one] )
   {
      if ( enable_tex_matrix[indx_one] )
         v_texcoord[indx_one] = tex_matrix[indx_one] *
                                 a_texcoordl;
      else
         v_texcoord[indx_one] = a_texcoordl;
   }
```

Example 8-9 OpenGL ES 1.1 Fixed-Function Vertex Pipeline *(continued)*

```
   v_ucp_factor = enable_ucp ? dot ( p_eye, ucp_eqn ) : c_zero;
   v_fog_factor = enable_fog ? compute_fog( ) : c_one;

   gl_Position = mvp_matrix * a_position;
}
```

Summary

In this chapter, we provided a high-level overview of how vertex shaders fit into the pipeline and how to perform transformation, lighting, skinning, and displacement mapping in a vertex shader through some vertex shader examples. In addition, you learned how to use the transform feedback mode to capture the vertex outputs into buffer objects and how to implement the fixed-function pipeline using vertex shaders. Next, before we will discuss fragment shaders, we will cover the texturing functionality in OpenGL ES 3.0.

Chapter 9

Texturing

Now that we have covered vertex shaders in detail, you should be familiar with all of the gritty details of transforming vertices and preparing primitives for rendering. The next step in the pipeline is the fragment shader, where much of the visual magic of OpenGL ES 3.0 occurs. A central aspect of fragment shaders is the application of textures to surfaces. This chapter covers all the details of creating, loading, and applying textures:

- Texturing basics
- Loading textures and mipmapping
- Texture filtering and wrapping
- Texture level-of-detail, swizzles, and depth comparison
- Texture formats
- Using textures in the fragment shader
- Texture subimage specification
- Copying texture data from the framebuffer
- Compressed textures
- Sampler objects
- Immutable textures
- Pixel unpack buffer objects

Texturing Basics

One of the most fundamental operations used in rendering 3D graphics is the application of textures to a surface. Textures allow for the representation of additional detail not available just from the geometry of a mesh. Textures in OpenGL ES 3.0 come in several forms: 2D textures, 2D texture arrays, 3D textures, and cubemap textures.

Textures are typically applied to a surface by using texture coordinates, which can be thought of as indices into texture array data. The following sections introduce the different texture types in OpenGL ES and explain how they are loaded and accessed.

2D Textures

A 2D texture is the most basic and common form of texture in OpenGL ES. A 2D texture is—as you might guess—a two-dimensional array of image data. The individual data elements of a texture are known as *texels* (short for "texture pixels"). Texture image data in OpenGL ES can be represented in many different basic formats. The basic formats available for texture data are shown in Table 9-1.

Each texel in the image is specified according to both its basic format and its data type. Later, we describe in more detail the various data types that can represent a texel. For now, the important point to understand is that a 2D texture is a two-dimensional array of image data. When rendering with a 2D texture, a texture coordinate is used as an index into the texture image. Generally, a mesh will be authored in a 3D content authoring program, with each vertex having a texture coordinate. Texture coordinates for 2D textures are given by a 2D pair of coordinates (s, t), sometimes also called (u, v) coordinates. These coordinates represent normalized coordinates used to look up a texture map, as shown in Figure 9-1.

The lower-left corner of the texture image is specified by the *st*-coordinates (0.0, 0.0). The upper-right corner of the texture image is specified by the *st*-coordinates (1.0, 1.0). Coordinates outside of the range [0.0, 1.0] are allowed, and the behavior of texture fetches outside of that range is defined by the texture wrapping mode (described in the section on texture filtering and wrapping).

Table 9-1 Texture Base Formats

Base Format	Texel Data Description
`GL_RED`	(Red)
`GL_RG`	(Red, Green)
`GL_RGB`	(Red, Green, Blue)
`GL_RGBA`	(Red, Green, Blue, Alpha)
`GL_LUMINANCE`	(Luminance)
`GL_LUMINANCE_ALPHA`	(Luminance, Alpha)
`GL_ALPHA`	(Alpha)
`GL_DEPTH_COMPONENT`	(Depth)
`GL_DEPTH_STENCIL`	(Depth, Stencil)
`GL_RED_INTEGER`	(iRed)
`GL_RG_INTEGER`	(iRed, iGreen)
`GL_RGB_INTEGER`	(iRed, iGreen, iBlue)
`GL_RGBA_INTEGER`	(iRed, iGreen, iBlue, iAlpha)

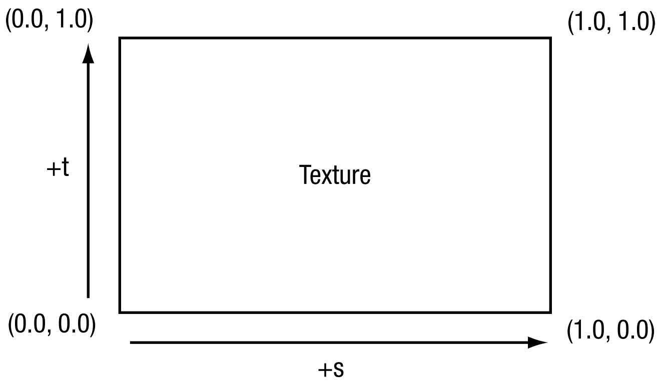


Figure 9-1 2D Texture Coordinates

Cubemap Textures

In addition to 2D textures, OpenGL ES 3.0 supports cubemap textures. At its most basic, a cubemap is a texture made up of six individual 2D texture faces. Each face of the cubemap represents one of the six sides of a cube. Although cubemaps have a variety of advanced uses in 3D rendering, the most common use is for an effect known as *environment mapping*. For this effect, the reflection of the environment onto the object is rendered by using a cubemap to represent the environment. Typically, a cubemap is generated for environment mapping by placing a camera in the center of the scene and capturing an image of the scene from each of the six axis directions (+*X*, –*X*, +*Y*, –*Y*, +*Z*, –*Z*) and storing the result in each cube face.

Texels are fetched out of a cubemap by using a 3D vector (*s*, *t*, *r*) as the texture coordinate to look up into the cubemap. The texture coordinates (*s*, *t*, *r*) represent the (*x*, *y*, *z*) components of the 3D vector. The 3D vector is used to first select a face of the cubemap to fetch from, and then the coordinate is projected into a 2D (*s*, *t*) coordinate to fetch from the cubemap face. The actual math for computing the 2D (*s*, *t*) coordinate is outside our scope here, but suffice it to say that a 3D vector is used to look up into a cubemap. You can visualize the way this process works by picturing a 3D vector coming from the origin inside of a cube. The point at which that vector intersects the cube is the texel that would be fetched from the cubemap. This concept is illustrated in Figure 9-2, where a 3D vector intersects the cube face.

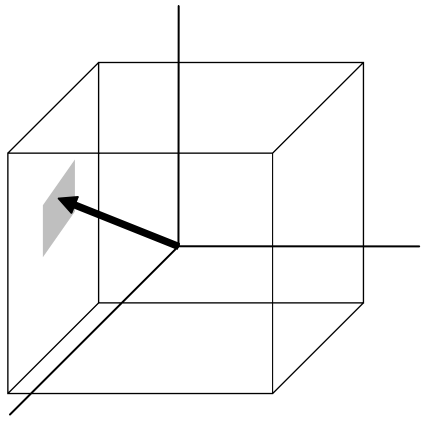


Figure 9-2 3D Texture Coordinate for Cubemap

The faces of a cubemap are each specified in the same manner as one would specify a 2D texture. Each of the faces must be square (e.g., the width and height must be equal), and each must have the same width and height. The 3D vector that is used for the texture coordinate is not normally stored directly on a per-vertex basis on the mesh as it is for 2D texturing. Instead, cubemaps are usually fetched from by using the normal vector as a basis for computing the cubemap texture coordinate. Typically, the normal vector is used along with a vector from the eye to compute a reflection vector that is then used to look up into a cubemap. This computation is described in the environment mapping example in Chapter 14, "Advanced Programming with OpenGL ES 3.0."

3D Textures

Another type of texture in OpenGL ES 3.0 is the 3D texture (or volume texture). 3D textures can be thought of as an array of multiple slices of 2D textures. A 3D texture is accessed with a three-tuple (*s*, *t*, *r*) coordinate, much like a cubemap. For 3D textures, the *r*-coordinate selects which slice of the 3D texture to sample from and the (*s*, *t*) coordinate is used to fetch into the 2D map at each slice. Figure 9-3 shows a 3D texture where each slice is made up of an individual 2D texture. Each mipmap level in a 3D texture contains half the number of slices in the texture above it (more on this later).

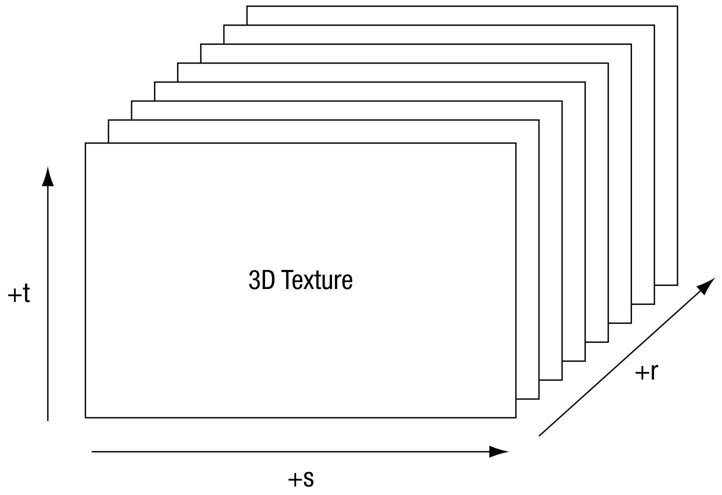


Figure 9-3 3D Texture

2D Texture Arrays

The final type of texture in OpenGL ES 3.0 is a 2D texture array. The 2D texture array is very similar to a 3D texture, but is used for a different purpose. For example, 2D texture arrays are often used to store an animation of a 2D image. Each slice of the array represents one frame of the texture animation. The difference between 2D texture arrays and 3D textures is subtle but important. For a 3D texture, filtering occurs *between* slices, whereas fetching from a 2D texture array will sample from only an individual slice. As such, mipmapping is also different. Each mipmap level in a 2D texture array contains the same number of slices as the level above it. Each 2D slice is entirely mipmapped independently from any other slices (unlike the case with a 3D texture, for which each mipmap level has half as many slices as above it).

To address a 2D texture array, three texture coordinates (*s*, *t*, *r*) are used just like with a 3D texture. The *r*-coordinate selects which slice in the 2D texture array to use and the (*s*, *t*) coordinates are used on the selected slice in exactly the same way as a 2D texture.

Texture Objects and Loading Textures

The first step in the application of textures is to create a *texture object*. A texture object is a container object that holds the texture data needed for rendering, such as image data, filtering modes, and wrap modes. In OpenGL ES, a texture object is represented by an unsigned integer that is a handle to the texture object. The function that is used for generating texture objects is `glGenTextures`.

```
void   glGenTextures(GLsizei n,   GLuint *textures)
```

n	specifies the number of texture objects to generate
textures	an array of unsigned integers that will hold *n* texture object IDs

At the point of creation, the texture objects(s) generated by `glGenTextures` are an empty container that will be used for loading texture data and parameters. Texture objects also need to be deleted when an application no longer needs them. This step is typically done either at application shutdown or, for example, when changing levels in a game. It can be accomplished by using `glDeleteTextures`.

```
void glDeleteTextures(GLsizei n, GLuint *textures)
```

n	specifies the number of texture objects to delete
textures	an array of unsigned integers that hold *n* texture object IDs to delete

Once texture object IDs have been generated with `glGenTextures`, the application must bind the texture object to operate on it. Once texture objects are bound, subsequent operations such as `glTexImage2D` and `glTexParameter` affect the bound texture object. The function used to bind texture objects is `glBindTexture`.

```
void glBindTexture(GLenum target, GLuint texture)
```

target	bind the texture object to target `GL_TEXTURE_2D`, `GL_TEXTURE_3D`, `GL_TEXTURE_2D_ARRAY`, or `GL_TEXTURE_CUBE_MAP`
texture	the handle to the texture object to bind

Once a texture is bound to a particular texture target, that texture object will remain bound to its target until it is deleted. After generating a texture object and binding it, the next step in using a texture is to actually load the image data. The basic function that is used for loading 2D and cubemap textures is `glTexImage2D`. In addition, several alternative methods may be used to specify 2D textures in OpenGL ES 3.0, including using immutable textures (`glTexStorage2D`) in conjunction with `glTexSubImage2D`. We start first with the most basic method—using `glTexImage2D`—and describe immutable textures later in the chapter. For best performance, we recommend using immutable textures.

```
void glTexImage2D(GLenum target, GLint level,
                  GLenum internalFormat, GLsizei width,
                  GLsizei height, GLint border,
                  GLenum format, GLenum type,
                  const void* pixels)
```

target	specifies the texture target, either `GL_TEXTURE_2D` or one of the cubemap face targets (`GL_TEXTURE_CUBE_MAP_POSITIVE_X`, `GL_TEXTURE_CUBE_MAP_NEGATIVE_X, and so on`).

(continues)

(continued)

level	specifies which mip level to load. The first level is specified by 0, followed by an increasing level for each successive mipmap.
internalFormat	the internal format for the texture storage; can be either an unsized base internal format or a sized internal format. The full list of valid *internalFormat*, *format*, and *type* combinations is provided in Tables 9-4 through 9-10. The unsized internal formats can be GL_RGBA, GL_RGB, GL_LUMINANCE_ALPHA GL_LUMINANCE, GL_ALPHA The sized internal formats can be GL_R8, GL_R8_SNORM, GL_R16F, GL_R32F GL_R8UI, GL_R16UI, GL_R32UI, GL_R32I GL_RG8, GL_RG8_SNORM, GL_RG16F, GL_RG32F GL_RG8UI, GL_RG8I, GL_RG16UI, GL_RG32UI GL_RG32I, GL_RGB8, GL_SRGB8, GL_RGB565 GL_RGB8_SNORM, GL_R11F_G11F_B10F GL_RGB9_E5, GL_RGB16F, GL_RGB32F GL_RGB8UI, GL_RGB16UI, GL_RGB16I, GL_RGB32UI GL_RGB32I, GL_RGBA8, GL_SRGB8_ALPHA8 GL_RGBA8_SNORM, GL_RGB5_A1, GL_RGBA4 GL_RGB10_A2, GL_RGBA16F, GL_RGBA32F GL_RGBA8UI, GL_RGBA8I, GL_RGB10_A2UI GL_RGBA16UI, GL_RGBA16I, GL_RGBA32I GL_RGBA32UI, GL_DEPTH_COMPONENT16 GL_DEPTH_COMPONENT24, GL_DEPTH_COMPONENT32F GL_DEPTH24_STENCIL8, GL_DEPTH24F_STENCIL8
width	the width of the image in pixels.
height	the height of the image in pixels.
border	this parameter is ignored in OpenGL ES, but was kept for compatibility with the desktop OpenGL interface; should be 0.
format	the format of the incoming texture data; can be GL_RED GL_RED_INTEGER GL_RG

	`GL_RG_INTEGER`
	`GL_RGB`
	`GL_RGB_INTEGER`
	`GL_RGBA`
	`GL_RGBA_INTEGER`
	`GL_DEPTH_COMPONENT`
	`GL_DEPTH_STENCIL`
	`GL_LUMINANCE_ALPHA`
	`GL_ALPHA`

`type`	the type of the incoming pixel data; can be
	`GL_UNSIGNED_BYTE`
	`GL_BYTE`
	`GL_UNSIGNED_SHORT`
	`GL_SHORT`
	`GL_UNSIGNED_INT`
	`GL_INT`
	`GL_HALF_FLOAT`
	`GL_FLOAT`
	`GL_UNSIGNED_SHORT_5_6_5`
	`GL_UNSIGNED_SHORT_4_4_4_4`
	`GL_UNSIGNED_SHORT_5_5_5_1`
	`GL_UNSIGNED_INT_2_10_10_10_REV`
	`GL_UNSIGNED_INT_10F_11F_11F_REV`
	`GL_UNSIGNED_INT_5_9_9_9_REV`
	`GL_UNSIGNED_INT_24_8`
	`GL_FLOAT_32_UNSIGNED_INT_24_8_REV`
	`GL_UNSIGNED_SHORT_5_6_5`

`pixels`	contains the actual pixel data for the image. The data must contain (*`width*height`*) number of pixels with the appropriate number of bytes per pixel based on the format and *type* specification. The pixel rows must be aligned to the `GL_UNPACK_ALIGNMENT` set with `glPixelStorei` (defined next).

Example 9-1, from the `Simple_Texture2D` example, demonstrates generating a texture object, binding it, and then loading a 2 × 2 2D texture with RGB image data made from unsigned bytes.

Example 9-1 Generating a Texture Object, Binding It, and Loading Image Data

```
// Texture object handle
GLuint textureId;

// 2 x 2 Image, 3 bytes per pixel (R, G, B)
GLubyte pixels[4 * 3] =

{
   255,   0,   0,   // Red
     0, 255,   0,   // Green
     0,   0, 255,   // Blue
   255, 255,   0    // Yellow
};

// Use tightly packed data
glPixelStorei(GL_UNPACK_ALIGNMENT, 1);

// Generate a texture object
glGenTextures(1, &textureId);

// Bind the texture object
glBindTexture(GL_TEXTURE_2D, textureId);

// Load the texture
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, 2, 2, 0, GL_RGB,
             GL_UNSIGNED_BYTE, pixels);

// Set the filtering mode
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                GL_NEAREST);
```

In the first part of the code, the `pixels` array is initialized with simple 2 × 2 texture data. The data is composed of unsigned byte RGB triplets that are in the range [0, 255]. When data is fetched from an 8-bit unsigned byte texture component in the shader, the values are mapped from the range [0, 255] to the floating-point range [0.0, 1.0]. Typically, an application would not create texture data in this simple manner, but rather would load the data from an image file. This example is provided to demonstrate the use of the API.

Prior to calling `glTexImage2D`, the application makes a call to `glPixelStorei` to set the unpack alignment. When texture data is uploaded via `glTexImage2D`, the rows of pixels are assumed to be aligned to the value set for `GL_UNPACK_ALIGNMENT`. By default, this value is 4, meaning that rows of pixels are assumed to begin on 4-byte boundaries.

This application sets the unpack alignment to 1, meaning that each row of pixels begins on a byte boundary (in other words, the data is tightly packed). The full definition for `glPixelStorei` is given next.

```
void   glPixelStorei(GLenum pname,   GLint param)
```

pname	specifies the pixel storage type to set. The following options impact how data is unpacked from memory when calling `glTexImage2D`, `glTexImage3D`, `glTexSubImage2D`, and `glTexSubImage3D`: `GL_UNPACK_ROW_LENGTH`, `GL_UNPACK_IMAGE_HEIGHT`, `GL_UNPACK_SKIP_PIXELS`, `GL_UNPACK_SKIP_ROWS`, `GL_UNPACK_SKIP_IMAGES`, `GL_UNPACK_ALIGNMENT` The following options impact how data is packed into memory when calling `glReadPixels`: `GL_PACK_ROW_LENGTH`, `GL_PACK_IMAGE_HEIGHT`, `GL_PACK_SKIP_PIXELS`, `GL_PACK_SKIP_ROWS`, `GL_PACK_SKIP_IMAGES`, `GL_PACK_ALIGNMENT` All of these options are described in Table 9-2.
param	specifies the integer value for the pack or unpack option.

The `GL_PACK_xxxxx` arguments to `glPixelStorei` do not have any impact on texture image uploading. The pack options are used by `glReadPixels`, which is described in Chapter 11, "Fragment Operations." The pack and unpack options set by `glPixelStorei` are global state and are not stored or associated with a texture object. In practice, it is rare to use any options other than `GL_UNPACK_ALIGNMENT` for specifying textures. For completeness, the full list of pixel storage options is provided in Table 9-2.

Returning to the program in Example 9-1, after defining the image data, a texture object is generated using `glGenTextures` and then that object is bound to the `GL_TEXTURE_2D` target using `glBindTexture`. Finally, the image data is loaded into the texture object using `glTexImage2D`. The format is set as `GL_RGB`, which signifies that the image data is composed of (R, G, B) triplets. The type is set as `GL_UNSIGNED_BYTE`, which signifies that each channel of the data is stored in an 8-bit unsigned byte. There are a number of other options for loading texture data, including the different formats described in Table 9-1. All of the texture formats are described later in this chapter in the *Texture Formats* section.

Table 9-2 Pixel Storage Options

Pixel Storage Option	Initial Value	Description
`GL_UNPACK_ALIGNMENT` `GL_PACK_ALIGNMENT`	4	Specifies the alignment of rows in an image. By default, images begin at 4-byte boundaries. Setting the value to 1 means that the image is tightly packed and rows are aligned to a byte boundary.
`GL_UNPACK_ROW_LENGTH` `GL_PACK_ROW_LENGTH`	0	If the value is non-zero, gives the number of pixels in a row of the image. If the value is zero, then the row length is the width of the image (i.e., it is tightly packed).
`GL_UNPACK_IMAGE_HEIGHT` `GL_PACK_IMAGE_HEIGHT`	0	If the value is non-zero, gives the number of pixels in a column of an image that is part of a 3D texture. This option can be used to have padding of columns in between slices of a 3D texture. If the value is zero, then the number of columns in the image is equal to the height (i.e., it is tightly packed).
`GL_UNPACK_SKIP_PIXELS` `GL_PACK_SKIP_PIXELS`	0	If the value is non-zero, gives the number of pixels to skip at the beginning of a row.
`GL_UNPACK_SKIP_ROWS` `GL_PACK_SKIP_ROWS`	0	If the value is non-zero, gives the number of rows to skip at the beginning of the image.
`GL_UNPACK_SKIP_IMAGES` `GL_PACK_SKIP_IMAGES`	0	If the value is non-zero, gives the number of images in a 3D texture to skip.

The last part of the code uses `glTexParameteri` to set the minification and magnification filtering modes to `GL_NEAREST`. This code is required because we have not loaded a complete mipmap chain for the texture; thus we must select a non-mipmapped minification filter. The other option would have been to use minification and magnification modes of `GL_LINEAR`, which provides bilinear non-mipmapped filtering. The details of texture filtering and mipmapping are explained in the next section.

Texture Filtering and Mipmapping

So far, we have limited our explanation of 2D textures to single 2D images. Although this allowed us to explain the concept of texturing, there is actually a bit more to how textures are specified and used in OpenGL ES. This complexity relates to the visual artifacts and performance issues that occur due to using a single texture map. As we have described texturing so far, the texture coordinate is used to generate a 2D index to fetch from the texture map. When the minification and magnification filters are set to `GL_NEAREST`, this is exactly what will happen: A single texel will be fetched at the texture coordinate location provided. This is known as point or nearest sampling.

However, nearest sampling might produce significant visual artifacts. The artifacts occur because as a triangle becomes smaller in screen space, the texture coordinates take large jumps when being interpolated from pixel to pixel. As a result, a small number of samples are taken from a large texture map, resulting in aliasing artifacts and a potentially large performance penalty. The solution that is used to resolve this type of artifact in OpenGL ES is known as *mipmapping*. The idea behind mipmapping is to build a chain of images known as a mipmap chain. The mipmap chain begins with the originally specified image and then continues with each subsequent image being half as large in each dimension as the one before it. This chain continues until we reach a single 1 × 1 texture at the bottom of the chain. The mip levels can be generated programmatically, typically by computing each pixel in a mip level as an average of the four pixels at the same location in the mip level above it (box filtering).

In the `Chapter_9/MipMap2D` sample program, we provide an example demonstrating how to generate a mipmap chain for a texture using a box filtering technique. The code to generate the mipmap chain is given by the `GenMipMap2D` function. This function takes an RGB8 image as input and generates the next mipmap level by performing a box filter on the preceding image. See the source code in the example for details on how the box filtering is done. The mipmap chain is then loaded using `glTexImage2D`, as shown in Example 9-2.

With a mipmap chain loaded, we can then set up the filtering mode to use mipmaps. The result is that we achieve a better ratio between screen pixels and texture pixels, thereby reducing aliasing artifacts. Aliasing is also reduced because each image in the mipmap chain is successively filtered so that high-frequency elements are attenuated more and more as we move down the chain.

Example 9-2 Loading a 2D Mipmap Chain

```
// Load mipmap level 0
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, width, height,
             0, GL_RGB, GL_UNSIGNED_BYTE, pixels);

level = 1;
prevImage = &pixels[0];

while(width > 1 && height > 1)
{
   int newWidth,
       newHeight;

   // Generate the next mipmap level
   GenMipMap2D(prevImage, &newImage, width, height, &newWidth,
               &newHeight);

   // Load the mipmap level
   glTexImage2D(GL_TEXTURE_2D, level, GL_RGB,
                newWidth, newHeight, 0, GL_RGB,
                GL_UNSIGNED_BYTE, newImage);

   // Free the previous image
   free(prevImage);

   // Set the previous image for the next iteration
   prevImage = newImage;
   level++;

   // Half the width and height
   width = newWidth;
   height = newHeight;
}

free(newlmage);
```

Two types of filtering occur when texturing: minification and magnification. Minification is what happens when the size of the projected polygon on the screen is smaller than the size of the texture. Magnification is what happens when the size of the projected polygon on screen is larger than the size of the texture. The determination of which filter type to use is handled automatically by the hardware, but the API provides control over which type of filtering to use in each case. For magnification, mipmapping is not relevant, because we will always be sampling from the largest level available. For minification, a variety of sampling modes can be used. The choice of which mode to use is based on which level of visual quality you need to achieve and how much performance you are willing to give up for texture filtering.

The filtering modes are specified (along with many other texture options) with `glTexParameter[i|f][v]`. The texture filtering modes are described next, and the remaining options are described in subsequent sections.

```
void    glTexParameteri(GLenum target,   GLenum pname,
                        GLint param)
void    glTexParameteriv(GLenum target,   GLenum pname,
                         const GLint *params)
void    glTexParameterf(GLenum target,   GLenum pname,
                        GLfloat param)
void    glTexParameterfv(GLenum target,   GLenum pname,
                         const GLfloat *params)
```

target	the texture target can be `GL_TEXTURE_2D`, `GL_TEXTURE_3D`, `GL_TEXTURE_2D_ARRAY`, or `GL_TEXTURE_CUBE_MAP`

pname	the parameter to set; one of
	`GL_TEXTURE_BASE_LEVEL`
	`GL_TEXTURE_COMPARE_FUNC`
	`GL_TEXTURE_COMPARE_MODE`
	`GL_TEXTURE_MIN_FILTER`
	`GL_TEXTURE_MAG_FILTER`
	`GL_TEXTURE_MIN_LOD`
	`GL_TEXTURE_MAX_LOD`
	`GL_TEXTURE_MAX_LEVEL`
	`GL_TEXTURE_SWIZZLE_R`
	`GL_TEXTURE_SWIZZLE_G`
	`GL_TEXTURE_SWIZZLE_B`
	`GL_TEXTURE_SWIZZLE_A`
	`GL_TEXTURE_WRAP_S`
	`GL_TEXTURE_WRAP_T`
	`GL_TEXTURE_WRAP_R`

params	the value (or array of values for the "v" entrypoints) to set the texture parameter to If *pname* is `GL_TEXTURE_MAG_FILTER`, then *param* can be `GL_NEAREST` or `GL_LINEAR` If *pname* is `GL_TEXTURE_MIN_FILTER`, then *param* can be `GL_NEAREST`, `GL_LINEAR`, `GL_NEAREST_MIPMAP_NEAREST`, `GL_NEAREST_MIPMAP_LINEAR`, `GL_LINEAR_MIPMAP_NEAREST`, or `GL_LINEAR_MIPMAP_LINEAR`

(continues)

(continued)

If *pname* is GL_TEXTURE_WRAP_S, GL_TEXTURE_WRAP_R, or GL_TEXTURE_WRAP_T, then *param* can be GL_REPEAT, GL_CLAMP_TO_EDGE, or GL_MIRRORED_REPEAT

If *pname* is GL_TEXTURE_COMPARE_FUNC, then *param* can be GL_LEQUAL, GL_EQUAL, GL_LESS, GL_GREATER, GL_EQUAL, GL_NOTEQUAL, GL_ALWAYS, or GL_NEVER

If *pname* is GL_TEXTURE_COMPARE_MODE, then *param* can be GL_COMPARE_REF_TO_TEXTURE or GL_NONE

If *pname* is GL_TEXTURE_SWIZZLE_R, GL_TEXTURE_SWIZZLE_G, GL_TEXTURE_SWIZZLE_B, or GL_TEXTURE_SWIZZLE_A, then *param* can be GL_RED, GL_GREEN, GL_BLUE, GL_ALPHA, GL_ZERO, or GL_ONE

The magnification filter can be either GL_NEAREST or GL_LINEAR. In GL_NEAREST magnification filtering, a single point sample will be taken from the texture nearest to the texture coordinate. In GL_LINEAR magnification filtering, a bilinear (average of four samples) will be taken from the texture about the texture coordinate.

The minification filter can be set to any of the following values:

- GL_NEAREST—Takes a single point sample from the texture nearest to the texture coordinate.
- GL_LINEAR—Takes a bilinear sample from the texture nearest to the texture coordinate.
- GL_NEAREST_MIPMAP_NEAREST—Takes a single point sample from the closest mip level chosen.
- GL_NEAREST_MIPMAP_LINEAR—Takes a sample from the two closest mip levels and interpolates between those samples.
- GL_LINEAR_MIPMAP_NEAREST—Takes a bilinear fetch from the closest mip level chosen.
- GL_LINEAR_MIPMAP_LINEAR—Takes a bilinear fetch from each of the two closest mip levels and then interpolates between them. This last mode, which is typically referred to as trilinear filtering, produces the best quality of all modes.

Note: GL_NEAREST and GL_LINEAR are the only texture minification modes that do not require a complete mipmap chain to be specified for the texture. All of the other modes require that a complete mipmap chain exists for the texture.

The `MipMap2D` example in Figure 9-4 shows the difference between a polygon drawn with `GL_NEAREST` versus `GL_LINEAR_MIPMAP_LINEAR` filtering.

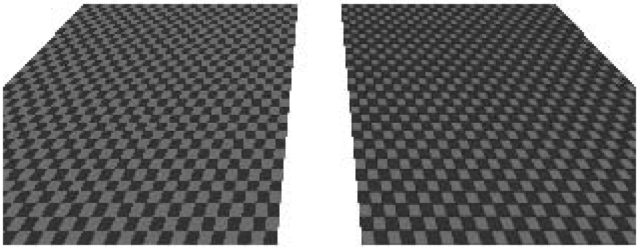


Figure 9-4 MipMap2D: Nearest Versus Trilinear Filtering

It is worth mentioning some performance implications for the texture filtering mode that you choose. If minification occurs and performance is a concern, using a mipmap filtering mode is usually the best choice on most hardware. You tend to get very poor texture cache utilization without mipmaps because fetches happen at sparse locations throughout a map. However, the higher the filtering mode you use, the greater the performance cost in the hardware. For example, on most hardware, doing bilinear filtering is less costly than doing trilinear filtering. You should choose a mode that gives you the quality desired without unduly negatively impacting performance. On some hardware, you might get high-quality filtering virtually for free, particularly if the cost of the texture filtering is not your bottleneck. This is something that needs to be tuned for the application and hardware on which you plan to run your application.

Seamless Cubemap Filtering

One change with respect to filtering that is new to OpenGL ES 3.0 relates to how cubemaps are filtered. In OpenGL ES 2.0, when a linear filter kernel fell on the edge of a cubemap border, the filtering would happen on only a single cubemap face. This would result in artifacts at the borders between cubemap faces. In OpenGL ES 3.0, cubemap filtering is now *seamless*—if the filter kernel spans more than one cubemap face, the kernel will fetch samples from all of the faces it covers. Seamless filtering results in smoother filtering along cubemap face borders. In OpenGL ES 3.0, there is nothing you need to do to enable seamless cubemap filtering; all linear filter kernels will use it automatically.

Automatic Mipmap Generation

In the `MipMap2D` example in the previous section, the application created an image for level zero of the mipmap chain. It then generated the rest of the mipmap chain by performing a box filter on each image and successively halving the width and height. This is one way to generate mipmaps, but OpenGL ES 3.0 also provides a mechanism for automatically generating mipmaps using `glGenerateMipmap`.

```
void    glGenerateMipmap(GLenum target)
```

target	the texture target to generate mipmaps for; can be `GL_TEXTURE_2D`, `GL_TEXTURE_3D`, `GL_TEXTURE_2D_ARRAY`, or `GL_TEXTURE_CUBE_MAP`

When calling `glGenerateMipmap` on a bound texture object, this function will generate the entire mipmap chain from the contents of the image in level zero. For a 2D texture, the contents of texture level zero will be successively filtered and used for each of the subsequent levels. For a cubemap, each of the cube faces will be generated from the level zero in each cube face. Of course, to use this function with cubemaps, you must have specified level zero for each cube face and each face must have a matching internal format, width, and height. For a 2D texture array, each slice of the array will be filtered as it would be for a 2D texture. Finally, for a 3D texture, the entire volume will be mipmapped by performing filtering across slices.

OpenGL ES 3.0 does not mandate that a particular filtering algorithm be used for generating mipmaps (although the specification recommends box filtering, implementations have latitude in choosing which algorithm they use). If you require a particular filtering method, then you will still need to generate the mipmaps on your own.

Automatic mipmap generation becomes particularly important when you start to use framebuffer objects for rendering to a texture. When rendering to a texture, we don't want to have to read back the contents of the texture to the CPU to generate mipmaps. Instead, `glGenerateMipmap` can be used and the graphics hardware can then potentially generate the mipmaps without ever having to read the data back to the CPU. When we cover framebuffer objects in more detail in Chapter 12, "Framebuffer Objects," this point should become clear.

Texture Coordinate Wrapping

Texture wrap modes are used to specify the behavior that occurs when a texture coordinate is outside of the range [0.0, 1.0]. The texture wrap modes are set using `glTexParameter[i|f][v]`. Such modes can be set independently for the *s*-coordinate, *t*-coordinate, and *r*-coordinate. The `GL_TEXTURE_WRAP_S` mode defines what the behavior is when the *s*-coordinate is outside of the range [0.0, 1.0], `GL_TEXTURE_WRAP_T` sets the behavior for the *t*-coordinate, and `GL_TEXTURE_WRAP_R` sets the behavior for the *r*-coordinate (the *r*-coordinate wrapping is used only for 3D textures and 2D texture arrays). In OpenGL ES, there are three wrap modes to choose from, as described in Table 9-3.

Table 9-3 Texture Wrap Modes

Texture Wrap Mode	Description
`GL_REPEAT`	Repeat the texture
`GL_CLAMP_TO_EDGE`	Clamp fetches to the edge of the texture
`GL_MIRRORED_REPEAT`	Repeat the texture and mirror

Note that the texture wrap modes also affect the behavior of filtering. For example, when a texture coordinate is at the edge of a texture, the bilinear filter kernel might span beyond the edge of the texture. In this case, the wrap mode will determine which texels are fetched for the portion of the kernel that lies outside the texture edge. You should use `GL_CLAMP_TO_EDGE` whenever you do not want any form of repeating.

In `Chapter_9/TextureWrap`, there is an example that draws a quad with each of the three different texture wrap modes. The quads have a checkerboard image applied to them and are rendered with texture coordinates in the range from [–1.0, 2.0]. The results are shown in Figure 9-5.

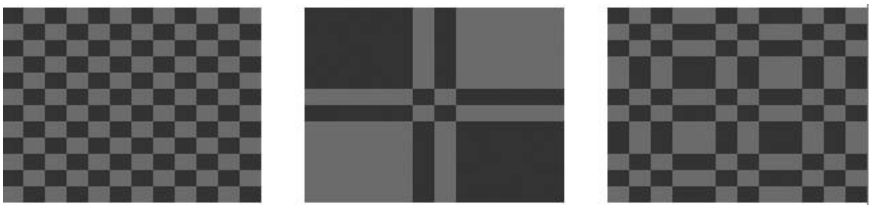


Figure 9-5 `GL_REPEAT`, `GL_CLAMP_TO_EDGE`, and `GL_MIRRORED_REPEAT` Modes

The three quads are rendered using the following setup code for the texture wrap modes:

```
// Draw left quad with repeat wrap mode
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
glUniform1f(userData->offsetLoc, -0.7f);
glDrawElements(GL_TRIANGLES, 6, GL_UNSIGNED_SHORT, indices);

// Draw middle quad with clamp to edge wrap mode
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
                GL_CLAMP_TO_EDGE);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
                GL_CLAMP_TO_EDGE);
glUniform1f(userData->offsetLoc, 0.0f);
glDrawElements(GL_TRIANGLES, 6, GL_UNSIGNED_SHORT, indices);

// Draw right quad with mirrored repeat
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
                GL_MIRRORED_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
                GL_MIRRORED_REPEAT);
glUniform1f(userData->offsetLoc, 0.7f);
glDrawElements GL_TRIANGLES, 6, GL_UNSIGNED_SHORT, indices);
```

In Figure 9-5, the quad on the far left is rendered using GL_REPEAT mode. In this mode, the texture simply repeats outside of the range [0, 1], resulting in a tiling pattern of the image. The quad in the center is rendered with GL_CLAMP_TO_EDGE mode. As you can see, when the texture coordinates go outside the range [0, 1], the texture coordinates are clamped to sample from the edge of the texture. The quad on the right is rendered with GL_MIRRORED_REPEAT, which mirrors and then repeats the image when the texture coordinates are outside the range [0, 1].

Texture Swizzles

Texture swizzles control how color components in the input R, RG, RGB, or RGBA texture map to components when fetched from in the shader. For example, an application might want a GL_RED texture to map to (0, 0, 0, R) or (R, R, R, 1) as opposed to the default mapping of (R, 0, 0, 1). The texture component that each R, G, B, and A value maps to can be independently controlled using texture swizzles set using glTexParameter[i|f][v]. The component to control is set by using GL_TEXTURE_SWIZZLE_R, GL_TEXTURE_SWIZZLE_G, GL_TEXTURE_SWIZZLE_B, or GL_TEXTURE_SWIZZLE_A. The texture value that will be the source for that component can be either GL_RED, GL_GREEN, GL_BLUE, or GL_ALPHA to fetch from the R, G, B, or A component, respectively. Additionally, the application can set the value to be the constant 0 or 1 using GL_ZERO or GL_ONE, respectively.

Texture Level of Detail

In some applications, it is useful to be able to start displaying a scene before all of the texture mipmap levels are available. For example, a GPS application that is downloading texture images over a data connection might start with the lowest-level mipmaps and display the higher levels when they become available. In OpenGL ES 3.0, this can be accomplished by using several of the arguments to glTexParameter[i|f][v]. The GL_TEXTURE_BASE_LEVEL sets the largest mipmap level that will be used for a texture. By default, this has a value of 0, but it can be set to a higher value if mipmap levels are not yet available. Likewise, GL_TEXTURE_MAX_LEVEL sets the smallest mipmap level that will be used. By default, it has a value of 1000 (beyond the largest level any texture could have), but it can be set to a lower number to control the smallest mipmap level to use for a texture.

To select which mipmap level to use for rendering, OpenGL ES automatically computes a level of detail (LOD) value. This floating-point value determines which mipmap level to filter from (and in trilinear filtering, controls how much of each mipmap is used). An application can also control the minimum and maximum LOD values with GL_TEXTURE_MIN_LOD and GL_TEXTURE_MAX_LOD. One reason it is useful to be able to control the LOD clamp separately from the base and maximum mipmap levels is to provide smooth transitioning when new mipmap levels become available. Setting just the texture base and maximum level might result in a popping artifact when new mipmap levels are available, whereas interpolating the LOD can make this transition look smoother.

Depth Texture Compare (Percentage Closest Filtering)

The last texture parameters to discuss are GL_TEXTURE_COMPARE_FUNC and GL_TEXTURE_COMPARE_MODE. These texture parameters were introduced to provide a feature known as percentage closest filtering (PCF). When performing the shadowing technique known as shadow mapping, the fragment shader needs to compare the current depth value of a fragment to the depth value in a depth texture to determine whether a fragment is within or outside of the shadow. To achieve smoother-looking shadow edges, it is useful to be able to perform bilinear filtering on the depth texture. However, when filtering a depth texture, we want the filtering to occur after we sample the depth value and compare to the current depth (or reference value). If filtering were to occur before comparison, then we would be averaging values in the depth texture, which does not provide the correct result. PCF provides the correct filtering, such that each depth value sampled is compared to the reference depth and then the results of those comparisons (0 or 1) are averaged together.

The `GL_TEXTURE_COMPARE_MODE` defaults to `GL_NONE`, but when it is set to `GL_COMPARE_REF_TO_TEXTURE`, the *r*-coordinate in the (*s*, *t*, *r*) texture coordinate will be compared with the value of the depth texture. The result of this comparison then becomes the result of the shadow texture fetch (either a value of 0 or 1, or an averaging of these values if texture filtering is enabled). The comparison function is set using `GL_TEXTURE_COMPARE_FUNC`, which can set the comparison function to `GL_LEQUAL`, `GL_EQUAL`, `GL_LESS`, `GL_GREATER`, `GL_EQUAL`, `GL_NOTEQUAL`, `GL_ALWAYS`, or `GL_NEVER`. More details on shadow mapping are covered in Chapter 14, "Advanced Programming with OpenGL ES 3.0."

Texture Formats

OpenGL ES 3.0 offers a wide range of data formats for textures. In fact, the number of formats has greatly increased from OpenGL ES 2.0. This section details the texture formats available in OpenGL ES 3.0.

As described in the previous section *Texture Objects and Loading Textures*, a 2D texture can be uploaded with either an unsized or sized internal format using `glTexImage2D`. If the texture is specified with an unsized format, the OpenGL ES implementation is free to choose the actual internal representation in which the texture data is stored. If the texture is specified with a sized format, then OpenGL ES will choose a format with at least as many bits as is specified.

Table 9-4 lists the valid combinations for specifying a texture with an unsized internal format.

If the application wants more control over how the data is stored internally, then it can use a sized internal format. The valid combinations for sized internal formats with `glTexImage2D` are listed in Tables 9-5 to 9-10. In the last two columns, "R" means renderable and "F" means filterable. OpenGL ES 3.0 mandates only that certain formats be available for rendering to or filtering from. Further, some formats can be specified with input data containing more bits than the internal format. In this case, the implementation may choose to convert to lesser bits or use a format with more bits.

Table 9-4 Valid Unsized Internal Format Combinations for `glTexImage2D`

internalFormat	format	type	Input Data
GL_RGB	GL_RGB	GL_UNSIGNED_BYTE	8/8/8 RGB 24-bit
GL_RGB	GL_RGB	GL_UNSIGNED_SHORT_5_6_5	5/6/5 RGB 16-bit
GL_RGBA	GL_RGBA	GL_UNSIGNED_BYTE	8/8/8/8 RGBA 32-bit
GL_RGBA	GL_RGBA	GL_UNSIGNED_SHORT_4_4_4_4	4/4/4/4 RGBA 16-bit
GL_RGBA	GL_RGBA	GL_UNSIGNED_SHORT_5_5_5_1	5/5/5/1 RGBA 16-bit
GL_LUMINANCE_ALPHA	GL_LUMINANCE_ALPHA	GL_UNSIGNED_BYTE	8/8 LA 16-bit
GL_LUMINANCE	GL_LUMINANCE	GL_UNSIGNED_BYTE	8L 8-bit
GL_ALPHA	GL_ALPHA	GL_UNSIGNED_BYTE	8A 8-bit

To explain the large variety of texture formats in OpenGL ES 3.0, we have organized them into the following categories: normalized texture formats, floating-point textures, integer textures, shared exponent textures, sRGB textures, and depth textures.

Normalized Texture Formats

Table 9-5 lists the set of internal format combinations that can be used to specify normalized texture formats. By "normalized," we mean that the results when fetched from the texture in the fragment shader will be in the [0.0, 1.0] range (or [–1.0, 1.0] range in the case of `*_SNORM` formats). For example, a `GL_R8` image specified with `GL_UNSIGNED_BYTE` data will take each 8-bit unsigned byte value in the range from [0, 255] and map it to [0.0, 1.0] when fetched in the fragment shader. A `GL_R8_SNORM` image specified with `GL_BYTE` data will take each 8-bit signed byte value in the range from [–128, 127] and map it to [–1.0, 1.0] when fetched.

The normalized formats can be specified with between one and four components per texel (R, RG, RGB, or RGBA). OpenGL ES 3.0 also introduces `GL_RGB10_A2`, which allows the specification of texture image data with 10 bits for each (R, G, B) value and 2 bits for each alpha value.

Table 9-5 Normalized Sized Internal Format Combinations for `glTexImage2D`

internalFormat	format	Type	Input Data	R[1]	F[2]
GL_R8	GL_RED	GL_UNSIGNED_BYTE	8-bit Red	X	X
GL_R8_SNORM	GL_RED	GL_BYTE	8-bit Red (signed)		X
GL_RG8	GL_RG	GL_UNSIGNED_BYTE	8/8 RG	X	X
GL_RG8_SNORM	GL_RG	GL_BYTE	8/8 RG (signed)		X
GL_RGB8	GL_RGB	GL_UNSIGNED_BYTE	8/8/8 RGB	X	X
GL_RGB8_SNORM	GL_RGB	GL_BYTE	8/8/8 RGB (signed)		X
GL_RGB565	GL_RGB	GL_UNSIGNED_BYTE	8/8/8 RGB	X	X
GL_RGB565	GL_RGB	GL_UNSIGNED_SHORT_565	5/6/5 RGB	X	X
GL_RGBA8	GL_RGBA	GL_UNSIGNED_BYTE	8/8/8/8 RGBA	X	X
GL_RGBA8_SNORM	GL_RGBA	GL_BYTE	8/8/8/8 RGBA (signed)		X
GL_RGB5_A1	GL_RGBA	GL_UNSIGNED_BYTE	8/8/8/8 RGBA	X	X
GL_RGB5_A1	GL_RGBA	GL_UNSIGNED_ SHORT_5_5_5_1	5/5/5/1 RGBA	X	X
GL_RGB5_A1	GL_RGBA	GL_UNSIGNED_ SHORT_2_10_10_10_ REV	10/1010/2 RGBA	X	X
GL_RGBA4	GL_RGBA	GL_UNSIGNED_BYTE	8/8/8/8 RGBA	X	X
GL_RGBA4	GL_RGBA	GL_UNSIGNED_ SHORT_4_4_4_4	4/4/4/4 RGBA	X	X
GL_RGB10_A2	GL_RGBA	GL_UNSIGNED_ INT_2_10_10_10_REV	10/10/10/2 RGBA	X	X

1. R = format is renderable.
2. F = format is filterable.

Floating-Point Texture Formats

OpenGL ES 3.0 also introduces floating-point texture formats. The majority of the floating-point formats are backed by either 16-bit half-floating-point data (described in detail in Appendix A) or 32-bit floating-point data. Floating-point texture formats can have one to four components, just like normalized texture formats (R, RG, RGB, RGBA). OpenGL ES 3.0 does not mandate that floating-point formats be used as render targets, and only 16-bit half-floating-point data is mandated to be filterable.

In addition to 16-bit and 32-bit floating-point data, OpenGL ES 3.0 introduces the 11/11/10 `GL_R11F_G11F_B10F` floating-point format. The motivation for this format is to provide higher-precision, three-channel textures while still keeping the storage of each texel at 32 bits. The use of this format may lead to higher performance than a 16/16/16 `GL_RGB16F` or 32/32/32 `GL_RGB32F` texture. This format has 11 bits for the Red and Green channel and 10 bits for the Blue channel. For the 11-bit Red and Green values, there are 6 bits of mantissa and 5 bits of exponent; the 10-bit Blue value has 5 bits of mantissa and 5 bits of exponent. The 11/11/10 format can be used only to represent positive values because there is no sign bit for any of the components. The largest value that can be represented in the 11-bit and 10-bit formats is 6.5×10^4 and the smallest value is 6.1×10^{-5}. The 11-bit format has 2.5 decimal digits of precision, and the 10-bit format has 2.32 decimal digits of precision.

Table 9-6 Valid Sized Floating-Point Internal Format Combinations for `glTexImage2D`

internalFormat	format	type	Input Data	R	F
GL_R16F	GL_RED	GL_HALF_FLOAT	16-bit Red (half-float)		X
GL_R16F	GL_RED	GL_FLOAT	32-bit Red (float)		X
GL_R32F	GL_RED	GL_FLOAT	32-bit Red (float)		
GL_RG16F	GL_RG	GL_HALF_FLOAT	16/16 RG (half-float)		X
GL_RG16F	GL_RG	GL_FLOAT	32/32 RG (float)		X
GL_RG32F	GL_RG	GL_FLOAT	32/32 RG (float)		
GL_RGB16F	GL_RGB	GL_HALF_FLOAT	16/16/16 RGB (half-float)		X

(continues)

Table 9-6 Valid Sized Floating-Point Internal Format Combinations for `glTexImage2D` *(continued)*

internalFormat	format	type	Input Data	R	F
GL_RGB16F	GL_RG	GL_FLOAT	16/16 RGB (float)		X
GL_RGB32F	GL_RG	GL_FLOAT	32/32/32 RGB (float)		
GL_R11F_G11F_B10F	GL_RGB	GL_UNSIGNED_INT_10F_11F_11F_REV	10/11/11 (float)		X
GL_R11F_G11F_B10F	GL_RGB	GL_HALF_FLOAT	16/16/16 RGB (half-float)		X
GL_R11F_G11F_B10F	GL_RGB	GL_FLOAT	32/32/32 RGB (half float)		X
GL_RGBA16F	GL_RGBA	GL_HALF_FLOAT	16/16/16/16 RGBA (half-float)		X
GL_RGBA16F	GL_RGBA	GL_FLOAT	32/32/32/32 RGBA (float)		X
GL_RGBA32F	GL_RGBA	GL_FLOAT	32/32/32/32 RGBA (float)		

Integer Texture Formats

Integer texture formats allow the specification of textures that can be fetched as integers in the fragment shader. That is, as opposed to normalized texture formats where the data are converted from their integer representation to a normalized floating-point value upon fetch in the fragment shader, the values in integer textures remain as integers when fetched in the fragment shader.

Integer texture formats are not filterable, but the R, RG, and RGBA variants can be used as a color attachment to render to in a framebuffer object. When using an integer texture as a color attachment, the alpha blend state is ignored (no blending is possible with integer render targets). The fragment shader used to fetch from integer textures and to output to an integer render target should use the appropriate signed or unsigned integer type that corresponds with the format.

Table 9-7 Valid Sized Internal Integer Texture Format Combinations for `glTexImage2D`

internalFormat	format	type	Input Data	R	F
`GL_R8UI`	`GL_RED_INTEGER`	`GL_UNSIGNED_BYTE`	8-bit Red (unsigned int)	X	
`GL_R8I`	`GL_RED_INTEGER`	`GL_BYTE`	8-bit Red (signed int)	X	
`GL_R16UI`	`GL_RED_INTEGER`	`GL_UNSIGNED_SHORT`	16-bit Red (unsigned int)	X	
`GL_R16I`	`GL_RED_INTEGER`	`GL_SHORT`	16-bit Red (signed int)	X	
`GL_R32UI`	`GL_RED_INTEGER`	`GL_UNSIGNED_INT`	32-bit Red (unsigned int)	X	
`GL_R32I`	`GL_RED_INTEGER`	`GL_INT`	32-bit Red (signed int)	X	
`GL_RG8UI`	`GL_RG_INTEGER`	`GL_UNSIGNED_BYTE`	8/8 RG (unsigned int)	X	
`GL_RG8I`	`GL_RG_INTEGER`	`GL_BYTE`	8/8 RG (signed int)	X	
`GL_RG16UI`	`GL_RG_INTEGER`	`GL_UNSIGNED_SHORT`	16/16 RG (unsigned int)	X	
`GL_RG16I`	`GL_RG_INTEGER`	`GL_SHORT`	16/16 RG (signed int)	X	
`GL_RG32UI`	`GL_RG_INTEGER`	`GL_UNSIGNED_INT`	32/32 RG (unsigned int)	X	
`GL_RG32I`	`GL_RG_INTEGER`	`GL_INT`	32/32 RG (signed int)	X	
`GL_RGBAUI`	`GL_RGBA_INTEGER`	`GL_UNSIGNED_BYTE`	8/8/8/8 RGBA (unsigned int)	X	
`GL_RGBAI`	`GL_RGBA_INTEGER`	`GL_BYTE`	8/8/8/8 RGBA (signed int)	X	
`GL_RGB8UI`	`GL_RGB_INTEGER`	`GL_UNSIGNED_BYTE`	8/8/8 RGB (unsigned int)		
`GL_RGB8I`	`GL_RGB_INTEGER`	`GL_BYTE`	8/8/8 RGB (signed int)		

(continues)

Table 9-7 Valid Sized Internal Integer Texture Format Combinations for `glTexImage2D` *(continued)*

internalFormat	format	type	Input Data	R	F
`GL_RGB16UI`	`GL_RGB_INTEGER`	`GL_UNSIGNED_SHORT`	16/16/16 RGB (unsigned int)		
`GL_RGB16I`	`GL_RGB_INTEGER`	`GL_SHORT`	16/16/16 RGB (signed int)		
`GL_RGB32UI`	`GL_RGB_INTEGER`	`GL_UNSIGNED_INT`	32/32/32 RGB (unsigned int)		
`GL_RGB32I`	`GL_RGB_INTEGER`	`GL_INT`	32/32/32 RG (signed int)		
`GL_RG32I`	`GL_RG_INTEGER`	`GL_INT`	32/32 RG (signed int)	X	
`GL_RGB10_A2_UI`	`GL_RGBA_INTEGER`	`GL_UNSIGNED_INT_2_10_10_10_REV`	10/10/10/2 RGBA (unsigned int)	X	
`GL_RGBA16UI`	`GL_RGBA_INTEGER`	`GL_UNSIGNED_SHORT`	16/16/16/16 RGBA (unsigned int)	X	
`GL_RGBA16I`	`GL_RGBA_INTEGER`	`GL_SHORT`	16/16/16/16 RGBA (signed int)	X	
`GL_RGBA32UI`	`GL_RGBA_INTEGER`	`GL_UNSIGNED_INT`	32/32/32/32 R/G/B/A (unsigned int)	X	
`GL_RGBA32I`	`GL_RGBA_INTEGER`	`GL_INT`	32/32/32/32 R/G/B/A (signed int)	X	

Shared Exponent Texture Formats

Shared exponent textures provide a way to store RGB textures that have a large range without requiring as much bit depth as used by floating-point textures. Shared exponent textures are typically used for high dynamic range (HDR) images where half- or full-floating-point data are not required. The shared exponent texture format in OpenGL ES 3.0 is `GL_RGB9_E5`. In this format, one 5-bit exponent is shared by all three RGB components. The 5-bit exponent is implicitly biased by the value 15. Each of the 9-bit values for RGB store the mantissa without a sign bit (and thus must be positive).

Upon fetch, the three RGB values are derived from the texture using the following equations:

$$R_{out} = R_{in} * 2^{(EXP - 15)}$$
$$G_{out} = G_{in} * 2^{(EXP - 15)}$$
$$B_{out} = B_{in} * 2^{(EXP - 15)}$$

If the input texture is specified in 16-bit half-float or 32-bit float, then the OpenGL ES implementation will automatically convert to the shared exponent format. The conversion is done by first determining the maximum color value:

$$MAX_c = \max(R,G,B)$$

The shared exponent is then computed using the following formula:

$$EXP = \max(-16, \text{floor}(\log_2(MAX_c))) + 16$$

Finally, the 9-bit mantissa values for RGB are computed as follows:

$$R_s = \text{floor}\left(R/(2^{(EXP - 15 + 9)}) + 0.5\right)$$
$$G_s = \text{floor}\left(G/(2^{(EXP - 15 + 9)}) + 0.5\right)$$
$$B_s = \text{floor}\left(B/(2^{(EXP - 15 + 9)}) + 0.5\right)$$

An application could use these conversion formulas to derive the 5-bit EXP and 9-bit RGB values from incoming data, or it can simply pass in the 16-bit half-float or 32-bit float data to OpenGL ES and let it perform the conversion.

Table 9-8 Valid Shared Exponent Sized Internal Format Combinations for `glTexImage2D`

internalFormat	format	type	Input Data	R	F
GL_RGB9_E5	GL_RGB	GL_UNSIGNED_INT_5_9_9_9_REV	9/9/9/ RGB with shared 5-bit exponent		X
GL_RGB9_E5	GL_RGB	GL_HALF_FLOAT	16/16/16 RGB (half-float)		X
GL_RGB9_E5	GL_RGB	GL_FLOAT	32/32/32 RGB (half-float)		X

sRGB Texture Formats

Another texture format introduced in OpenGL ES 3.0 is sRGB textures. sRGB is a nonlinear colorspace that approximately follows a power function. Most images are actually stored in the sRGB colorspace, as the nonlinearity accounts for the fact that humans can differentiate color better at different brightness levels.

If the images used for textures are authored in the sRGB colorspace but are fetched without using sRGB textures, all of the lighting calculations that occur in the shader happen in a nonlinear colorspace. That is, the textures created in standard authoring packages are stored in sRGB and remain in sRGB when fetched from in the shader. The lighting calculations then are occurring in the nonlinear sRGB space. While many applications make this mistake, it is not correct and actually results in discernibly different (and incorrect) output image.

To properly account for sRGB images, an application should use an sRGB texture format that will be converted from sRGB into a linear colorspace on fetch in the shader. Then, all calculations in the shader are done in linear colorspace. Finally, by rendering to a sRGB render target, the image will be correctly converted back to sRGB on write. It is possible to approximate sRGB → linear conversion using a shader instruction `pow(value, 2.2)` and then to approximate the linear → sRGB conversion using `pow(value, 1/2.2)`. However, it is preferable to use a sRGB texture where possible because it reduces the shader instructions and provides a more correct sRGB conversion.

Table 9-9 Valid sRGB Sized Internal Format Combinations for `glTexImage2D`

internalFormat	format	type	Input Data	R	F
GL_SRGB8	GL_RGB	GL_UNSIGNED_BYTE	8/8/8 SRGB		X
GL_SRGB8_ALPHA8	GL_RGBA	GL_UNSIGNED_BYTE	8/8/8/8 RGBA	X	X

Depth Texture Formats

The final texture format type in OpenGL ES 3.0 is depth textures. Depth textures allow the application to fetch the depth (and optionally, stencil) value from the depth attachment of a framebuffer object. This is useful in a variety of advanced rendering algorithms, including shadow mapping. Table 9-10 lists the valid depth texture formats in OpenGL ES 3.0.

Table 9-10 Valid Depth Sized Internal Format Combinations for `glTexImage2D`

internalFormat	format	type
GL_DEPTH_COMPONENT16	GL_DEPTH_COMPONENT	GL_UNSIGNED_SHORT
GL_DEPTH_COMPONENT16	GL_DEPTH_COMPONENT	GL_UNSIGNED_INT
GL_DEPTH_COMPONENT24	GL_DEPTH_COMPONENT	GL_UNSIGNED_INT
GL_DEPTH_COMPONENT32F	GL_DEPTH_COMPONENT	GL_FLOAT
GL_DEPTH24_STENCIL8	GL_DEPTH_STENCIL	GL_UNSIGNED_INT_24_8
GL_DEPTH32F_STENCIL8	GL_DEPTH_STENCIL	GL_FLOAT_32_UNSIGNED_INT_24_8_REV

Using Textures in a Shader

Now that we have covered the basics of setting up texturing, let's look at some sample shader code. The vertex–fragment shader pair in Example 9-3 from the `Simple_Texture2D` sample demonstrates the basics of how 2D texturing is done in a shader.

Example 9-3 Vertex and Fragment Shaders for Performing 2D Texturing

```
// Vertex shader
#version 300 es
layout(location = 0) in vec4 a_position;
layout(location = 1) in vec2 a_texCoord;
out vec2 v_texCoord;
void main()
{
   gl_Position = a_position;
   v_texCoord = a_texCoord;
}

// Fragment shader
#version 300 es
precision mediump float;
in vec2 v_texCoord;
layout(location = 0) out vec4 outColor;
uniform sampler2D s_texture;
void main()
{
   outColor = texture( s_texture, v_texCoord );
}
```

The vertex shader takes in a two-component texture coordinate as a vertex input and passes it as an output to the fragment shader. The fragment shader consumes that texture coordinate and uses it for the texture fetch. The fragment shader declares a uniform variable of type `sampler2D` called `s_texture`. A sampler is a special type of uniform variable that is used to fetch from a texture map. The sampler uniform will be loaded with a value specifying the texture unit to which the texture is bound; for example, specifying that a sampler with a value of 0 says to fetch from unit `GL_TEXTURE0`, specifying a value of 1 says to fetch from `GL_TEXTURE1`, and so on. Textures are bound to texture units in the OpenGL ES 3.0 API by using the `glActiveTexture` function.

`void` **`glActiveTexture`**`(GLenum` *`texture`*`)`

`texture`	the texture unit to make active: `GL_TEXTURE0`, `GL_TEXTURE1`, … , `GL_TEXTURE31`

The function `glActiveTexture` sets the current texture unit so that subsequent calls to `glBindTexture` will bind the texture to the currently active unit. The number of texture units available to the fragment shader on an implementation of OpenGL ES can be queried for by using `glGetintegerv` with the parameter `GL_MAX_TEXTURE_IMAGE_UNITS`. The number of texture units available to the vertex shader can be queried for by using `glGetIntegerv` with the parameter `GL_MAX_VERTEX_TEXTURE_IMAGE_UNITS`.

The following example code from the `Simple_Texture2D` example shows how the sampler and texture are bound to the texture unit.

```
// Get the sampler locations
userData->samplerLoc = glGetUniformLocation(
                              userData->programObject,
                              "s_texture");

// ...
// Bind the texture
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, userData->textureId);

// Set the sampler texture unit to 0
glUniformli(userData->samplerLoc, 0);
```

At this point, we have the texture loaded, the texture bound to texture unit 0, and the sampler set to use texture unit 0. Going back to the fragment shader in the `Simple_Texture2D` example, we see that the shader code then uses the built-in function `texture` to fetch from the texture map. The `texture` built-in function takes the form shown here:

```
vec4   texture(sampler2D sampler,   vec2 coord[,
                float bias])
```

`sampler`	a sampler bound to a texture unit specifying the texture from which to fetch.
`coord`	a 2D texture coordinate used to fetch from the texture map.
`bias`	an optional parameter that provides a mipmap bias used for the texture fetch. This allows the shader to explicitly bias the computed LOD value used for mipmap selection.

The `texture` function returns a `vec4` representing the color fetched from the texture map. The way the texture data is mapped into the channels of this color depends on the base format of the texture. Table 9-11 shows the way in which texture formats are mapped to `vec4` colors. The texture swizzle (described in the *Texture Swizzles* section earlier in this chapter) determines how the values from each of these components map to components in the shader.

Table 9-11 Mapping of Texture Formats to Colors

Base Format	**Texel Data Description**
`GL_RED`	(R, 0.0, 0.0, 1.0)
`GL_RG`	(R, G, 0.0, 1.0)
`GL_RGB`	(R, G, B, 1.0)
`GL_RGBA`	(R, G, B, A)
`GL_LUMINANCE`	(L, L, L, 1.0)
`GL_LUMINANCE_ALPHA`	(L, L, L, A)
`GL_ALPHA`	(0.0, 0.0, 0.0, A)

In the case of the `Simple_Texture2D` example, the texture was loaded as `GL_RGB` and the texture swizzles were left at the default values, so the result of the texture fetch will be a `vec4` with values (R, G, B, 1.0).

Example of Using a Cubemap Texture

Using a cubemap texture is very similar to using a 2D texture. The example `Simple_TextureCubemap` demonstrates drawing a sphere with a simple cubemap. The cubemap contains six 1 × 1 faces, each with a different color. The code in Example 9-4 is used to load the cubemap texture.

Example 9-4 Loading a Cubemap Texture

```
GLuint CreateSimpleTextureCubemap()
{
   GLuint textureId;
   // Six 1 x 1 RGB faces
   GLubyte cubePixels[6][3] =
   {
      // Face 0 - Red
      255, 0, 0,
      // Face 1 - Green,
      0, 255, 0,
      // Face 2 - Blue
      0, 0, 255,
      // Face 3 - Yellow
      255, 255, 0,
      // Face 4 - Purple
      255, 0, 255,
      // Face 5 - White
      255, 255, 255
   };

   // Generate a texture object
   glGenTextures(1, &textureId);

   // Bind the texture object
   glBindTexture(GL_TEXTURE_CUBE_MAP, textureId);

   // Load the cube face - Positive X
   glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_X, 0, GL_RGB, 1, 1,
                0, GL_RGB, GL_UNSIGNED_BYTE, &cubePixels[0]);

   // Load the cube face - Negative X
   glTexImage2D(GL_TEXTURE_CUBE_MAP_NEGATIVE_X, 0, GL_RGB, 1, 1,
             0, GL_RGB, GL_UNSIGNED_BYTE, &cubePixels[1]);

   // Load the cube face - Positive Y
   glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_Y, 0, GL_RGB, 1, 1,
                0, GL_RGB, GL_UNSIGNED_BYTE, &cubePixels[2]);

   // Load the cube face - Negative Y
   glTexImage2D(GL_TEXTURE_CUBE_MAP_NEGATIVE_Y, 0, GL_RGB, 1, 1,
                0, GL_RGB, GL_UNSIGNED_BYTE, &cubePixels[3]);
```

Example 9-4 Loading a Cubemap Texture *(continued)*

```
   // Load the cube face - Positive Z
   glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_Z, 0, GL_RGB, 1, 1,
                0, GL_RGB, GL_UNSIGNED_BYTE, &cubePixels[4]);

   // Load the cube face - Negative Z
   glTexImage2D(GL_TEXTURE_CUBE_MAP_NEGATIVE_Z, 0, GL_RGB, 1, 1,
                0, GL_RGB, GL_UNSIGNED_BYTE, &cubePixels[5]);

   // Set the filtering mode
   glTexParameteri(GL_TEXTURE_CUBE_MAP, GL_TEXTURE_MIN_FILTER,
                   GL_NEAREST);
   glTexParameteri(GL_TEXTURE_CUBE_MAP, GL_TEXTURE_MAG_FILTER,
                   GL_NEAREST);
   return   textureId;
}
```

This code loads each individual cubemap face with 1 × 1 RGB pixel data by calling `glTexImage2D` for each cubemap face. The shader code to render the sphere with a cubemap is provided in Example 9-5.

Example 9-5 Vertex and Fragment Shader Pair for Cubemap Texturing

```
// Vertex shader
#version 300 es
layout(location = 0) in vec4 a_position;
layout(location = 1) in vec3 a_normal;
out vec3 v_normal;
void main()
{
   gl_Position = a_position;
   v_normal = a_normal;
}

// Fragment shader
#version 300 es
precision mediump float;
in vec3 v_normal;
layout(location = 0) out vec4 outColor;
uniform samplerCube s_texture;
void main()
{
   outColor = texture( s_texture, v_normal );
}
```

The vertex shader takes in a position and a normal as vertex inputs. A normal is stored at each vertex of the sphere that will be used as a texture coordinate. The normal is passed to the fragment shader. The fragment shader then uses the built-in function `texture` to fetch from the cubemap using the normal as a texture coordinate. The `texture` built-in function for cubemaps takes the form shown here:

```
vec4   texture(samplerCube sampler, vec3 coord[,
                    float bias])
```

sampler	the sampler is bound to a texture unit specifying the texture from which to fetch.
coord	a 3D texture coordinate used to fetch from the cubemap.
bias	an optional parameter that provides a mipmap bias used for the texture fetch. This allows the shader to explicitly bias the computed LOD value used for mipmap selection.

The function for fetching a cubemap is very similar to a 2D texture. The only difference is that the texture coordinate has three components instead of two and the sampler type must be `samplerCube`. The same method is used to bind the cubemap texture and load the sampler as is used for the `Simple_Texture2D` example.

Loading 3D Textures and 2D Texture Arrays

As discussed earlier in the chapter, in addition to 2D textures and cubemaps, OpenGL ES 3.0 includes 3D textures and 2D texture arrays. The function to load 3D textures and 2D texture arrays is `glTexImage3D`, which is very similar to `glTexImage2D`.

```
void    glTexImage3D(GLenum target,   GLint level,
                     GLenum internalFormat,
                     GLsizei width, GLsizei height,
                     GLsizei depth, GLint border,
                     GLenum format, GLenum type,
                     const void* pixels)
```

target	specifies the texture target; should be `GL_TEXTURE_3D` or `GL_TEXTURE_2D_ARRAY`.

`level`	specifies which mip level to load. The base level is specified by 0, followed by an increasing level for each successive mipmap.
`internal Format`	the internal format for the texture storage; can be either an unsized base internal format or a sized internal format. The full valid `internalFormat`, `format`, and `type` combinations are provided in Tables 9-4 through 9-10.
`width`	the width of the image in pixels.
`height`	the height of the image in pixels.
`depth`	the number of slices of the 3D texture.
`border`	this parameter is ignored in OpenGL ES. It was kept for compatibility with the desktop OpenGL interface. Should be 0.

`format`	the format of the incoming texture data; can be
	`GL_RED`
	`GL_RED_INTEGER`
	`GL_RG`
	`GL_RG_INTEGER`
	`GL_RGB`
	`GL_RGB_INTEGER`
	`GL_RGBA`
	`GL_RGBA_INTEGER`
	`GL_DEPTH_COMPONENT`
	`GL_DEPTH_STENCIL`
	`GL_LUMINANCE_ALPHA`
	`GL_ALPHA`

`type`	the type of the incoming pixel data; can be
	`GL_UNSIGNED_BYTE`
	`GL_BYTE`
	`GL_UNSIGNED_SHORT`
	`GL_SHORT`
	`GL_UNSIGNED_INT`
	`GL_INT`
	`GL_HALF_FLOAT`
	`GL_FLOAT`

`pixels`	contains the actual pixel data for the image. The data must contain (`width * height * depth`) number of pixels with the appropriate number of bytes per pixel based on the format and type specification. The image data should be stored as a sequence of 2D texture slices.

Once a 3D texture or 2D texture array has been loaded using `glTexImage3D`, the texture can be fetched in the shader using the `texture` built-in function.

```
vec4   texture(sampler3D sampler, vec3 coord[,
                 float bias])

vec4   texture(sampler2DArray sampler, vec3 coord[,
                 float bias])
```

sampler	a sampler bound to a texture unit specifying the texture to fetch from.
coord	a 3D texture coordinate used to fetch from the texture map.
bias	an optional parameter that provides a mipmap bias use for the texture fetch. This allows the shader to explicitly bias the computed LOD value used for mipmap selection.

Note that the *r*-coordinate is a floating-point value. For 3D textures, depending on the filtering mode set, the texture fetch might span two slices of the volume.

Compressed Textures

Thus far, we have been dealing with textures that were loaded with uncompressed texture image data. OpenGL ES 3.0 also supports the loading of compressed texture image data. There are several reasons why compressing textures is desirable. The first and obvious reason to compress textures is to reduce the memory footprint of the textures on the device. A second, less obvious reason to compress textures is that a memory bandwidth savings occurs when you fetch from compressed textures in a shader. Finally, compressed textures might allow you to reduce the download size of your application by reducing the amount of image data that must be stored.

In OpenGL ES 2.0, the core specification did not define any compressed texture image formats. That is, the OpenGL ES 2.0 core simply defined a mechanism whereby compressed texture image data could be loaded, but no compressed formats were defined. As a result, many vendors, including Qualcomm, ARM, Imagination Technologies, and NVIDIA, provided hardware-specific texture compression extensions. In turn, developers of OpenGL ES 2.0 applications had to support different texture compression formats on different platforms and hardware.

OpenGL ES 3.0 has improved this situation by introducing standard texture compression formats that all vendors must support. Ericsson Texture Compression (ETC2 and EAC) was offered as a royalty-free standard to Khronos, and it was adopted as the standard texture compression format for OpenGL ES 3.0. There are variants of EAC for compressing one- and two-channel data as well as variants of ETC2 for compressing three- and four-channel data. The function used to load compressed image data for 2D textures and cubemaps is `glCompressedTexImage2D`; the corresponding function for 2D texture arrays is `glCompressedTexImage3D`. Note that ETC2/EAC is not supported for 3D textures (only 2D textures and 2D texture arrays), but `glCompressedTexImage3D` can be used to potentially load vendor-specific 3D texture compression formats.

```
void    glCompressedTexImage2D(GLenum target,  GLint level,
                               GLenum internalFormat,
                               GLsizei width,
                               GLsizei height,
                               GLint border,
                               GLsizei imageSize,
                               const void *data)

void    glCompressedTexImage3D(GLenum target, GLint level,
                               GLenum internalFormat,
                               GLsizei width,
                               GLsizei height,
                               GLsizei depth,
                               GLint border,
                               GLsizei imageSize,
                               const void *data)
```

target	specifies the texture target; should be `GL_TEXTURE_2D` or either the `GL_TEXTURE_CUBE_MAP_*` (for `glCompressedTexImage2D`) or `GL_TEXTURE_3D` or `GL_TEXTURE_2D_ARRAY` (for `glCompressedTexImage3D`).
level	specifies which mip level to load. The base level is specified by 0, followed by an increasing level for each successive mipmap.
internalFormat	the internal format for the texture storage. The standard compressed texture formats in OpenGL ES 3.0 are described in Table 9-12.

(continues)

(continued)	
width	the width of the image in pixels.
height	the height of the image in pixels.
depth	(`glCompressedTexImage3D` only) the depth of the image in pixels (or number of slices for a 2D texture array).
border	this parameter is ignored in OpenGL ES; it was kept for compatibility with the desktop OpenGL interface. Should be 0.
imageSize	the size of the image in bytes.
data	contains the actual compressed pixel data for the image; must hold *imageSize* number of bytes.

The standard ETC compressed texture formats supported by OpenGL ES 3.0 are listed in Table 9-12. All of the ETC formats store compressed image data in 4 × 4 blocks. Table 9-12 lists the number of bits per pixel in each of the ETC formats. The size of an individual ETC image can be computed from the bits-per-pixel (bpp) ratio as follows:

sizeInBytes = max(width, 4) * max(height, 4) * bpp/8

Table 9-12 Standard Texture Compression Formats

internalFormat	Size (bits per pixel)	Description
GL_COMPRESSED_R11_EAC	4	Single-channel unsigned compressed GL_RED format
GL_COMPRESSED_SIGNED_R11_EAC	4	Single-channel signed compressed GL_RED format
GL_COMPRESSED_RG11_EAC	8	Two-channel unsigned compressed GL_RG format
GL_COMPRESSED_SIGNED_ RG11_EAC	8	Two-channel signed compressed GL_RG format
GL_COMPRESSED_RGB8_ETC2	4	Three-channel unsigned compressed GL_RGB format
GL_COMPRESSED_SRGB8_ETC2	4	Three-channel unsigned compressed GL_RGB format in sRGB colorspace

Table 9-12 Standard Texture Compression Formats *(continued)*

internalFormat	Size (bits per pixel)	Description
`GL_COMPRESSED_RGB8_ PUNCHTHROUGH_ALPHA1_ETC2`	4	Four-channel unsigned compressed `GL_RGBA` format with 1-bit alpha
`GL_COMPRESSED_SRGB8_ PUNCHTHROUGH_ALPHA1_ETC2`	4	Four-channel unsigned compressed `GL_RGBA` format with 1-bit alpha in sRGB colorspace
`GL_COMPRESSED_RGBA8_ ETC2_EAC`	8	Four-channel unsigned compressed `GL_RGBA` format
`GL_COMPRESSED_SRGBA8_ ETC2_EAC`	8	Four-channel unsigned compressed `GL_RGBA` format in sRGB colorspace

Once a texture has been loaded as a compressed texture, it can be used for texturing in exactly the same way as an uncompressed texture. The details of the ETC2/EAC formats are beyond our scope here, and most developers will never write their own compressors. Freely available tools for generating ETC images include the open-source libKTX library from Khronos (http://khronos.org/opengles/sdk/tools/KTX/), the rg_etc project (https://code.google.com/p/rg-etc1/), the ARM Mali Texture Compression Tool, Qualcomm TexCompress (included in the Adreno SDK), and Imagination Technologies PVRTexTool. We would encourage readers to evaluate the available tools and choose the one that fits best with their development environment/platform.

Note that all implementations of OpenGL ES 3.0 will support the formats listed in Table 9-12. In addition, some implementations may support vendor-specific compressed formats not listed in Table 9-12. If you attempt to use a texture compression format on an OpenGL ES 3.0 implementation that does not support it, a `GL_INVALID_ENUM` error will be generated. It is important that you check that the OpenGL ES 3.0 implementation exports the extension string for any vendor-specific texture compression format you use. If it does not, you must fall back to using an uncompressed texture format.

In addition to checking extension strings, there is another method you can use to determine which texture compression formats are supported by an implementation. That is, you can query for `GL_NUM_COMPRESSED_TEXTURE_FORMATS` using `glGetIntegerv` to determine the number of compressed image formats supported. You can then query for `GL_COMPRESSED_TEXTURE_FORMATS` using `glGetIntegerv`, which will return an array of `GLenum` values. Each `GLenum` value in the array will be a compressed texture format that is supported by the implementation.

Texture Subimage Specification

After uploading a texture image using `glTexImage2D`, it is possible to update portions of the image. This ability would be useful if you wanted to update just a subregion of an image. The function to load a portion of a 2D texture image is `glTexSubImage2D`.

```
void   glTexSubImage2D(GLenum target,   GLint level,
                       GLint xoffset,   GLint yoffset,
                       GLsizei width,   GLsizei height,
                       GLenum format,   GLenum type,
                       const void* pixels)
```

target	specifies the texture target, either `GL_TEXTURE_2D` or one of the cubemap face targets (`GL_TEXTURE_CUBE_MAP_POSITIVE_X`, `GL_TEXTURE_CUBE_MAP_NEGATIVE_X`, and so on)
level	specifies which mip level to update
xoffset	the *x* index of the texel to start updating from
yoffset	the *y* index of the texel to start updating from
width	the width of the subregion of the image to update
height	the height of the subregion of the image to update
format	the format of the incoming texture data; can be `GL_RED`, `GL_RED_INTEGER`, `GL_RG`, `GL_RG_INTEGER`, `GL_GL_RGB`, `GL_RGB_INTEGER`, `GL_RGBA`, `GL_RGBA_INTEGER`, `GL_DEPTH_COMPONENT`, `GL_DEPTH_STENCIL`, `GL_LUMINANCE_ALPHA`, `GL_LUMINANCE`, or `GL_ALPHA`
type	the type of the incoming pixel data; can be `GL_UNSIGNED_BYTE`, `GL_BYTE`, `GL_UNSIGNED_SHORT`, `GL_SHORT`, `GL_UNSIGNED_INT`, `GL_INT`, `GL_HALF_FLOAT`, `GL_FLOAT`, `GL_UNSIGNED_SHORT_5_6_5`, `GL_UNSIGNED_SHORT_4_4_4_4`, `GL_UNSIGNED_SHORT_5_5_5_l`, `GL_UNSIGNED_INT_2_10_10_10_REV`, `GL_UNSIGNED_INT_10F_11F_11F_REV`, `GL_UNSIGNED_INT_5_9_9_9_REV`, `GL_UNSIGNED_INT_24_8`, or `GL_FLOAT_32_UNSIGNED_INT_24_8_REV`
pixels	contains the actual pixel data for the subregion of the image

This function will update the region of texels in the range (*xoffset*, *yoffset*) to (*xoffset* + *width* – 1, *yoffset* + *height* – 1). Note that to use this function, the texture must already be fully specified. The range of the subimage must be within the bounds of the previously specified texture image. The data in the `pixels` array must be aligned to the alignment that is specified by `GL_UNPACK_ALIGNMENT` with `glPixelStorei`.

There is also a function for updating a subregion of a compressed 2D texture image—that is, `glCompressedTexSubImage2D`. The definition for this function is more or less the same as that for `glTexImage2D`.

```
void   glCompressedTexSubImage2D(GLenum target,
                                 GLint level, GLint xoffset,
                                 GLint yoffset, GLsizei width,
                                 GLsizei height,
                                 GLenum format,
                                 GLenum imageSize,
                                 const void* pixels)
```

target	specifies the texture target, either `GL_TEXTURE_2D` or one of the cubemap face targets (`GL_TEXTURE_CUBE_MAP_POSITIVE_X`, `GL_TEXTURE_CUBE_MAP_NEGATIVE_X`, and so on)
level	specifies which mip level to update
xoffset	the *x* index of the texel to start updating from
yoffset	the *y* index of the texel to start updating from
width	the width of the subregion of the image to update
height	the height of the subregion of the image to update
format	the compressed texture format to use; must be the format with which the image was originally specified
pixels	contains the actual pixel data for the subregion of the image

In addition, as with 2D textures, it is possible to update just a subregion of an existing 3D texture and 2D texture arrays using `glTexSubImage3D`.

```
void      glTexSubImage3D(GLenum target,   GLint level,
                          GLint xoffset,  GLint yoffset,
                          GLint zoffset,  GLsizei width,
                          GLsizei height,  GLsizei depth,
                          GLenum format,   GLenum type,
                          const void* pixels)
```

(continues)

(continued)

target	specifies the texture target, either GL_TEXTURE_3D or GL_TEXTURE_2D_ARRAY
level	specifies which mip level to update
xoffset	the *x* index of the texel to start updating from
yoffset	the *y* index of the texel to start updating from
zoffset	the *z* index of the texel to start updating from
width	the width of the subregion of the image to update
height	the height of the subregion of the image to update
depth	the depth of the subregion of the image to update
format	the format of the incoming texture data; can be GL_RED, GL_RED_INTEGER, GL_RG, GL_RG_INTEGER, GL_GL_RGB, GL_RGB_INTEGER, GL_RGBA, GL_RGBA_INTEGER, GL_DEPTH_COMPONENT, GL_DEPTH_STENCIL, GL_LUMINANCE_ALPHA, GL_LUMINANCE, or GL_ALPHA
type	the type of the incoming pixel data; can be GL_UNSIGNED_BYTE, GL_BYTE, GL_UNSIGNED_SHORT, GL_SHORT, GL_UNSIGNED_INT, GL_INT, GL_HALF_FLOAT, GL_FLOAT, GL_UNSIGNED_SHORT_5_6_5, GL_UNSIGNED_SHORT_4_4_4_4, GL_UNSIGNED_SHORT_5_5_5_1, GL_UNSIGNED_INT_2_10_10_10_REV, GL_UNSIGNED_INT_10F_11F_11F_REV, GL_UNSIGNED_INT_5_9_9_9_REV, GL_UNSIGNED_INT_24_8, or GL_FLOAT_32_UNSIGNED_INT_24_8_REV
pixels	contains the actual pixel data for the subregion of the image

glTexSubImage3D behaves just like glTexSubImage2D, with the only difference being that the subregion contains a zoffset and a depth for specifying the subregion within the depth slices to update. For compressed 2D texture arrays, it is also possible to update a subregion of the texture using glCompressedTexSubImage3D. For 3D textures, this function can be used only with vendor-specific 3D compressed texture formats, because ETC2/EAC are supported only for 2D textures and 2D texture arrays.

```
void    glCompressedTexSubImage3D(GLenum target,
                                  GLint level,
                                  GLint xoffset,
                                  GLint yoffset,
                                  GLint zoffset,
                                  GLsizei width,
                                  GLsizei height,
                                  GLsizei depth,
                                  GLenum format,
                                  GLenum imageSize,
                                  const void* data)
```

target	specifies the texture target, either `GL_TEXTURE_2D` or `GL_TEXTURE_2D_ARRAY`)
level	specifies which mip level to update
xoffset	the *x* index of the texel to start updating from
yoffset	the *y* index of the texel to start updating from
zoffset	the z index of the texel to start updating from
width	the width of the subregion of the image to update
height	the height of the subregion of the image to update
depth	the depth of the subregion of the image to update
format	the compressed texture format to use; must be the format with which the image was originally specified
pixels	contains the actual pixel data for the subregion of the image

Copying Texture Data from the Color Buffer

An additional texturing feature that is supported in OpenGL ES 3.0 is the ability to copy data from a color buffer to a texture. This can be useful if you want to use the results of rendering as an image in a texture. Framebuffer objects (Chapter 12) provide a fast method for doing render-to-texture and are a faster method than copying image data. However, if performance is not a concern, the ability to copy image data out of the color buffer can be a useful feature.

The color buffer from which to copy image data from can be set using the function `glReadBuffer`. If the application is rendering to a double-buffered EGL displayable surface, then `glReadBuffer` must be set to `GL_BACK` (the back buffer—the default state). Recall that OpenGL ES 3.0 supports only double-buffered EGL displayable surfaces. As a consequence, all OpenGL

ES 3.0 applications that draw to the display will have a color buffer for both the front and back buffers. The buffer that is currently the front or back is determined by the most recent call to `eglSwapBuffers` (described in Chapter 3, "An Introduction to EGL"). When you copy image data out of the color buffer from a displayable EGL surface, you will always be copying the contents of the back buffer. If you are rendering to an EGL pbuffer, then copying will occur from the pbuffer surface. Finally, if you are rendering to a framebuffer object, then the framebuffer object color attachment to copy from is set by calling `glReadBuffer` with `GL_COLOR_ATTACHMENTi`.

```
void    glReadBuffer(GLenum mode)
```

mode	specifies the color buffer to read from. This will set the source color buffer for future calls to `glReadPixels`, `glCopyTexImage2D`, `glCopyTexSubImage2D`, and `glCopyTexSubImage3D`. The value can be either `GL_BACK`, `GL_COLOR_ATTACHMENTi`, or `GL_NONE`.

The functions to copy data from the color buffer to a texture are `glCopyTexImage2D`, `glCopyTexSubImage2D`, and `glCopyTexSubImage3D`.

```
void    glCopyTexImage2D(GLenum target,   GLint level,
                         GLenum internalFormat, GLint x,
                         GLint y, GLsizei width,
                         GLsizei height,   Glint border   )
```

target	specifies the texture target, either `GL_TEXTURE_2D` or one of the cubemap face targets (`GL_TEXTURE_CUBE_MAP_POSITIVE_X`, `GL_TEXTURE_CUBE_MAP_NEGATIVE_X, and so on`)
level	specifies which mip level to load
internalFormat	the internal format of the image; can be `GL_ALPHA`, `GL_LUMINANCE`, `GL_LUMINANCE_ALPHA`, `GL_RGB`, `GL_RGBA`, `GL_R8`, `GL_RG8`, `GL_RGB565`, `GL_RGB8`, `GL_RGBA4`, `GL_RGB5_A1`, `GL_RGBA8`, `GL_RGB10_A2`, `GL_SRGB8`, `GL_SRGB8_ALPHA8`,

	`GL_R8I`, `GL_R8UI`, `GL_R16I`, `GL_R16UI`, `GL_R32I`, `GL_R32UI`, `GL_RG8I`, `GL_RG8UI`, `GL_RG16I`, `GL_RG16UI`, `GL_RG32I`, `GL_RG32UI`, `GL_RGBA8I`, `GL_RGBA8UI`, `GL_RGB10_A2UI`, `GL_RGBA16I`, `GL_RGBA16UI`, `GL_RGBA32I`, or `GL_RGBA32UI`
x	the *x* window-coordinate of the lower-left rectangle in the framebuffer to read from
y	the *y* window-coordinate of the lower-left rectangle in the framebuffer to read from
width	the width in pixels of the region to read
height	the height in pixels of the region to read
border	borders are not supported in OpenGL ES 3.0, so this parameter must be 0

Calling this function will cause the texture image to be loaded with the pixels in the color buffer from region (*x*, *y*) to (*x* + *width* – 1, *y* + *height* – 1). This width and height of the texture image will be the size of the region copied from the color buffer. You should use this information to fill the entire contents of the texture.

In addition, you can update just the subregion of an already-specified image using `glCopyTexSubImage2D`.

```
void   glCopyTexSubImage2D(GLenum target,
                           GLint level,    GLint xoffset,
                           GLint yoffset, GLint x, GLint y,
                           GLsizei width,   GLsizei height)
```

target	specifies the texture target, either `GL_TEXTURE_2D` or one of the cubemap face targets (`GL_TEXTURE_CUBE_MAP_POSITIVE_X, GL_TEXTURE_CUBE_MAP_NEGATIVE_X, and so on`)
level	specifies which mip level to update
xoffset	the *x* index of the texel to start updating from
yoffset	the *y* index of the texel to start updating from
x	the *x* window-coordinate of the lower-left rectangle in the framebuffer to read from
y	the *y* window-coordinate of the lower-left rectangle in the framebuffer to read from

(continues)

(continued)

width	the width in pixels of the region to read
height	the height in pixels of the region to read

This function will update the subregion of the image starting at (*xoffset*, *yoffset*) to (*xoffset* + *width* – 1, *yoffset* + *height* – 1) with the pixels in the color buffer from (*x*, *y*) to (*x* + *width* – 1, *y* + *height* – 1).

Finally, you can also copy the contents of the color buffer into a slice (or subregion of a slice) of a previously specified 3D texture or 2D texture array using `glCopyTexSubImage3D`.

```
void glCopyTexSubImage3D(GLenum target,   GLint level,
                         GLint xoffset, GLint yoffset,
                         GLint zoffset,   GLint x, GLint y,
                         GLsizei width,   GLsizei height)
```

target	specifies the texture target, either `GL_TEXTURE_3D` or `GL_TEXTURE_2D_ARRAY`
level	specifies which mip level to update
xoffset	the *x* index of the texel to start updating from
yoffset	the *y* index of the texel to start updating from
zoffset	the *z* index of the texel to start updating from
x	the *x* window-coordinate of the lower-left rectangle in the framebuffer to read from
y	the *y* window-coordinate of the lower-left rectangle in the framebuffer to read from
width	the width in pixels of the region to read
height	the height in pixels of the region to read

One thing to keep in mind with `glCopyTexImage2D`, `glCopyTexSubImage2D`, and `glCopyTexSubImage3D` is that the texture image format cannot have more components than the color buffer. In other words, when copying data out of the color buffer, it is possible to convert to a format with fewer components, but not with more. Table 9-13 shows the valid format conversions when doing a texture copy. For example, you can copy an RGBA image into any of the possible formats, but you cannot copy an RGB into an RGBA image because no alpha component exists in the color buffer.

Table 9-13 Valid Format Conversions for `glCopyTex*Image*`

	(To) Texture Format						
Color Format (From)	A	L	LA	R	RG	RGB	RGBA
R	N	Y	N	Y	N	N	N
RG	N	Y	N	Y	Y	N	N
RGB	N	Y	N	Y	Y	Y	N
RGBA	Y	Y	Y	Y	Y	Y	Y

Sampler Objects

Previously in the chapter, we covered how to set texture parameters such as filter modes, texture coordinate wrap modes, and LOD settings using `glTexParameter[i|f][v]`. The issue with using `glTexParameter[i|f][v]` is that it can result in a significant amount of unnecessary API overhead. Very often, an application will use the same texture settings for a large number of textures. In such a case, having to set the sampler state with `glTexParameter[i|f][v]` for every texture object can result in a lot of extra overhead. To mitigate this problem, OpenGL ES 3.0 introduces *sampler objects* that separate sampler state from texture state. In short, all of the settings that can be set with `glTexParameter[i|f][v]` can be set for a sampler object and can be bound for use with a texture unit in a single function call. Sampler objects can be used across many textures and, therefore, reduce API overhead.

The function used to generate sampler objects is `glGenSamplers`.

```
void    glGenSamplers(GLsizei n,   GLuint *samplers)
```

n	specifies the number of sampler objects to generate
samplers	an array of unsigned integers that will hold *n* sampler object IDs

Sampler objects also need to be deleted when an application no longer needs them. This can be done using `glDeleteSamplers`.

```
void    glDeleteSamplers(GLsizei n,  const GLuint *samplers)
```

n	specifies the number of sampler objects to delete
samplers	an array of unsigned integers that hold *n* sampler object IDs to delete

Once sampler object IDs have been generated with `glGenSamplers`, the application must bind the sampler object to use its state. Sampler objects are bound to texture units. Binding the sampler object to the texture unit supersedes any of the state set in the texture object using `glTexParameter[i|f][v]`. The function used to bind a sampler object is `glBindSampler`.

```
void    glBindSampler(GLenum unit, GLuint sampler)
```

unit	specifies the texture unit to bind the sampler object to
sampler	the handle to the sampler object to bind

If the *sampler* passed to `glBindSampler` is 0 (the default sampler), then the state set for the texture object will be used. The sampler object state can be set using `glSamplerParameter[f|i][v]`. The parameters that can be set by `glSamplerParameter[f|i][v]` are the exact same ones that are set by using `glTexParameter[i|f][v]`. The only difference is that the state is set to the sampler object rather than the texture object.

```
void    glSamplerParameteri(GLuint sampler, GLenum pname,
                            GLint param)
void    glSamplerParameteriv(GLuint sampler, GLenum pname,
                             const GLint *params)
void    glSamplerParameterf(GLuint sampler, GLenum pname,
                            GLfloat param)
void    glSamplerParameterfv(GLuint sampler, GLenum pname,
                             const GLfloat *params)
```

sampler	the sampler object to set
pname	the parameter to set; one of GL_TEXTURE_BASE_LEVEL GL_TEXTURE_COMPARE_FUNC GL_TEXTURE_COMPARE_MODE GL_TEXTURE_MIN_FILTER GL_TEXTURE_MAG_FILTER GL_TEXTURE_MIN_LOD GL_TEXTURE_MAX_LOD GL_TEXTURE_MAX_LEVEL GL_TEXTURE_SWIZZLE_R GL_TEXTURE_SWIZZLE_G GL_TEXTURE_SWIZZLE_B GL_TEXTURE_SWIZZLE_A GL_TEXTURE_WRAP_S GL_TEXTURE_WRAP_T GL_TEXTURE_WRAP_R
params	the value (or array of values for the "v" entrypoints) to set the texture parameter to If *pname* is GL_TEXTURE_MAG_FILTER, then *param* can be GL_NEAREST or GL_LINEAR If *pname* is GL_TEXTURE_MIN_FILTER, then *param* can be GL_NEAREST, GL_LINEAR, GL_NEAREST_MIPMAP_NEAREST, GL_NEAREST_MIPMAP_LINEAR, GL_LINEAR_MIPMAP_NEAREST, or GL_LINEAR_MIPMAP_LINEAR If *pname* is GL_TEXTURE_WRAP_S, GL_TEXTURE_WRAP_R, or GL_TEXTURE_WRAP_T, then *param* can be GL_REPEAT, GL_CLAMP_TO_EDGE, or GL_MIRRORED_REPEAT If *pname* is GL_TEXTURE_COMPARE_FUNC, then *param* can be GL_LEQUAL, GL_EQUAL, GL_LESS, GL_GREATER, GL_EQUAL, GL_NOTEQUAL, GL_ALWAYS, or GL_NEVER If *pname* is GL_TEXTURE_COMPARE_MODE, then *param* can be GL_COMPARE_REF_TO_TEXTURE or GL_NONE If *pname* is GL_TEXTURE_SWIZZLE_R, GL_TEXTURE_SWIZZLE_G, GL_TEXTURE_SWIZZLE_B, or GL_TEXTURE_SWIZZLE_A, then *param* can be GL_RED, GL_GREEN, GL_BLUE, GL_ALPHA, GL_ZERO, or GL_ONE

Immutable Textures

Another feature introduced in OpenGL ES 3.0 to help improve application performance is *immutable textures*. As discussed earlier in this chapter, an application specifies each mipmap level of a texture independently using functions such as `glTexImage2D` and `glTexImage3D`. The problem this creates for the OpenGL ES driver is that it cannot determine until draw time whether a texture has been fully specified. That is, it has to check whether each mipmap level or subimage has matching formats, whether each level has the correct dimensions, and whether there is sufficient memory. This draw time check can be costly and can be avoided by using immutable textures.

The idea behind immutable textures is simple: The application specifies the format and size of a texture before loading it with data. In doing so, the texture format becomes immutable and the OpenGL ES driver can perform all consistency and memory checks up-front. Once a texture has become immutable, its format and dimensions cannot change. However, the application can still load it with image data by using `glTexSubImage2D`, `glTexSubImage3D`, or `glGenerateMipMap`, or by rendering to the texture.

To create an immutable texture, an application would bind the texture using `glBindTexture` and then allocate its immutable storage using `glTexStorage2D` or `glTexStorage3D`.

```
void    glTexStorage2D(GLenum target, GLsizei levels,
                       GLenum internalFormat, GLsizei width,
                       GLsizei height)
void    glTexStorage3D(GLenum target, GLsizei levels,
                       GLenum internalFormat, GLsizei width,
                       GLsizei height, GLsizei depth)
```

target	specifies the texture target, either `GL_TEXTURE_2D` or one of the cubemap face targets (`GL_TEXTURE_CUBE_MAP_POSITIVE_X`, `GL_TEXTURE_CUBE_MAP_NEGATIVE_X`, and so on) for `glTexStorage2D`, or `GL_TEXTURE_3D` or `GL_TEXTURE_2D_ARRAY` for `glTexStorage3D`
levels	specifies the number of mipmap levels
internalFormat	the sized internal format for the texture storage; the full list of valid *internalFormat* values is the same as the valid sized `internalFormat` values for `glTexImage2D` provided in the Texture Objects and Loading Textures section earlier in this chapter.

width	the width of the base image in pixels
height	the height of the base image in pixels
depth	(glTexStorage3D only) the depth of the base image in pixels

Once the immutable texture is created, it is invalid to call glTexImage*, glCompressedTexImage*, glCopyTexImage*, or glTexStorage* on the texture object. Doing so will result in a GL_INVALID_OPERATION error being generated. To fill the immutable texture with image data, the application needs to use glTexSubImage2D, glTexSubImage3D, or glGenerateMipMap, or else render to the image as a texture (by using it as an attachment to a framebuffer object).

Internally, when glTexStorage* is used, OpenGL ES marks the texture object as being immutable by setting GL_TEXTURE_IMMUTABLE_FORMAT to GL_TRUE and GL_TEXTURE_IMMUTABLE_LEVELS to the number of levels passed to glTexStorage*. The application can query for these values by using glGetTexParameter[i|f][v], although it cannot set them directly. The glTexStorage* function must be used to set up the immutable texture parameters.

Pixel Unpack Buffer Objects

In Chapter 6, "Vertex Attributes, Vertex Arrays, and Buffer Objects," we introduced buffer objects, concentrating the discussion on vertex buffer objects (VBOs) and copy buffer objects. As you will recall, buffer objects allow the storage of data in server-side (or GPU) memory as opposed to client-side (or host) memory. The advantage of using buffer objects is that they reduce the transfer of data from CPU to GPU and, therefore, can improve performance (as well as reduce memory utilization). OpenGL ES 3.0 also introduces *pixel unpack buffer objects* that are bound and specified with the GL_PIXEL_UNPACK_BUFFER target. The functions that operate on pixel unpack buffer objects are described in Chapter 6. Pixel unpack buffer objects allow the specification of texture data that resides in server-side memory. As a consequence, the pixel unpack operations glTexImage*, glTexSubImage*, glCompressedTexImage*, and glCompressedTexSubImage* can come directly from a buffer object. Much like VBOs with glVertexAttribPointer, if a pixel unpack buffer object is bound during one of those calls, the *data* pointer is an offset into the pixel unpack buffer rather than a pointer to client memory.

Pixel unpack buffer objects can be used to stream texture data to the GPU. The application could allocate a pixel unpack buffer and then map regions of the buffer for updates. When the calls to load the data to OpenGL are made (e.g., `glTexSubImage*`), these functions can return immediately because the data already resides in the GPU (or can be copied at a later time, but an immediate copy does not need to be made as it does with client-side data). We recommend using pixel unpack buffer objects in situations where the performance/memory utilization of texture upload operations is important for the application.

Summary

This chapter covered how to use textures in OpenGL ES 3.0. We introduced the various types of textures: 2D, 3D, cubemaps, and 2D texture arrays. For each texture type, we showed how the texture can be loaded with data either in full, in subimages, or by copying data from the framebuffer. We detailed the wide range of texture formats available in OpenGL ES 3.0, which include normalized texture formats, floating-point textures, integer textures, shared exponent textures, sRGB textures, and depth textures. We covered all of the texture parameters that can be set for texture objects, including filter modes, wrap modes, depth texture comparison, and level-of-detail settings. We explored how to set texture parameters using the more efficient sampler objects. Finally, we showed how to create immutable textures that can help reduce the draw-time overhead of using textures. We also saw how textures can be read in the fragment shader with several example programs. With all this information under your belt, you are well on your way toward using OpenGL ES 3.0 for many advanced rendering effects. Next, we cover more details of the fragment shader that will help you further understand how textures can be used to achieve a wide range of rendering techniques.

Chapter 10

Fragment Shaders

Chapter 9, “Texturing,” introduced you to the basics of creating and applying textures in the fragment shader. In this chapter, we provide more details on the fragment shader and describe some of its uses. In particular, we focus on how to implement fixed-function techniques using the fragment shader. The topics we cover in this chapter include the following:

- Fixed function fragment shaders
- Programmable fragment shader overview
- Multitexturing
- Fog
- Alpha test
- User clip planes

In Figure 10-1, we have previously covered the vertex shader, primitive assembly, and rasterization stages of the programmable pipeline. We have talked about using textures in the fragment shader. Now, we focus on the fragment shader portion of the pipeline and fill in the remaining details on writing fragment shaders.

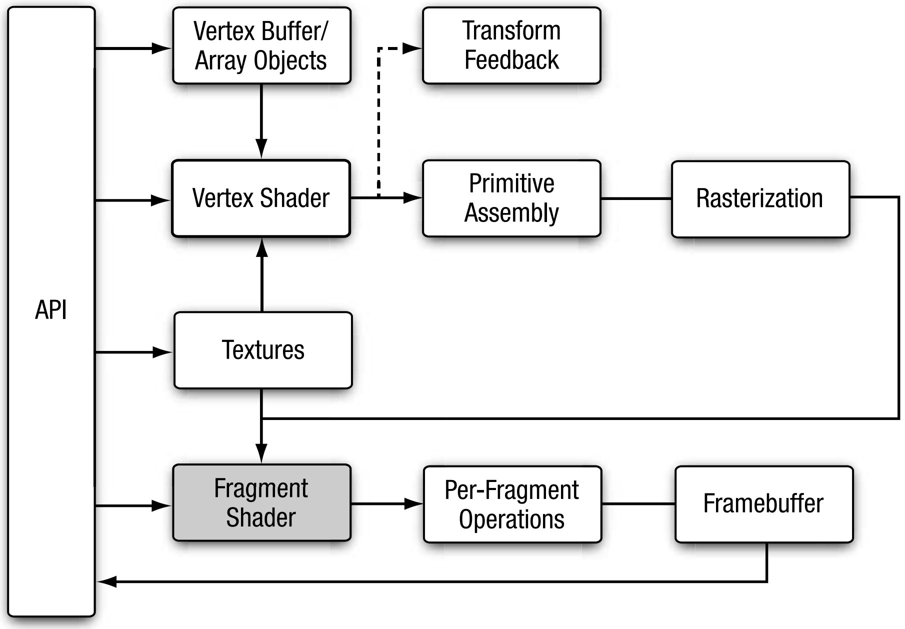


Figure 10-1 OpenGL ES 3.0 Programmable Pipeline

Fixed-Function Fragment Shaders

Readers who are new to the programmable fragment pipeline but have worked with OpenGL ES 1.x (or earlier versions of desktop OpenGL) are probably familiar with the fixed-function fragment pipeline. Before diving into details of the fragment shader, we think it is worthwhile to briefly review the old fixed-function fragment pipeline. This will give you an understanding of how the old fixed-function pipeline maps into fragment shaders. It's a good way to start before moving into more advanced fragment programming techniques.

In OpenGL ES 1.1 (and fixed-function desktop OpenGL), you had a limited set of equations that could be used to determine how to combine the various inputs to the fragment shader. In the fixed-function pipeline, you essentially had three inputs you could use: the interpolated vertex color, the texture color, and the constant color. The vertex color would typically hold either a precomputed color or the result of the vertex lighting computation. The texture color came from fetching from whichever texture was bound using the primitive's texture coordinates and the constant color could be set for each texture unit.

The set of equations you could use to combine these inputs together was quite limited. For example, in OpenGL ES 1.1, the equations listed in Table 10-1 were available. The inputs *A*, *B*, and *C* to these equations could come from the vertex color, texture color, or constant color.

Table 10-1 OpenGL ES 1.1 RGB Combine Functions

RGB Combine Function	**Equation**
`REPLACE`	A
`MODULATE`	$A \times B$
`ADD`	$A + B$
`ADD_SIGNED`	$A + B - 0.5$
`INTERPOLATE`	$A \times C + B \times (1 - C)$
`SUBTRACT`	$A - B$
`DOT3_RGB` (and `DOT3_RGBA`)	$4 \times ((A.r - 0.5) \times (B.r - 0.5) + (A.g - 0.5) \times (B.g - 0.5) + (A.b - 0.5) \times (B.b \times 0.5))$

There actually was a great number of interesting effects one could achieve, even with this limited set of equations. However, this was far from programmable, as the fragment pipeline could be configured only in a very fixed set of ways.

So why are we reviewing this history here? It helps give an understanding of how traditional fixed-function techniques can be achieved with shaders. For example, suppose we had configured the fixed-function pipeline with a single base texture map that we wanted to modulate (multiply) by the vertex color. In fixed-function OpenGL ES (or OpenGL), we would enable a single texture unit, choose a combine equation of `MODULATE`, and set up the inputs to the equation to come from the vertex color and texture color. The code to do this in OpenGL ES 1.1 is provided here for reference:

```
glTexEnvi(GL_TEXTURE_ENV,  GL_TEXTURE_ENV_MODE, GL_COMBINE);
glTexEnvi(GL_TEXTURE_ENV,  GL_COMBINE_RGB, GL_MODULATE);
glTexEnvi(GL_TEXTURE_ENV,  GL_SOURCE0_RGB, GL_PRIMARY_COLOR);
glTexEnvi(GL_TEXTURE_ENV,  GL_SOURCE1_RGB, GL_TEXTURE);
glTexEnvi(GL_TEXTURE_ENV,  GL_COMBINE_ALPHA, GL_MODULATE);
glTexEnvi(GL_TEXTURE_ENV,  GL_SOURCE0_ALPHA, GL_PRIMARY_COLOR);
glTexEnvi(GL_TEXTURE_ENV,  GL_SOURCE1_ALPHA, GL_TEXTURE);
```

This code configures the fixed-function pipeline to perform a modulate ($A \times B$) between the primary color (the vertex color) and the texture color. If this code doesn't make sense to you, don't worry, as none of it exists in OpenGL ES 3.0. Rather, we are simply trying to show how this would map to a fragment shader. In a fragment shader, this same modulate computation could be accomplished as follows:

```
#version 300 es
precision mediump float;
uniform sampler2D s_tex0;
in vec2 v_texCoord;
in vec4 v_primaryColor;
layout(location = 0) out vec4 outColor;
void main()
{
   outColor = texture(s_tex0, v_texCoord) * v_primaryColor;
}
```

The fragment shader performs the exact same operations that would be performed by the fixed-function setup. The texture value is fetched from a sampler (that is bound to texture unit 0) and a 2D texture coordinate is used to look up that value. Then, the result of that texture fetch is multiplied by `v_primaryColor`, an input value that is passed in from the vertex shader. In this case, the vertex shader would have passed the color to the fragment shader.

It is possible to write a fragment shader that would perform the equivalent computation as any possible fixed-function texture combine setup. It is also possible, of course, to write shaders with much more complex and varied computations than just fixed functions would allow. However, the point of this section was just to drive home how we have transitioned from fixed-function to programmable shaders. Now, we begin to look at some specifics of fragment shaders.

Fragment Shader Overview

The fragment shader provides a general-purpose programmable method for operating on fragments. The inputs to the fragment shader consist of the following:

- Inputs (or varyings)—Interpolated data produced by the vertex shader. The outputs of the vertex shader are interpolated across the primitive and passed to the fragment shader as inputs.
- Uniforms—State used by the fragment shader. These are constant values that do not vary per fragment.

- Samplers—Used to access texture images in the shader.
- Code—Fragment shader source or binary that describes the operations that will be performed on the fragment.

The output of the fragment shader is one or more fragment colors that get passed on to the per-fragment operations portion of the pipeline (the number of output colors depends on how many color attachments are being used). The inputs and outputs to the fragment shader are illustrated in Figure 10-2.

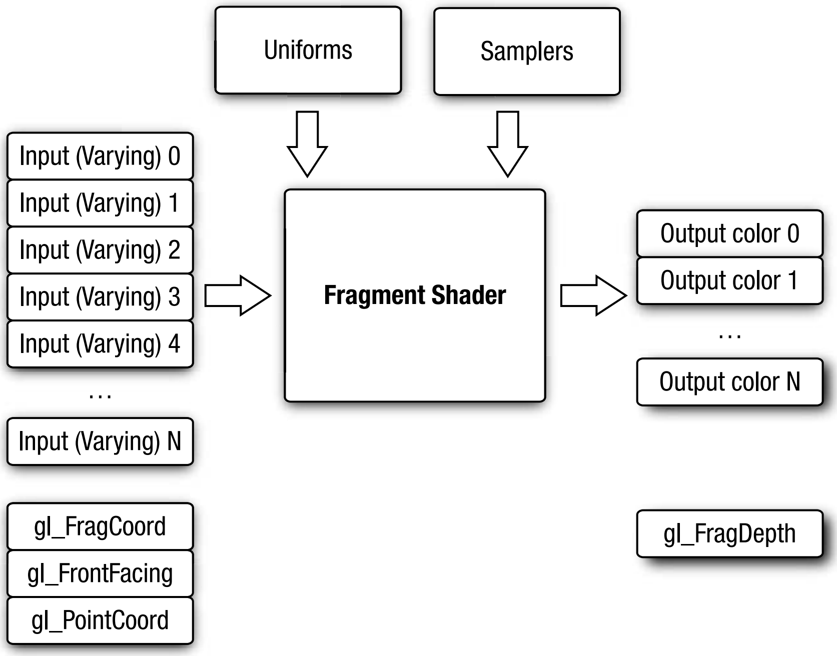


Figure 10-2 OpenGL ES 3.0 Fragment Shader

Built-In Special Variables

OpenGL ES 3.0 has built-in special variables that are output by the fragment shader or are input to the fragment shader. The following built-in special variables are available to the fragment shader:

- `gl_FragCoord`—A read-only variable that is available in the fragment shader. This variable holds the window relative coordinates (*x*, *y*, *z*, 1/*w*) of the fragment. There are a number of algorithms where it can be useful to know the window coordinates of the current fragment. For example, you can use the window coordinates as offsets into a texture fetch into a random noise map whose value is used to rotate a filter kernel on a shadow map. This technique is used to reduce shadow map aliasing.

- `gl_FrontFacing`—A read-only variable that is available in the fragment shader. This boolean variable has a value of `true` if the fragment is part of a front-facing primitive and `false` otherwise.
- `gl_PointCoord`—A read-only variable that can be used when rendering point sprites. It holds the texture coordinate for the point sprite that is automatically generated in the [0, 1] range during point rasterization. In Chapter 14, "Advanced Programming with OpenGL ES 3.0," there is an example of rendering point sprites that uses this variable.
- `gl_FragDepth`—A write-only output variable that, when written to in the fragment shader, overrides the fragment's fixed-function depth value. This functionality should be used sparingly (and only when necessary) because it can disable depth optimization in many GPUs. For example, many GPUs have a feature called Early-Z where the depth test is performed ahead of executing the fragment shader. The benefit of using Early-Z is that fragments that fail the depth test are never shaded (thus saving performance). However, when `gl_FragDepth` is used, this feature must be disabled because the GPU does not know the depth value ahead of executing the fragment shader.

Built-In Constants

The following built-in constants are also relevant to the fragment shader:

```
const mediump int gl_MaxFragmentInputVectors = 15;
const mediump int gl_MaxTextureImageUnits = 16;
const mediump int gl_MaxFragmentUniformVectors = 224;
const mediump int gl_MaxDrawBuffers = 4;
const mediump int gl_MinProgramTexelOffset = -8;
const mediump int gl_MaxProgramTexelOffset = 7;
```

The built-in constants describe the following maximum terms:

- `gl_MaxFragmentInputVectors`—The maximum number of fragment shader inputs (or varyings). The minimum value supported by all ES 3.0 implementations is 15.

- `gl_MaxTextureImageUnits`—The maximum number of texture image units that are available. The minimum value supported by all ES 3.0 implementations is 16.
- `gl_MaxFragmentUniformVectors`—The maximum number of `vec4` uniform entries that can be used inside a fragment shader. The minimum value supported by all ES 3.0 implementations is 224. The number of `vec4` uniform entries that can actually be used by a developer can vary from implementation to implementation and from one fragment shader to another. This issue is described in Chapter 8, "Vertex Shaders," and the same issue applies to fragment shaders.
- `gl_MaxDrawBuffers`—The maximum number of multiple render targets (MRTs) supported. The minimum value supported by all ES 3.0 implementations is 4.
- `gl_MinProgramTexelOffset/gl_MaxProgramTexelOffset`—The minimum and maximum offsets supported by the offset parameter to the `texture*Offset()` built-in ESSL functions.

The values specified for each built-in constant are the minimum values that must be supported by all OpenGL ES 3.0 implementations. It is possible that implementations may support values greater than the minimum values described. The actual hardware-dependent values for fragment shader built-in values can also be queried from API code. The following code shows how you would query the values of `gl_MaxTextureImageUnits` and `gl_MaxFragmentUniformVectors`:

```
GLint   maxTextureImageUnits, maxFragmentUniformVectors;

glGetIntegerv(GL_MAX_TEXTURE_IMAGE_UNITS,
                &maxTextureImageUnits);
glGetIntegerv(GL_MAX_FRAGMENT_UNIFORM_VECTORS
                &maxFragmentUniformVectors);
```

Precision Qualifiers

Precision qualifiers were briefly introduced in Chapter 5, "OpenGL ES Shading Language" and were covered in detail in Chapter 8, "Vertex Shaders." Please review those sections for full details on precision qualifiers. We remind you here that there is no default precision for fragment shaders. As a consequence, every fragment shader must declare a default precision (or provide precision qualifiers for all variable declarations).

Implementing Fixed-Function Techniques Using Shaders

Now that we have given an overview of fragment shaders, we will demonstrate how to implement several fixed-function techniques using shaders. The fixed-function pipeline in OpenGL ES l.x and desktop OpenGL provided APIs to perform multitexturing, fog, alpha test, and user clip planes. Although none of these techniques is provided explicitly in OpenGL ES 3.0, all of them can still be implemented using shaders. This section reviews each of these fixed-function processes and provides example fragment shaders that demonstrate each technique.

Multitexturing

We start with multitexturing, which is a very common operation in fragment shaders used for combining multiple texture maps. For example, a technique that has been used in many games, such as Quake III, is to store precomputed lighting from radiosity calculations in a texture map. That map is then combined with the base texture map in the fragment shader to represent static lighting. Many other examples of using multiple textures exist, some of which we cover in Chapter 14, "Advanced Programming with OpenGL ES 3.0." For example, often a texture map is used to store a specular exponent and mask to attenuate and mask specular lighting contributions. Many games also use normal maps, which are textures that store normal information at a higher level of detail than per-vertex normals so that lighting can be computed in the fragment shader.

The point of mentioning this information here is to highlight that you have now learned about all of the parts of the API that are needed to accomplish multitexturing techniques. In Chapter 9, "Texturing," you learned how to load textures on various texture units and fetch from them in the fragment shader. Combining the textures in various ways in the fragment shader is simply a matter of employing the many operators and built-in functions that exist in the shading language. Using these techniques, you can easily achieve all of the effects that were made possible with the fixed-function fragment pipeline in previous versions of OpenGL ES.

An example of using multiple textures is provided in the `Chapter_10/MultiTexture` example, which renders the image in Figure 10-3.

This example loads a base texture map and light map texture and combines them in the fragment shader on a single quad. The fragment shader for the sample program is provided in Example 10-1.

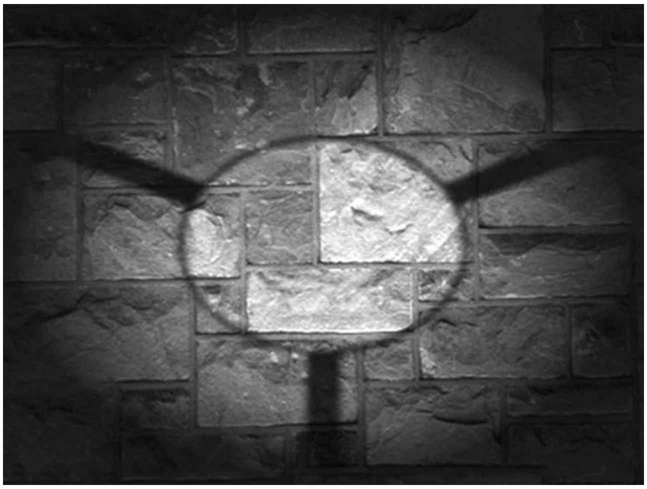


Figure 10-3 Multitextured Quad

Example 10-1 Multitexture Fragment Shader

```
#version 300 es
precision mediump float;
in vec2 v_texCoord;
layout(location = 0) out vec4 outColor;
uniform sampler2D s_baseMap;
uniform sampler2D s_lightMap;
void main()
{
   vec4 baseColor;
   vec4 lightColor;

   baseColor = texture( s_baseMap, v_texCoord );
   lightColor = texture( s_lightMap, v_texCoord );
   // Add a 0.25 ambient light to the texture light color
   outColor = baseColor * (lightColor + 0.25);
}
```

The fragment shader has two samplers, one for each of the textures. The relevant code for setting up the texture units and samplers follows.

```
// Bind the base map
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, userData->baseMapTexId);
// Set the base map sampler to texture unit 0
glUniform1i(userData->baseMapLoc, 0);
```

```
// Bind the light map
glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE_2D, userData->lightMapTexId);
// Set the light map sampler to texture unit 1
glUniform1i(userData->lightMapLoc, 1);
```

As you can see, this code binds each of the individual texture objects to textures units 0 and 1. The samplers are set with values to bind the samplers to the respective texture units. In this example, a single texture coordinate is used to fetch from both of the maps. In typical light mapping, there would be a separate set of texture coordinates for the base map and light map. The light maps are typically paged into a single large texture and the texture coordinates can be generated using offline tools.

Fog

A common technique that is used in rendering 3D scenes is the application of fog. In OpenGL ES 1.1, fog was provided as a fixed-function operation. One of the reasons fog is such a prevalent technique is that it can be used to reduce draw distances and remove “popping” of geometry as it comes in closer to the viewer.

There are a number of possible ways to compute fog, and with programmable fragment shaders you are not limited to any particular equation. Here we show how you would go about computing linear fog with a fragment shader. To compute any type of fog, we will need two inputs: the distance of the pixel to the eye and the color of the fog. To compute linear fog, we also need the minimum and maximum distance range that the fog should cover.

The equation for the linear fog factor

$$F = \frac{MaxDist - EyeDist}{MaxDist - MinDist}$$

computes a linear fog factor to multiply the fog color by. This color gets clamped in the [0.0, 1.0] range and then is linear interpolated with the overall color of a fragment to compute the final color. The distance to the eye is best computed in the vertex shader and interpolated across the primitive using a varying variable.

A PVRShaman (.POD) workspace is provided as an example in the `Chapter_10/PVR_LinearFog` folder that demonstrates the fog computation. Figure 10-4 is a screenshot of the workspace. PVRShaman is a shader development integrated development environment (IDE) that is part of the Imagination Technologies PowerVR SDK downloadable from http://powervrinsider.com/. Several subsequent examples in the book use PVRShaman to demonstrate various shading techniques.

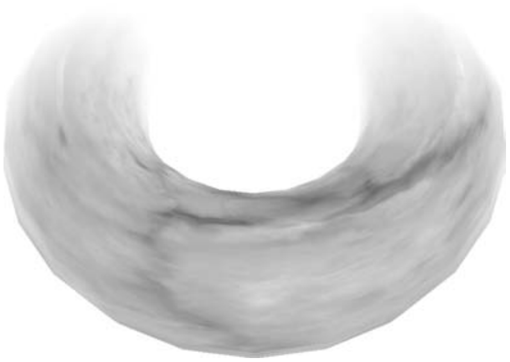


Figure 10-4 Linear Fog on Torus in PVRShaman

Example 10-2 provides the code for the vertex shader that computes the distance to the eye.

Example 10-2 Vertex Shader for Computing Distance to Eye

```
#version 300 es
uniform mat4 u_matViewProjection;
uniform mat4 u_matView;
uniform vec4 u_eyePos;

in vec4 a_vertex;
in vec2 a_texCoord0;

out vec2 v_texCoord;
out float v_eyeDist;

void main( void )
{
   // Transform vertex to view space
   vec4 vViewPos = u_matView * a_vertex;
   // Compute the distance to eye
   v_eyeDist = sqrt( (vViewPos.x - u_eyePos.x) *
                     (vViewPos.x - u_eyePos.x) +
                     (vViewPos.y - u_eyePos.y) *
                     (vViewPos.y - u_eyePos.y) +
                     (vViewPos.z - u_eyePos.z) *
                     (vViewPos.z - u_eyePos.z) );

   gl_Position = u_matViewProjection * a_vertex;
   v_texCoord = a_texCoord0.xy;
}
```

The important part of this vertex shader is the computation of the v_eyeDist vertex shader output variable. First, the input vertex is transformed into view space using the view matrix and stored in vViewPos. Then, the distance from this point to the u_eyePos uniform variable is computed. This computation gives us the distance in eye space from the viewer to the transformed vertex. We can use this value in the fragment shader to compute the fog factor, as shown in Example 10-3.

Example 10-3 Fragment Shader for Rendering Linear Fog

```
#version 300 es
precision mediump float;

uniform vec4 u_fogColor;
uniform float u_fogMaxDist;
uniform float u_fogMinDist;
uniform sampler2D baseMap;

in vec2 v_texCoord;
in float v_eyeDist;

layout( location = 0 ) out vec4 outColor;

float computeLinearFogFactor()
{
   float factor;
   // Compute linear fog equation
   factor = (u_fogMaxDist - v_eyeDist) /
            (u_fogMaxDist - u_fogMinDist );

   // Clamp in the [0, 1] range
   factor = clamp( factor, 0.0, 1.0 );
   return factor;
}

void main( void )
{
   float fogFactor = computeLinearFogFactor();
   vec4 baseColor = texture( baseMap, v_texCoord );

   // Compute final color as a lerp with fog factor
   outColor = baseColor * fogFactor +
              u_fogColor * (1.0 - fogFactor);
}
```

In the fragment shader, the `computeLinearFogFactor()` function performs the computation for the linear fog equation. The minimum and maximum fog distances are stored in uniform variables, and the interpolated eye distance that was computed in the vertex shader is used to compute the fog factor. The fog factor is then used to perform a linear interpolation (abbreviated as "lerp" in Example 10-3) between the base texture color and the fog color. The result is that we now have linear fog and can easily adjust the distances and colors by changing the uniform values.

Note that with the flexibility of programmable fragment shaders, it is very easy to implement other methods to compute fog. For example, you could easily compute exponential fog by simply changing the fog equation. Alternatively, rather than compute fog based on distance to the eye, you could compute fog based on distance to the ground. A number of possible fog effects can be easily achieved with small modifications to the fog computations provided here.

Alpha Test (Using Discard)

A common effect used in 3D applications is to draw primitives that are fully transparent in certain fragments. This is very useful for rendering something like a chain-link fence. Representing a fence using geometry would require a significant amount of primitives. However, an alternative to using geometry is to store a mask value in a texture that specifies which texels should be transparent. For example, you could store the chain-link fence in a single RGBA texture, where the RGB values represent the color of the fence and the A value represents the mask of whether the texture is transparent. Then you could easily render a fence using just one or two triangles and masking off pixels in the fragment shader.

In traditional fixed-function rendering, this effect was achieved using the alpha test. The alpha test allowed you to specify a comparison test whereby if comparison of an alpha value of a fragment with a reference value failed, that fragment would be killed. That is, if a fragment failed the alpha test, the fragment would not be rendered. In OpenGL ES 3.0, there is no fixed-function alpha test, but the same effect can be achieved in the fragment shader using the `discard` keyword.

The PVRShaman example in `Chapter_10/PVR_AlphaTest` gives a very simple example of doing the alpha test in the fragment shader, as shown in Figure 10-5.

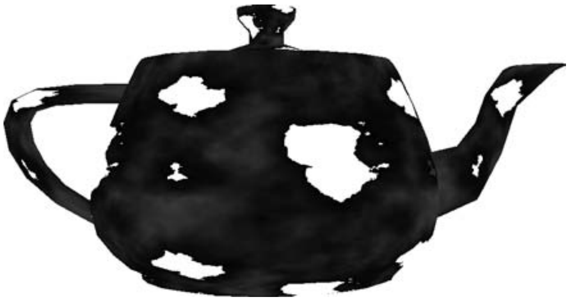


Figure 10-5 Alpha Test Using Discard

Example 10-4 gives the fragment shader code for this example.

Example 10-4 Fragment Shader for Alpha Test Using Discard

```
#version 300 es
precision mediump float;

uniform sampler2D baseMap;

in vec2 v_texCoord;
layout( location = 0 ) out vec4 outColor;
void main( void )
{
   vec4 baseColor = texture( baseMap, v_texCoord );
   // Discard all fragments with alpha value less than 0.25
   if( baseColor.a < 0.25 )
   {
      discard;
   }
   else
   {
      outColor = baseColor;
   }
}
```

In this fragment shader, the texture is a four-channel RGBA texture. The alpha channel is used for the alpha test. The alpha color is compared with 0.25; if it is less than that value, the fragment is killed using `discard`.

Otherwise, the fragment is drawn using the texture color. This technique can be used for implementing the alpha test by simply changing the comparison or alpha reference value.

User Clip Planes

As described in Chapter 7, "Primitive Assembly and Rasterization," all primitives are clipped against the six planes that make up the view frustum. However, sometimes a user might want to clip against one or more additional user clip planes. There are a number of reasons why you might want to clip against user clip planes. For example, when rendering reflections, you need to flip the geometry about the reflection plane and then render it into an off-screen texture. When rendering into the texture, you need to clip the geometry against the reflection plane, which requires a user clip plane.

In OpenGL ES 1.1, user clip planes could be provided to the API via a plane equation and the clipping would be handheld automatically. In OpenGL ES 3.0, you can still accomplish this same effect, but now you need to do it yourself in the shader. The key to implementing user clip planes is using the `discard` keyword, which was introduced in the previous section.

Before showing you how to implement user clip planes, let's review the basics of the mathematics. A plane is specified by the equation

$$Ax + By + Cz + D = 0$$

The vector (A, B, C) represents the normal of the plane and the value D is the distance of the plane along that vector from the origin. To figure out whether a point should or should not be clipped against a plane, we need to evaluate the distance from a point P to a plane with the equation

$$\text{Dist} = (A \times P{\cdot}x) + (B \times P{\cdot}y) + (C \times P{\cdot}z) + D$$

If the distance is less than 0, we know the point is behind the plane and should be clipped. If the distance is greater than or equal to 0, it should not be clipped. Note that the plane equation and P must be in the same coordinate space. A PVRShaman example is provided in the `Chapter_10/PVR_ClipPlane` workspace and illustrated in Figure 10-6. In the example, a teapot is rendered and clipped against a user clip plane.

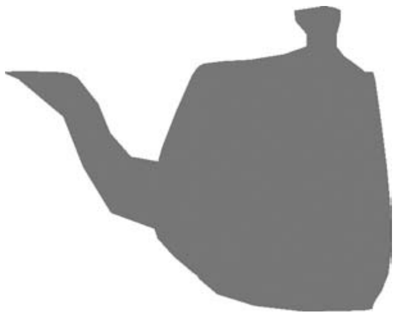


Figure 10-6 User Clip Plane Example

The first thing the shader needs to do is compute the distance to the plane, as mentioned earlier. This could be done in either the vertex shader (and passed into a varying) or the fragment shader. It is cheaper in terms of performance to do this computation in the vertex shader rather than having to compute the distance in every fragment. The vertex shader listing in Example 10-5 shows the distance-to-plane computation.

Example 10-5 User Clip Plane Vertex Shader

```
#version 300 es
uniform vec4 u_clipPlane;
uniform mat4 u_matViewProjection;
in vec4 a_vertex;

out float v_clipDist;

void main( void )
{
   // Compute the distance between the vertex and
   // the clip plane
   v_clipDist = dot( a_vertex.xyz, u_clipPlane.xyz ) +
                u_clipPlane.w;
   gl_Position = u_matViewProjection * a_vertex;
}
```

The `u_clipPlane` uniform variable holds the plane equation for the clip plane and is passed into the shader using `glUniform4f`. The `v_clipDist` varying variable then stores the computed clip distance. This value is passed into the fragment shader, which uses the interpolated distance to determine whether the fragment should be clipped, as shown in Example 10-6.

Example 10-6 User Clip Plane Fragment Shader

```
#version 300 es
precision mediump float;
in float v_clipDist;
layout( location = 0 ) out vec4 outColor;
void main( void )
{
   // Reject fragments behind the clip plane
   if( v_clipDist < 0.0 )
      discard;
   outColor = vec4( 0.5, 0.5, 1.0, 0.0 );
}
```

As you can see, if the `v_clipDist` varying variable is negative, this means the fragment is behind the clip plane and must be discarded. Otherwise, the fragment is processed as usual. This simple example just demonstrates the computations needed to implement user clip planes. You can easily implement multiple user clip planes by simply computing multiple clip distances and having multiple discard tests.

Summary

This chapter introduced implementing several rendering techniques using fragment shaders. We focused on implementing fragment shaders that accomplish techniques that were part of fixed-function OpenGL ES 1.1. Specifically, we showed you how to implement multitexturing, linear fog, alpha test, and user clip planes. The number of shading techniques that become possible when using programmable fragment shaders is nearly limitless. This chapter gave you grounding in how to develop some fragment shaders that you can build on to create more sophisticated effects.

Now we are just ready to introduce a number of advanced rendering techniques. The next topics to cover before getting there are what happens after the fragment shader—namely, per-fragment operations and framebuffer objects. These topics are covered in the next two chapters.

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Chapter 11

Fragment Operations

This chapter discusses the operations that can be applied either to the entire framebuffer or to individual fragments after the execution of the fragment shader in the OpenGL ES 3.0 fragment pipeline. As you'll recall, the output of the fragment shader is the fragment's colors and depth value. The following operations occur after fragment shader execution and can affect the visibility and final color of a pixel:

- Scissor box testing
- Stencil buffer testing
- Depth buffer testing
- Multisampling
- Blending
- Dithering

The tests and operations that a fragment goes through on its way to the framebuffer are shown in Figure 11-1.

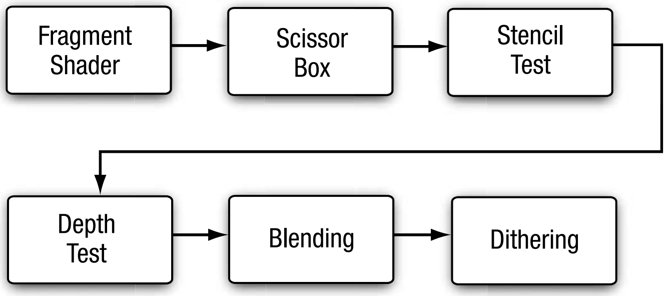

Figure 11-1 The Post-Shader Fragment Pipeline

As you might have noticed, there isn't a stage named "multisampling." Multisampling is an anti-aliasing technique that duplicates operations at a subfragment level. We describe how multisampling affects fragment processing in more depth later in the chapter.

The chapter concludes with a discussion of methods for reading pixels from and writing pixels to the framebuffer.

Buffers

OpenGL ES supports three types of buffers, each of which stores different data for every pixel in the framebuffer:

- Color buffer (composed of front and back color buffers)
- Depth buffer
- Stencil buffer

The size of a buffer—commonly referred to as the "depth of the buffer" (but not to be confused with the depth buffer)—is measured by the number of bits that are available for storing information for a single pixel. The color buffer, for example, will have three components for storing the red, green, and blue color components, and optional storage for the alpha component. The depth of the color buffer is the sum of the number of bits for all of its components. For the depth and stencil buffers, in contrast, a single value represents the bit depth of a pixel in those buffers. For example, a depth buffer might have 16 bits per pixel. The overall size of the buffer is the sum of the bit depths of all of the components. Common framebuffer depths include 16-bit RGB buffers, with 5 bits for red and blue, and 6 bits for green (the human visual system is more sensitive to green than to red or blue), and 32 bits divided equally for an RGBA buffer.

Additionally, the color buffer may be double buffered, such that it contains two buffers: one that is displayed on the output device (usually a monitor or LCD display), named the "front" buffer; and another buffer that is hidden from the viewer, but used for constructing the next image to be displayed, and called the "back" buffer. In double-buffered applications, animation is accomplished by drawing into the back buffer, and then swapping the front and back buffers to display the new image. This swapping of buffers is usually synchronized with the refresh cycle of the display device, which will give the illusion of a continuously smooth animation. Recall that double buffering was discussed in Chapter 3, "An Introduction to EGL."

Although every EGL configuration will have a color buffer, the depth and stencil buffers are optional. However, every EGL implementation must provide at least one configuration that contains all three of the buffers, with the depth buffer being at least 16 bits deep, and at least 8 bits for the stencil buffer.

Requesting Additional Buffers

To include a depth or stencil buffer along with your color buffer, you need to request them when you specify the attributes for your EGL configuration. As discussed in Chapter 3, you pass a set of attribute–value pairs into the EGL that specify the type of rendering surface your application needs. To include a depth buffer in addition to the color buffer, you would specify `EGL_DEPTH_SIZE` in the list of attributes along with the desired bit depth you need. Likewise, you would add `EGL_STENCIL_SIZE` along with the number of required bits to obtain a stencil buffer.

Our convenience library, `esUtil`, simplifies those operations by merely allowing you to say that you would like those buffers along with a color buffer, and it takes care of the rest of the work (requesting a maximally sized buffer). When using our library, you would add (by means of a bit-wise or operation) `ES_WINDOW_DEPTH` and `ES_WINDOW_STENCIL` in your call to `esCreateWindow`. For example,

```
esCreateWindow ( &esContext,     "Application Name",
                 window_width,    window_height,
                 ES_WINDOW_RGB | ES_WINDOW_DEPTH |
                 ES_WINDOW_STENCIL );
```

Clearing Buffers

OpenGL ES is an interactive rendering system, and it assumes that at the start of each frame, you'll want to initialize all of the buffers to their default value. Buffers are cleared by calling the `glClear` function, which takes a bitmask representing the various buffers that should be cleared to their specified clear values.

```
void    glClear(GLbitfield mask)
```

mask	specifies the buffers to be cleared, and is composed of the union of the following bitmasks representing the various OpenGL ES buffers: `GL_COLOR_BUFFER_BIT`, `GL_DEPTH_BUFFER_BIT`, `GL_STENCIL_BUFFER_BIT`

You're required neither to clear every buffer nor to clear them all at the same time, but you might obtain the best performance by calling `glClear` only once per frame with all the buffers you want simultaneously cleared.

Each buffer has a default value that's used when you request that buffer be cleared. For each buffer, you can specify your desired clear value using the functions shown here:

```
void    glClearColor(GLfloat red,  GLfloat green,
                     GLfloat blue, GLfloat alpha)
```

red, green, blue, alpha	specifies the color value (in the range [0, 1]) that all pixels in the color buffers should be initialized to when `GL_COLOR_BUFFER_BIT` is present in the bitmask passed to `glClear`

```
void    glClearDepthf(GLfloat depth)
```

depth	specifies the depth value (in the range [0, 1]) that all pixels in the depth buffer should be initialized to when `GL_DEPTH_BUFFER_BIT` is present in the bitmask passed to `glClear`

```
void    glClearStencil(GLint s)
```

s	specifies the stencil value (in the range [0, $2^n - 1$], where n is the number of bits available in the stencil buffer) that all pixels in the stencil buffer should be initialized to when `GL_STENCIL_BUFFER_BIT` is present in the bitmask passed to `glClear`

If you have multiple draw buffers in a framebuffer object (see the *Multiple Render Targets* section), you can clear a specific draw buffer with the following calls:

```
void   glClearBufferiv(GLenum buffer, GLint drawBuffer,
                       const GLint *value)
void   glClearBufferuiv(GLenum buffer, GLint drawBuffer,
                        const GLuint *value)
void   glClearBufferfv(GLenum buffer, GLint drawBuffer,
                       const GLfloat *value)
```

buffer	specifies the type of buffer to clear. Can be `GL_COLOR`, `GL_FRONT`, `GL_BACK`, `GL_FRONT_AND_BACK`, `GL_LEFT`, `GL_RIGHT`, `GL_DEPTH` (`glClearBufferfv` only) or `GL_STENCIL` (`glClearBufferiv` only).
drawBuffer	specifies the draw buffer name to clear. Must be zero for depth or stencil buffers. Otherwise, must be less than `GL_MAX_DRAW_BUFFERS` for color buffers.
value	specifies a pointer to a four-element vector (for color buffers) or to a single value (for depth or stencil buffers) to clear the buffer to.

To reduce the number of function calls, you can clear the depth and stencil buffers at the same time using `glClearBufferfi`.

```
void   glClearBufferfi(GLenum buffer, GLint drawBuffer,
                       GLfloat depth, GLint stencil)
```

buffer	specifies the type of buffer to clear; must be `GL_DEPTH_STENCIL`
drawBuffer	specifies the draw buffer name to clear; must be zero
depth	specifies the value to clear the depth buffer to
stencil	specifies the value to clear the stencil buffer to

Using Masks to Control Writing to Framebuffers

You can also control which buffers, or components, in the case of the color buffer, are writable by specifying a buffer write mask. Before a pixel's value is written into a buffer, the buffer's mask is used to verify that the buffer is writable.

For the color buffer, the `glColorMask` routine specifies which components in the color buffer will be updated if a pixel is written. If the mask for a particular component is set to `GL_FALSE`, that component will not be updated if written to. By default, all color components are writable.

```
void   glColorMask(GLboolean red,  GLboolean green,
                   GLboolean blue, GLboolean alpha)
```

red, green, blue, alpha	specify whether the particular color component in the color buffer is modifiable while rendering

Likewise, writing to the depth buffer is controlled by calling `glDepthMask` with `GL_TRUE` or `GL_FALSE` to specify whether the depth buffer is writable.

Often, writing to the depth buffer is disabled when rendering translucent objects. Initially, you would render all of the opaque objects in the scene with writing to the depth buffer enabled (i.e., set to `GL_TRUE`). This would ensure that all of the opaque objects are correctly depth sorted, and the depth buffer contains the appropriate depth information for the scene. Then, before rendering the translucent objects, you would disable writing to the depth buffer by calling `glDepthMask (GL_FALSE)`. While writing to the depth buffer is disabled, values can still be read from it and used for depth comparisons. This allows translucent objects that are obscured by opaque objects to be correctly depth buffered, but does not modify the depth buffer such that opaque objects would be obscured by translucent ones.

```
void   glDepthMask(GLboolean depth)
```

depth	specifies whether the depth buffer is modifiable

Finally, you can disable writing to the stencil buffer by calling `glStencilMask`. Unlike with `glColorMask` or `glDepthMask`, you can specify which bits of the stencil buffer are writable by providing a mask.

void	**glStencilMask**(GLuint *mask*)
mask	specifies a bitmask (in the range [0, $2^n - 1$], where *n* is the number of bits in the stencil buffer) of which bits in a pixel in the stencil buffer are modifiable.

The `glStencilMaskSeparate` routine allows you to set the stencil mask based on the face vertex order (sometimes called "facedness") of the primitive. This allows different stencil masks for front- and back-facing primitives. `glStencilMaskSeparate(GL_FRONT_AND_BACK, mask)` is identical to calling `glStencilMask`, which sets the same mask for the front and back polygon faces.

void	**glStencilMaskSeparate**(GLenum *face*, GLuint *mask*)
face	specifies the stencil mask to be applied based on the face vertex order of the rendered primitive. Valid values are `GL_FRONT`, `GL_BACK`, and `GL_FRONT_AND_BACK`.
mask	specifies a bitmask (in the range [0, 2^n], where *n* is the number of bits in the stencil buffer) of which bits in a pixel in the stencil buffer are specified by face.

Fragment Tests and Operations

The following sections describe the various tests that can be applied to a fragment in OpenGL ES. By default, all fragment tests and operations are disabled, and fragments become pixels as they are written to the framebuffer in the order in which they are received. By enabling the various fragments, operational tests can be applied to choose which fragments become pixels and affect the final image.

Each fragment test is individually enabled by calling `glEnable` with the appropriate token listed in Table 11-1.

Table 11-1 Fragment Test Enable Tokens

glEnable Token	Description
`GL_DEPTH_TEST`	Control depth testing of fragments
`GL_STENCIL_TEST`	Control stencil testing of fragments
`GL_BLEND`	Control blending of fragments with colors stored in the color buffer
`GL_DITHER`	Control dithering of fragment colors before being written in the color buffer
`GL_SAMPLE_COVERAGE`	Control computation of sample coverage values
`GL_SAMPLE_ALPHA_TO_COVERAGE`	Control use of a sample's alpha in the computation of a sample coverage value

Using the Scissor Test

The scissor test provides an additional level of clipping by specifying a rectangular region that further limits which pixels in the framebuffer are writable. Using the scissor box is a two-step process. First, you need to specify the rectangular region using the `glScissor` function.

```
void   glScissor(GLint x, GLint y, GLsizei width,
                 GLsizei height)
```

x, y	specify the lower-left corner of the scissor rectangle in viewport coordinates
width	specifies the width of the scissor box (in pixels)
height	specifies the height of the scissor box (in pixels)

After specifying the scissor box, you need to enable it by calling `glEnable(GL_SCISSOR_TEST)` to employ the additional clipping. All rendering, including clearing the viewport, is restricted to the scissor box.

Generally, the scissor box is a subregion in the viewport, but the two regions are not required to actually intersect. When the two regions do not intersect, the scissoring operation will be performed on pixels that are rendered outside of the viewport region. Note that the viewport transformation happens before the fragment shader stage, while the scissor test happens after the fragment shader stage.

Stencil Buffer Testing

The next operation that might be applied to a fragment is the stencil test. The stencil buffer is a per-pixel mask that holds values that can be used to determine whether a pixel should be updated. The stencil test is enabled or disabled by the application.

Using the stencil buffer can be considered a two-step operation. The first step is to initialize the stencil buffer with the per-pixel masks, which is done by rendering geometry and specifying how the stencil buffer should be updated. The second step is generally to use those values to control subsequent rendering into the color buffer. In both cases, you specify how the parameters are to be used in the stencil test.

The stencil test is essentially a bit test, as you might do in a C program where you use a mask to determine if a bit is set, for example. The stencil function, which controls the operator and values of the stencil test, is controlled by the `glStencilFunc` or `glStencilFuncSeparate` functions.

```
void   glStencilFunc(GLenum func, GLint ref, GLuint mask)
void   glStencilFuncSeparate(GLenum face, GLenum func,
                             GLint ref,   GLuint mask)
```

face	specifies the face associated with the provided stencil function. Valid values are `GL_FRONT`, `GL_BACK`, and `GL_FRONT_AND_BACK` (`glStencilFuncSeparate` only).
func	specifies the comparison function for the stencil test. Valid values are `GL_EQUAL`, `GL_NOTEQUAL`, `GL_LESS`, `GL_GREATER`, `GL_LEQUAL`, `GL_GEQUAL`, `GL_ALWAYS`, and `GL_NEVER`.
ref	specifies the comparison value for the stencil test.
mask	specifies the mask that is bit-wise anded with the bits in the stencil buffer before being compared with the reference value.

To allow finer control of the stencil test, a masking parameter is used to select which bits of the stencil values should be considered for the test. After selecting those bits, their value is compared with a reference value using the operator provided. For example, to specify that the stencil test passes where the lowest three bits of the stencil buffer are equal to 2, you would call

```
glStencilFunc ( GL_EQUAL, 2, 0x7 );
```

and enable the stencil test. Note that in binary format, the last three bits of `0x7` are `111`.

With the stencil test configured, you generally also need to let OpenGL ES 3.0 know what to do with the values in the stencil buffer when the stencil test passes. In fact, modifying the values in the stencil buffer relies on more than just the stencil tests, but also incorporates the results of the depth test (discussed in the next section). Three possible outcomes can occur for a fragment with the combined stencil and depth tests:

1. The fragment fails the stencil tests. If this occurs, no further testing (i.e., the depth test) is applied to that fragment.
2. The fragment passes the stencil test, but fails the depth test.
3. The fragment passes both the stencil and depth tests.

Each of those possible outcomes can be used to affect the value in the stencil buffer for that pixel location. The `glStencilOp` and `glStencilOpSeparate` functions control the actions done on the stencil buffer's value for each of those test outcomes, and the possible operations on the stencil values are shown in Table 11-2.

Table 11-2 Stencil Operations

Stencil Function	Description
`GL_ZERO`	Set the stencil value to zero
`GL_REPLACE`	Replace the current stencil value with the reference value specified in `glStencilFunc` or `glStencilFuncSeparate`
`GL_INCR, GL_DECR`	Increment or decrement the stencil value; the stencil value is clamped to zero or 2^n, where n is the number of bits in the stencil buffer
`GL_INCR_WRAP`, `GL_DECR_WRAP`	Increment or decrement the stencil value, but "wrap" the value if the stencil value overflows

Table 11-2 Stencil Operations *(continued)*

Stencil Function	**Description**
	(incrementing the maximum value will result in a new stencil value of zero) or underflows (decrementing zero will result in the maximum stencil value)
`GL_KEEP`	Keep the current stencil value, effectively not modifying the value for that pixel
`GL_INVERT`	Bit-wise invert the value in the stencil buffer

```
void   glStencilOp(GLenum sfail, GLenum zfail,
                   GLenum zpass)
void   glStencilOpSeparate(GLenum face,  GLenum sfail,
                           GLenum zfail, GLenum zpass)
```

face	specifies the face associated with the provided stencil function. Valid values are `GL_FRONT`, `GL_BACK`, and `GL_FRONT_AND_BACK` (`glStencilOpSeparate` only).
sfail	specifies the operation applied to the stencil bits if the fragment fails the stencil test. Valid values are `GL_KEEP`, `GL_ZERO`, `GL_REPLACE`, `GL_INCR`, `GL_DECR`, `GL_INCR_WRAP`, `GL_DECR_WRAP`, and `GL_INVERT`.
zfail	specifies the operation applied when the fragment passes the stencil test, but fails the depth test
zpass	specifies the operation applied when the fragment passes both the stencil and depth tests

The following example illustrates using `glStencilFunc` and `glStencilOp` to control rendering in various parts of the viewport:

```
GLfloat vVertices[] =

     {
        -0.75f,  0.25f, 0.50f, // Quad #0
        -0.25f,  0.25f, 0.50f,
        -0.25f,  0.75f, 0.50f,
        -0.75f,  0.75f, 0.50f,
```

(continues)

(continued)

```
         0.25f,  0.25f, 0.90f, // Quad #1
         0.75f,  0.25f, 0.90f,
         0.75f,  0.75f, 0.90f,
         0.25f,  0.75f, 0.90f,
        -0.75f, -0.75f, 0.50f, // Quad #2
        -0.25f, -0.75f, 0.50f,
        -0.25f, -0.25f, 0.50f,
        -0.75f, -0.25f, 0.50f,
         0.25f, -0.75f, 0.50f, // Quad #3
         0.75f, -0.75f, 0.50f,
         0.75f, -0.25f, 0.50f,
         0.25f, -0.25f, 0.50f,
        -1.00f, -1.00f, 0.00f, // Big Quad
         1.00f, -1.00f, 0.00f,
         1.00f,  1.00f, 0.00f,
        -1.00f,  1.00f, 0.00f
     };

   GLubyte indices[][6] =
   {
       {  0,  1,  2,  0,  2,  3 }, // Quad #0
       {  4,  5,  6,  4,  6,  7 }, // Quad #1
       {  8,  9, 10,  8, 10, 11 }, // Quad #2
       { 12, 13, 14, 12, 14, 15 }, // Quad #3
       { 16, 17, 18, 16, 18, 19 }  // Big Quad
   };

   #define NumTests 4
      GLfloat colors[NumTests][4] =
      {
         { 1.0f, 0.0f, 0.0f, 1.0f },
         { 0.0f, 1.0f, 0.0f, 1.0f },
         { 0.0f, 0.0f, 1.0f, 1.0f },
         { 1.0f, 1.0f, 0.0f, 0.0f }
      };

      GLint numStencilBits;
      GLuint stencilValues[NumTests] =
      {
         0x7, // Result of test 0
         0x0, // Result of test 1
         0x2, // Result of test 2
         0xff // Result of test 3. We need to fill this
              // value in a run-time
      };

      // Set the viewport
      glViewport ( 0, 0, esContext->width, esContext->height );
```

```
// Clear the color, depth, and stencil buffers. At this
// point, the stencil buffer will be 0x1 for all pixels.
glClear ( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT |
          GL_STENCIL_BUFFER_BIT );

// Use the program object
glUseProgram ( userData->programObject );

// Load the vertex position
glVertexAttribPointer ( userData->positionLoc, 3, GL_FLOAT,
                        GL_FALSE, 0, vVertices );

glEnableVertexAttribArray ( userData->positionLoc );

// Test 0:
//
// Initialize upper-left region. In this case, the stencil-
// buffer values will be replaced because the stencil test
// for the rendered pixels will fail the stencil test,
// which is
//
//        ref mask stencil mask
//      ( 0x7 & 0x3 ) < ( 0x1 & 0x7 )
//
// The value in the stencil buffer for these pixels will
// be 0x7.
//
glStencilFunc ( GL_LESS, 0x7, 0x3 );
glStencilOp ( GL_REPLACE, GL_DECR, GL_DECR );
glDrawElements ( GL_TRIANGLES, 6, GL_UNSIGNED_BYTE,
                 indices[0] );

// Test 1:
//
// Initialize the upper-right region. Here, we'll decrement
// the stencil-buffer values where the stencil test passes
// but the depth test fails. The stencil test is
//
//       ref mask stencil mask
//     ( 0x3 & 0x3 ) > ( 0x1 & 0x3 )
//
//    but where the geometry fails the depth test. The
//    stencil values for these pixels will be 0x0.
//
glStencilFunc ( GL_GREATER, 0x3, 0x3 );
glStencilOp ( GL_KEEP, GL_DECR, GL_KEEP );
glDrawElements ( GL_TRIANGLES, 6, GL_UNSIGNED_BYTE,
                 indices[1] );
```

(continues)

(continued)

```
// Test 2:
//
// Initialize the lower-left region. Here we'll increment
// (with saturation) the stencil value where both the
// stencil and depth tests pass. The stencil test for
// these pixels will be
//
//        ref mask        stencil mask
//     (  0x1 & 0x3 ) == ( 0x1 & 0x3 )
//
// The stencil values for these pixels will be 0x2.
//
glStencilFunc ( GL_EQUAL, 0x1, 0x3 );
glStencilOp ( GL_KEEP, GL_INCR, GL_INCR );
glDrawElements ( GL_TRIANGLES, 6, GL_UNSIGNED_BYTE,
                 indices[2] );

// Test 3:
//
// Finally, initialize the lower-right region. We'll invert
// the stencil value where the stencil tests fails. The
// stencil test for these pixels will be
//
//       ref mask        stencil mask
//     ( 0x2 & 0x1 ) == ( 0x1 & 0x1 )
//
// The stencil value here will be set to ~((2^s-1) & 0x1),
// (with the 0x1 being from the stencil clear value),
// where 's' is the number of bits in the stencil buffer.
//
glStencilFunc ( GL_EQUAL, 0x2, 0x1 );
glStencilOp ( GL_INVERT, GL_KEEP, GL_KEEP );
glDrawElements ( GL_TRIANGLES, 6, GL_UNSIGNED_BYTE,indices[3]);

// As we don't know at compile-time how many stencil bits are
// present, we'll query, and update, the correct value in the
// stencilValues arrays for the fourth tests. We'll use this
// value later in rendering.
glGetIntegerv ( GL_STENCIL_BITS, &numStencilBits );

stencilValues[3] = ~( ( (1 << numStencilBits) - 1 ) & 0x1 ) &
                       0xff;

// Use the stencil buffer for controlling where rendering
// will occur. We disable writing to the stencil buffer so we
// can test against them without modifying the values we
// generated.
glStencilMask ( 0x0 );
```

```
for ( i = 0; i < NumTests; ++i )
{
   glStencilFunc ( GL_EQUAL, stencilValues[i], 0xff );
   glUniform4fv ( userData->colorLoc, 1, colors[i] );
   glDrawElements ( GL_TRIANGLES, 6, GL_UNSIGNED_BYTE,
                    indices[4] );
}
```

Depth Buffer Testing

The depth buffer is typically used for hidden-surface removal. It traditionally keeps the distance value of the closest object to the viewpoint for each pixel in the rendering surface, and for every new incoming fragment, compares its distance from the viewpoint with the stored value. By default, if the incoming fragment's depth value is less than the value stored in the depth buffer (meaning it's closer to the viewer), the incoming fragment's depth value replaces the values stored in the depth buffer, and then its color value replaces the color value in the color buffer. This is the standard method for depth buffering—and if that's what you would like to do, you simply need to request a depth buffer when you create a window, and then enable the depth test by calling `glEnable` with `GL_DEPTH_TEST`. If no depth buffer is associated with the color buffer, the depth test always passes.

Of course, that's only one way to use the depth buffer. You can modify the depth comparison operator by calling `glDepthFunc`.

`void`	**`glDepthFunc`**`(GLenum` *`func`*`)`
`func`	specifies the depth value comparison function, which can be one of `GL_LESS`, `GL_GREATER`, `GL_LEQUAL`, `GL_GEQUAL`, `GL_EQUAL`, `GL_NOTEQUAL`, `GL_ALWAYS`, or `GL_NEVER`

Blending

This section discusses blending pixel colors. Once a fragment passes all of the enabled fragment tests, its color can be combined with the color that's already present in the fragment's pixel location. Before the two colors are combined, they're multiplied by a scaling factor and combined using the specified blending operator. The blending equation is

$$C_{final} = f_{source} C_{source} \text{ op } f_{destination} C_{destination}$$

where f_{source} and C_{source} are the incoming fragment's scaling factor and color, respectively. Likewise, $f_{destination}$ and $C_{destination}$ are the pixel's scaling factor and color, and op is the mathematical operator for combining the scaled values.

The scaling factors are specified by calling either `glBlendFunc` or `glBlendFuncSeparate`.

```
void   glBlendFunc(GLenum sfactor, GLenum dfactor)
```

sfactor	specifies the blending coefficient for the incoming fragment
dfactor	specifies the blending coefficient for the destination pixel

```
void   glBlendFuncSeparate(GLenum srcRGB,   GLenum dstRGB,
                           GLenum srcAlpha, GLenum dstAlpha)
```

srcRGB	specifies the blending coefficient for the incoming fragment's red, green, and blue components
dstRGB	specifies the blending coefficient for the destination pixel's red, green, and blue components
srcAlpha	specifies the blending coefficient for the incoming fragment's alpha value
dstAlpha	specifies the blending coefficient for the destination pixel's alpha value

The possible values for the blending coefficients are shown in Table 11-3.

Table 11-3 Blending Functions

Blending Coefficient Enum	RGB Blending Factors	Alpha Blending Factor
`GL_ZERO`	(0, 0, 0)	0
`GL_ONE`	(1, 1, 1)	1
`GL_SRC_COLOR`	(R_s, G_s, B_s)	A_s
`GL_ONE_MINUS_SRC_COLOR`	$(1 - R_s, 1 - G_s, 1 - B_s)$	$1 - A_s$
`GL_SRC_ALPHA`	(A_s, A_s, A_s)	A_s
`GL_ONE_MINUS_SRC_ALPHA`	$(1 - A_s, 1 - A_s, 1 - A_s)$	$1 - A_s$

Table 11-3 Blending Functions *(continued)*

Blending Coefficient Enum	RGB Blending Factors	Alpha Blending Factor
GL_DST_COLOR	(R_d, G_d, B_d)	A_d
GL_ONE_MINUS_DST_COLOR	$(1 - R_d, 1 - G_d, 1 - B_d)$	$1- A_d$
GL_DST_ALPHA	(A_d, A_d, A_d)	A_d
GL_ONE_MINUS_DST_ALPHA	$(1 - A_d, 1 - A_d, 1 - A_d)$	$1 - A_d$
GL_CONSTANT_COLOR	(R_c, G_c, B_c)	A_c
GL_ONE_MINUS_CONSTANT_COLOR	$(1 - R_c, 1 - G_c, 1 - B_c)$	$1 - A_c$
GL_CONSTANT_ALPHA	(A_c, A_c, A_c)	A_c
GL_ONE_MINUS_CONSTANT_ALPHA	$(1 - A_c, 1 - A_c, 1 - A_c)$	$1 - A_c$
GL_SRC_ALPHA_SATURATE	$min(A_s, 1 - A_d)$	1

In Table 11-3, (R_s, G_s, B_s, A_s) are the color components associated with the incoming fragment color, (R_d, G_d, B_d, A_d) are the components associated with the pixel color already in the color buffer, and (R_a, G_c, B_c, A_c) represent a constant color that you set by calling `glBlendColor`. In the case of `GL_SRC_ALHPA_SATURATE`, the minimum value computed is applied to the source color only.

```
void   glBlendColor(GLfloat red,  GLfloat green,
                    GLfloat blue, GLfloat alpha)
```

red, green, blue, alpha	specify the component values for the constant blending color

Once the incoming fragment and pixel color have been multiplied by their respective scaling factors, they are combined using the operator specified by `glBlendEquation` or `glBlendEquationSeparate`. By default, blended colors are accumulated using the `GL_FUNC_ADD` operator. The `GL_FUNC_SUBTRACT` operator subtracts the scaled color from the framebuffer from the incoming fragment's value. Likewise, the

`GL_FUNC_REVERSE_SUBTRACT` operator reverses the blending equation, such that the incoming fragment colors are subtracted from the current pixel value.

```
void    glBlendEquation(GLenum mode)
```

mode	specifies the blending operator. Valid values are `GL_FUNC_ADD`, `GL_FUNC_SUBTRACT`, `GL_FUNC_REVERSE_SUBTRACT`, `GL_MIN`, or `GL_MAX`.

```
void    glBlendEquationSeparate(GLenum modeRGB,
                                GLenum modeAlpha)
```

modeRGB	specifies the blending operator for the red, green, and blue components
modeAlpha	specifies the alpha component blending operator

Dithering

On a system where the number of colors available in the framebuffer is limited due to the number of bits per component in the framebuffer, we can simulate greater color depth using dithering. Dithering algorithms arrange colors in such a way that the image appears to have more available colors than are really present. OpenGL ES 3.0 doesn't specify which dithering algorithm is to be used in supporting its dithering stage; the technique is very implementation dependent.

The only control your application has over dithering is whether it is applied to the final pixels. This decision is entirely controlled by calling `glEnable` or `glDisable` with `GL_DITHER` to specify dithering's use in the pipeline. Initially, dithering is enabled.

Multisampled Anti-Aliasing

Anti-aliasing is an important technique for improving the quality of generated images by trying to reduce the visual artifacts of rendering into discrete pixels. The geometric primitives that OpenGL ES 3.0 renders are rasterized onto a grid, and their edges may become deformed in that process. You have almost certainly seen the staircase effect that happens to lines drawn diagonally across a monitor.

Various techniques can be used to reduce those aliasing effects, and OpenGL ES 3.0 supports a variant called *multisampling*. Multisampling divides every pixel into a set of samples, each of which is treated like a "mini-pixel" during rasterization. That is, when a geometric primitive is rendered, it's like rendering into a framebuffer that has many more pixels than the real display surface. Each sample has its own color, depth, and stencil value, and those values are preserved until the image is ready for display. When it's time to compose the final image, the samples are *resolved* into the final pixel color. What makes this process special is that in addition to using every sample's color information, OpenGL ES 3.0 has even more information about how many samples for a particular pixel were occupied during rasterization. Each sample for a pixel is assigned a bit in the *sample coverage mask*. Using that coverage mask, we can control how the final pixels are resolved. Every rendering surface created for an OpenGL ES 3.0 application will be configured for multisampling, even if only a single sample per pixel is available. Unlike in supersampling, the fragment shader is executed per pixel rather than per sample.

Multisampling has multiple options that can be turned on and off (using `glEnable` and `glDisable`, respectively) to control the usage of sample coverage value.

First, you can specify that the sample's alpha value should be used to determine the coverage value by enabling `GL_SAMPLE_ALPHA_TO_COVERAGE`. In this mode, if the geometric primitive covers a sample, the alpha value of incoming fragment is used to determine an additional sample coverage mask computed that is bit-wise anded into the coverage mask that is computed using the samples of the fragment. This newly computed coverage value replaces the original one generated directly from the sample coverage calculation. These sample computations are implementation dependent.

Additionally, you can specify `GL_SAMPLE_COVERAGE` or `GL_SAMPLE_COVERAGE_INVERT`, which uses the fragment's (potentially modified by previous operations) coverage value or its inverted bits, respectively, and computes the bit-wise and of that value with one specified using the `glSampleCoverage` function. The value specified with `glSampleCoverage` is used to generate an implementation-specific coverage mask, and includes an inversion flag, *`invert`*, that inverts the bits in the generated mask. Using this inversion flag, it becomes possible to create two transparency masks that don't use entirely distinct sets of samples.

```
void   glSampleCoverage(GLfloat value, GLboolean invert)
```

value	specifies a value in the range [0, 1] that is converted into a sample mask; the resulting mask should have a proportional number of bits set corresponding to the value
invert	specifies that after determining the mask's value, all of the bits in the mask should be inverted

Centroid Sampling

When rendering with multisampling, the fragment data is picked from a sample that is closest to a pixel center. This can lead to rendering artifacts near triangle edges, as the pixel center may sometimes fall outside of the triangle. In such case, the fragment data can be extrapolated to a point outside of the triangle. Centroid sampling solves this problem by ensuring that the fragment data is picked from a sample that falls inside the triangle.

To enable centroid sampling, you can declare the output variables of the vertex shader (and input variables to the fragment shader) with the `centroid` qualifier as follows:

```
smooth centroid out vec3 v_color;
```

Note that using centroid sampling can lead to less accurate derivatives for pixels near the triangle edges.

Reading and Writing Pixels to the Framebuffer

If you want to preserve your rendered image for posterity's sake, you can read the pixel values back from the color buffer, but not from the depth or stencil buffers. When you call `glReadPixels`, the pixels in the color buffer are returned to your application in an array that has been previously allocated.

```
void   glReadPixels(GLint x,        GLint y, GLsizei width,
                    GLsizei height, GLenum format,
                    GLenum type,    GLvoid *pixels)
```

x, y	specify the viewport coordinates of the lower-left corner of the pixel rectangle read from the color buffer.
width *height*	specify the dimensions of the pixel rectangle read from the color buffer.

format	specifies the pixel format that you would like returned. Three formats are available: `GL_RGBA`, `GL_RGBA_INTEGER`, and the value returned by querying `GL_IMPLEMENTATION_COLOR_READ_FORMAT`, which is an implementation-specific pixel format.
type	specifies the data type of the pixels returned. Five types are available: `GL_UNSIGNED_BYTE`, `GL_UNSIGNED_INT`, `GL_INT`, `GL_FLOAT`, and the value returned from querying `GL_IMPLEMENTATION_COLOR_READ_TYPE`, which is an implementation-specific pixel type.
pixels	a contiguous array of bytes that contain the values read from the color buffer after `glReadPixels` returns.

Aside from the fixed format (`GL_RGBA` and `GL_RGBA_INTEGER`) and type (`GL_UNSIGNED_BYTE`, `GL_UNSIGNED_INT`, `GL_INT`, and `GL_FLOAT`), notice that there are implementation-dependent values that should return the best format and type combination for the implementation you're using. The implementation-specific values can be queried as follows:

```
GLint   readType, readFormat;
GLubyte *pixels;

glGetIntegerv ( GL_IMPLEMENTATION_COLOR_READ_TYPE, &readType );
glGetIntegerv ( GL_IMPLEMENTATION_COLOR_READ_FORMAT,
                &readFormat );

unsigned int bytesPerPixel = 0;

switch ( readType )
{
   case GL_UNSIGNED_BYTE:
   case GL_BYTE:
      switch ( readFormat )
      {
         case GL_RGBA:
            bytesPerPixel = 4;
            break;

         case GL_RGB:
         case GL_RGB_INTEGER:
            bytesPerPixel = 3;
            break;

         case GL_RG:
         case GL_RG_INTEGER:
         case GL_LUMINANCE_ALPHA:
```

(continues)

(continued)

```
                bytesPerPixel = 2;
                break;

             case GL_RED:
             case GL_RED_INTEGER:
             case GL_ALPHA:
             case GL_LUMINANCE:
             case GL_LUMINANCE_ALPHA:
                bytesPerPixel = 1;
                break;

             default:
                // Undetected format/error
                break;
       }
       break;

case GL_FLOAT:
case GL_UNSIGNED_INT:
case GL_INT:
       switch ( readFormat )
       {
             case GL_RGBA:
             case GL_RGBA_INTEGER:
                bytesPerPixel = 16;
                break;

             case GL_RGB:
             case GL_RGB_INTEGER:
                bytesPerPixel = 12;
                break;

             case GL_RG:
             case GL_RG_INTEGER:
                bytesPerPixel = 8;
                break;

             case GL_RED:
             case GL_RED_INTEGER:
             case GL_DEPTH_COMPONENT:
                bytesPerPixel = 4;
                break;

             default:
                // Undetected format/error
                break;
       }
       break;

case GL_HALF_FLOAT:
case GL_UNSIGNED_SHORT:
```

```
case GL_SHORT:
   switch ( readFormat )
   {
         case GL_RGBA:
         case GL_RGBA_INTEGER:
            bytesPerPixel = 8;
            break;

         case GL_RGB:
         case GL_RGB_INTEGER:
            bytesPerPixel = 6;
            break;

         case GL_RG:
         case GL_RG_INTEGER:
            bytesPerPixel = 4;
            break;

         case GL_RED:
         case GL_RED_INTEGER:
            bytesPerPixel = 2;
            break;

         default:
            // Undetected format/error
            break;
   }
   break;

case GL_FLOAT_32_UNSIGNED_INT_24_8_REV: // GL_DEPTH_STENCIL
   bytesPerPixel = 8;
   break;

// GL_RGBA, GL_RGBA_INTEGER format
case GL_UNSIGNED_INT_2_10_10_10_REV:
case GL_UNSIGNED_INT_10F_11F_11F_REV: // GL_RGB format
case GL_UNSIGNED_INT_5_9_9_9_REV:     // GL_RGB format
case GL_UNSIGNED_INT_24_8:            // GL_DEPTH_STENCIL format
   bytesPerPixel = 4;
   break;

case GL_UNSIGNED_SHORT_4_4_4_4:  // GL_RGBA format
case GL_UNSIGNED_SHORT_5_5_5_1:  // GL_RGBA format
case GL_UNSIGNED_SHORT_5_6_5:    // GL_RGB format
   bytesPerPixel = 2;
   break;

   default:
      // Undetected type/error
}
```

(continues)

(continued)

```
pixels = ( GLubyte* ) malloc( width * height * bytesPerPixel );

glReadPixels ( 0, 0, windowWidth, windowHeight, readFormat,
               readType, pixels );
```

You can read pixels from any currently bound framebuffer, whether it's one allocated by the windowing system or from a framebuffer object. Because each buffer can have a different layout, you'll probably need to query the type and format for each buffer you want to read.

OpenGL ES 3.0 provides an efficient mechanism to copy a rectangular block of pixels into the framebuffer, which will be described in Chapter 12, "Framebuffer Objects."

Pixel Pack Buffer Objects

When a non-zero buffer object is bound to the `GL_PIXEL_PACK_BUFFER` using `glBindBuffer`, the `glReadPixels` command can return immediately and invoke DMA transfer to read pixels from the framebuffer and write the data into the pixel buffer object (PBO).

To keep the CPU busy, you can schedule some CPU processing after the `glReadPixels` call to overlap CPU computations and the DMA transfer. Depending on the applications, the data may not be available immediately; in such cases, you can use multiple PBO solutions so that while the CPU is waiting for the data transfer from one PBO, it can process the data from an earlier transfer from another PBO.

Multiple Render Targets

Multiple render targets (MRTs) allow the application to render to several color buffers at one time. With multiple render targets, the fragment shader outputs several colors (which can be used to store RGBA colors, normals, depths, or texture coordinates), one for each attached color buffer. MRTs are used in many advanced rendering algorithms, such as deferred shading and fast ambient occlusion approximation (SSAO).

In deferred shading, lighting calculations are performed only once per pixel. This is achieved by separating the geometry and lighting calculations into two separate rendering passes. The first geometry pass outputs multiple attributes (such as position, normal, material color, or texture coordinates) into multiple buffers (using MRTs). The second lighting pass performs the lighting calculations by sampling the attributes from each buffer created in the first pass. As the depth testing has been performed on the first pass, we will perform only one lighting calculation per pixel.

The following steps show how to set up MRTs:

1. Initialize framebuffer objects (FBOs) using `glGenFramebuffers` and `glBindFramebuffer` commands (described in more detail in Chapter 12, “Framebuffer Objects”) as shown here:

    ```
    glGenFramebuffers ( 1, &fbo );
    glBindFramebuffer ( GL_FRAMEBUFFER, fbo );
    ```

2. Initialize textures using `glGenTextures` and `glBindTexture` commands (described in more detail in Chapter 9, “Texturing”) as shown here:

    ```
    glBindTexture ( GL_TEXTURE_2D, textureId );

    glTexImage2D ( GL_TEXTURE_2D, 0, GL_RGBA,
                   textureWidth, textureHeight,
                   0, GL_RGBA, GL_UNSIGNED_BYTE, NULL );

    // Set the filtering mode
    glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                      GL_NEAREST );
    glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                      GL_NEAREST );
    ```

3. Bind relevant textures to the FBO using `glFramebufferTexture2D` or `glFramebufferTextureLayer` command (described in more detail in Chapter 12) as shown here:

    ```
    glFramebufferTexture2D ( GL_DRAW_FRAMEBUFFER,
                             GL_COLOR_ATTACHMENT0,
                             GL_TEXTURE_2D,
                             textureId, 0 );
    ```

4. Specify color attachments for rendering using the following `glDrawBuffers` command:

```
void   glDrawBuffers(GLsizei n, const GLenum* bufs)
```

n	specifies the number of buffers in *bufs*
bufs	points to an array of symbolic constants specifying the buffers into which fragment colors or data values will be written

For example, you can set up a FBO with four color outputs (attachments) as follows:

```
const GLenum attachments[4] = { GL_COLOR_ATTACHMENT0,
                                GL_COLOR_ATTACHMENT1,
                                GL_COLOR_ATTACHMENT2,
                                GL_COLOR_ATTACHMENT3 };
glDrawBuffers ( 4, attachments );
```

You can query the maximum number of color attachments by calling `glGetIntegerv` with the symbolic constant `GL_MAX_COLOR_ATTACHMENTS`. The minimum number of color attachments supported by all OpenGL 3.0 implementations is 4.

5. Declare and use multiple shader outputs in the fragment shader. For example, the following declaration will copy fragment shader outputs `fragData0` to `fragData3` to draw buffers 0–3, respectively:

```
layout(location = 0) out vec4 fragData0;
layout(location = 1) out vec4 fragData1;
layout(location = 2) out vec4 fragData2;
layout(location = 3) out vec4 fragData3;
```

Putting everything together, Example 11-1 (as part of the `Chapter_11/MRTs` example) illustrates how to set up four draw buffers for a single framebuffer object.

Example 11-1 Setting up Multiple Render Targets

```
int InitFBO ( ESContext *esContext)
{
   UserData *userData = esContext->userData;
   int i;
   GLint defaultFramebuffer = 0;
   const GLenum attachments[4] =
   {
      GL_COLOR_ATTACHMENT0,
      GL_COLOR_ATTACHMENT1,
      GL_COLOR_ATTACHMENT2,
      GL_COLOR_ATTACHMENT3
   };

   glGetIntegerv ( GL_FRAMEBUFFER_BINDING, &defaultFramebuffer );
```

Example 11-1 Setting up Multiple Render Targets *(continued)*

```
   // Set up fbo
   glGenFramebuffers ( 1, &userData->fbo );
   glBindFramebuffer ( GL_FRAMEBUFFER, userData->fbo );

   // Set up four output buffers and attach to fbo
   userData->textureHeight = userData->textureWidth = 400;
   glGenTextures ( 4, &userData->colorTexId[0] );
   for (i = 0; i < 4; ++i)
   {
      glBindTexture ( GL_TEXTURE_2D, userData->colorTexId[i] );

      glTexImage2D ( GL_TEXTURE_2D, 0, GL_RGBA,
                     userData->textureWidth,
                     userData->textureHeight,
                     0, GL_RGBA, GL_UNSIGNED_BYTE, NULL );

      // Set the filtering mode
      glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                        GL_NEAREST );
      glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                        GL_NEAREST );

      glFramebufferTexture2D ( GL_DRAW_FRAMEBUFFER,
                               attachments[i],
                               GL_TEXTURE_2D,
                               userData->colorTexId[i], 0 );
   }

   glDrawBuffers ( 4, attachments );

   if ( GL_FRAMEBUFFER_COMPLETE !=
           glCheckFramebufferStatus ( GL_FRAMEBUFFER ) )
   {
      return FALSE;
   }

   // Restore the original framebuffer
   glBindFramebuffer ( GL_FRAMEBUFFER, defaultFramebuffer );

   return TRUE;
}
```

Example 11-2 (as part of the `Chapter_11/MRTs` example) illustrates how to output four colors per fragment in a fragment shader.

Example 11-2 Fragment Shader with Multiple Render Targets

```
#version 300 es
precision mediump float;
layout(location = 0) out vec4 fragData0;
layout(location = 1) out vec4 fragData1;
layout(location = 2) out vec4 fragData2;
layout(location = 3) out vec4 fragData3;
void main()
{
   // first buffer will contain red color
   fragData0 = vec4 ( 1, 0, 0, 1 );

   // second buffer will contain green color
   fragData1 = vec4 ( 0, 1, 0, 1 );

   // third buffer will contain blue color
   fragData2 = vec4 ( 0, 0, 1, 1 );

   // fourth buffer will contain gray color
   fragData3 = vec4 ( 0.5, 0.5, 0.5, 1 );
}
```

Summary

In this chapter, you learned about tests and operations (scissor box testing, stencil buffer testing, depth buffer testing, multisampling, blending and dithering) that happen after the fragment shader. This is the final phase in the OpenGL ES 3.0 pipeline. In the next chapter, you will learn an efficient method for rendering to a texture or an off-screen surface using framebuffer objects.

Chapter 12

Framebuffer Objects

In this chapter, we describe what framebuffer objects are, how applications can create them, and how applications can use them for rendering to an off-screen buffer or rendering to a texture. We start by discussing why we need framebuffer objects. We then introduce framebuffer objects and new object types they add to OpenGL ES, and explain how they differ from the EGL surfaces described in Chapter 3, "An Introduction to EGL." We go on to discuss how to create framebuffer objects; explore how to specify color, depth, and stencil attachments to a framebuffer object; and then provide examples that demonstrate rendering to a framebuffer object. Last but not least, we discuss performance tips and tricks that can help ensure good performance when using framebuffer objects.

Why Framebuffer Objects?

A rendering context and a drawing surface need to be first created and made current before any OpenGL ES commands can be called by an application. The rendering context and the drawing surface are usually provided by the native windowing system through an API such as EGL. Chapter 3 describes how to create an EGL context and surface and how to attach them to a rendering thread. The rendering context contains the appropriate state required for correct operation. The drawing surface provided by the native windowing system can be a surface that will be displayed on the screen, referred to as the window system–provided framebuffer, or it can be an off-screen surface, referred to as a pbuffer. The calls to create the EGL drawing surfaces let you specify the width and height of the surface in pixels; whether the surface uses color, depth, and stencil buffers; and the bit depths of these buffers.

By default, OpenGL ES uses the window system–provided framebuffer as the drawing surface. If the application is drawing only to an on-screen surface, the window system–provided framebuffer is usually sufficient. However, many applications need to render to a texture, and for this purpose using the window system–provided framebuffer as your drawing surface is usually not an ideal option. Examples of where the render-to-texture approach is useful are shadow mapping, dynamic reflections and environment mapping, multipass techniques for depth-of-field, motion blur effects, and postprocessing effects.

Applications can use either of two techniques to render to a texture:

- Implement render to texture by drawing to the window system–provided framebuffer and then copy the appropriate region of the framebuffer to the texture. This can be implemented using the `glCopyTexImage2D` and `glCopyTexSubImage2D` APIs. As their names imply, these APIs perform a copy from the framebuffer to the texture buffer, and this copy operation can often adversely impact performance. In addition, this approach works only if the dimensions of the texture are less than or equal to the dimensions of the framebuffer.
- Implement render to texture by using a pbuffer that is attached to a texture. We know that a window system–provided surface must be attached to a rendering context. This can be inefficient on some implementations that require separate contexts for each pbuffer and window surface. Additionally, switching between window system–provided drawables can sometimes require the implementation to flush all previous rendering prior to the switch. This can introduce expensive "bubbles" (idling the GPU) into the rendering pipeline. On such systems, our recommendation is to avoid using pbuffers to render to textures because of the overhead associated with context- and window system–provided drawable switching.

Neither of these two methods is ideal for rendering to a texture or other off-screen surface. What is needed instead are APIs that allow applications to directly render to a texture or the ability to create an off-screen surface within the OpenGL ES API and use it as a rendering target. Framebuffer objects and renderbuffer objects allow applications to do exactly this, without requiring additional rendering contexts to be created. As a consequence, we no longer have to worry about the overhead of a context and drawable switch that can occur when using window system–provided drawables. Framebuffer objects, therefore, provide a better and more efficient method for rendering to a texture or an off-screen surface.

The framebuffer objects API supports the following operations:

- Creating framebuffer objects using OpenGL ES commands only
- Creating and using multiple framebuffer objects within a single EGL context—that is, without requiring a rendering context per framebuffer
- Creating off-screen color, depth, or stencil renderbuffers and textures, and attaching these to a framebuffer object
- Sharing color, depth, or stencil buffers across multiple framebuffers
- Attaching textures directly to a framebuffer as color or depth, thereby avoiding the need to do a copy operation
- Copying between framebuffers and invalidating framebuffer contents

Framebuffer and Renderbuffer Objects

In this section, we describe what renderbuffer and framebuffer objects are, explain how they differ from window system–provided drawables, and consider when to use a renderbuffer instead of a texture.

A *renderbuffer object* is a 2D image buffer allocated by the application. The renderbuffer can be used to allocate and store color, depth, or stencil values and can be used as a color, depth, or stencil attachment in a framebuffer object. A renderbuffer is similar to an off-screen window system–provided drawable surface, such as a pbuffer. A renderbuffer, however, cannot be directly used as a GL texture.

A *framebuffer object* (FBO) is a collection of color, depth, and stencil textures or render targets. Various 2D images can be attached to the color attachment point in the framebuffer object. These include a renderbuffer object that stores color values, a mip level of a 2D texture or a cubemap face, a layer of a 2D array textures, or even a mip level of a 2D slice in a 3D texture. Similarly, various 2D images containing depth values can be attached to the depth attachment point of an FBO. These can include a renderbuffer, a mip level of a 2D texture, or a cubemap face that stores depth values. The only 2D image that can be attached to the stencil attachment point of an FBO is a renderbuffer object that stores stencil values.

Figure 12-1 shows the relationships among framebuffer objects, renderbuffer objects, and textures. Note that there can be only one color, depth, and stencil attachment in a framebuffer object.

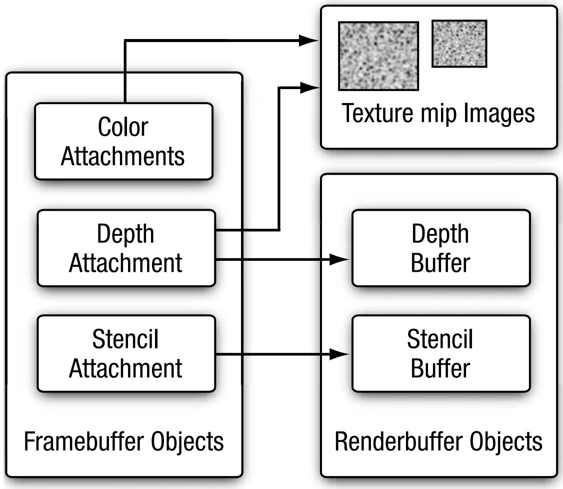

Figure 12-1 Framebuffer Objects, Renderbuffer Objects, and Textures

Choosing a Renderbuffer Versus a Texture as a Framebuffer Attachment

For render-to-texture use cases, you would attach a texture object to the framebuffer object. Examples include rendering to a color buffer that will be used as a color texture, and rendering into a depth buffer that will be used as a depth texture for shadows.

There are several reasons to use renderbuffers instead of textures:

- Renderbuffers support multisampling.
- If the image will not be used as a texture, using a renderbuffer may deliver a performance advantage. This advantage occurs because the implementation might be able to store the renderbuffer in a much more efficient format, better suited for rendering than for texturing. The implementation can only do so, however, if it knows in advance that the image will not be used as a texture.

Framebuffer Objects Versus EGL Surfaces

The differences between an FBO and the window system–provided drawable surface are as follows:

- Pixel ownership test determines whether the pixel at location (x_w, y_w) in the framebuffer is currently owned by OpenGL ES. This test allows the window system to control which pixels in the framebuffer belong to the current OpenGL ES context—for example, when a window that is being rendered into by OpenGL ES is obscured. For an application-created framebuffer object, the pixel ownership test always succeeds, as the framebuffer object owns all the pixels.
- The window system might support only double-buffered surfaces. Framebuffer objects, in contrast, support only single-buffered attachments.
- Sharing of stencil and depth buffers between framebuffers is possible using framebuffer objects but usually not with the window system–provided framebuffer. Stencil and depth buffers and their corresponding state are usually allocated implicitly with the window system–provided drawable surface and, therefore, cannot be shared between drawable surfaces. With application-created framebuffer objects, stencil and depth renderbuffers can be created independently and then associated with a framebuffer object by attaching these buffers to appropriate attachment points in multiple framebuffer objects, if desired.

Creating Framebuffer and Renderbuffer Objects

Creating framebuffer and renderbuffer objects is similar to how texture or vertex buffer objects are created in OpenGL ES 3.0.

The `glGenRenderbuffers` API call is used to allocate renderbuffer object names. This API is described next.

```
void   glGenRenderbuffers(GLsizei n,   GLuint *renderbuffers)
```

n	number of renderbuffer object names to return
renderbuffers	pointer to an array of *n* entries, where the allocated renderbuffer object names are returned

`glGenRenderbuffers` allocates *`n`* renderbuffer object names and returns them in `renderbuffers`. The renderbuffer object names returned by `glGenRenderbuffers` are unsigned integer numbers other than 0. These names returned are marked *in use* but do not have any state associated with them. The value `0` is reserved by OpenGL ES and does not refer to a renderbuffer object. Applications trying to modify or query the buffer object state for renderbuffer object 0 will generate an appropriate error.

The `glGenFramebuffers` API call is used to allocate framebuffer object names. This API is described here.

```
void   glGenFramebuffers(GLsizei n,   GLuint *ids)
```

`n`	number of framebuffer object names to return
`ids`	pointer to an array of *`n`* entries, where allocated framebuffer object are returned

`glGenFramebuffers` allocates *`n`* framebuffer object names and returns them in `ids`. The framebuffer object names returned by `glGenFramebuffers` are unsigned integer numbers other than 0. The framebuffer names returned are marked *in use* but do not have any state associated with them. The value 0 is reserved by OpenGL ES and refers to the window system–provided framebuffer. Applications trying to modify or query the buffer object state for framebuffer object 0 will generate an appropriate error.

Using Renderbuffer Objects

In this section, we describe how to specify the data storage, format, and dimensions of the renderbuffer image. To specify this information for a specific renderbuffer object, we need to make this object the current renderbuffer object. The `glBindRenderbuffer` command is used to set the current renderbuffer object.

```
void   glBindRenderbuffer(GLenum target, GLuint renderbuffer)
```

`target`	must be set to `GL_RENDERBUFFER`
`renderbuffer`	renderbuffer object name

Note that glGenRenderbuffers is not required to assign a renderbuffer object name before it is bound using glBindRenderbuffer. Although it is a good practice to call glGenRenderbuffers, many applications specify compile-time constants for their buffers. An application can specify an unused renderbuffer object name to glBindRenderbuffer. However, we do recommend that OpenGL ES applications call glGenRenderbuffers and use renderbuffer object names returned by glGenRenderbuffers instead of specifying their own buffer object names.

The first time the renderbuffer object name is bound by calling glBindRenderbuffer, the renderbuffer object is allocated with the appropriate default state. If this allocation is successful, the allocated object will become the newly bound renderbuffer object.

The following state and default values are associated with a renderbuffer object:

- Width and height in pixels—The default value is zero.
- Internal format—This describes the format of the pixels stored in the renderbuffer. It must be a color-, depth-, or stencil-renderable format.
- Color bit-depth—This is valid only if the internal format is a color-renderable format. The default value is zero.
- Depth bit-depth—This is valid only if the internal format is a depth-renderable format. The default value is zero.
- Stencil bit-depth—This is valid only if the internal format is a stencil-renderable format. The default value is zero.

glBindRenderbuffer can also be used to bind to an existing renderbuffer object (i.e., an object that has been assigned and used before and, therefore, has a valid state associated with it). No changes to the state of the newly bound renderbuffer object are made by the bind command.

Once a renderbuffer object is bound, we can specify the dimensions and format of the image stored in the renderbuffer. The glRenderbufferStorage command can be used for this purpose.

glRenderbufferStorage looks very similar to glTexImage2D, except that no image data is supplied. You can also create a multisample renderbuffer by using the glRenderbufferStorageMultisample command. glRenderbufferStorage is equivalent to glRenderStorageMultisample with samples set to zero. The width and height of the renderbuffer are specified in pixels and must

```
void   glRenderbufferStorage(GLenum target,
                             GLenum internalformat,
                             GLsizei width, GLsizei height)
void   glRenderbufferStorageMultisample(GLenum target,
                             GLsizei samples,
                             GLenum internalformat,
                             GLsizei width, GLsizei height)
```

target	must be set to `GL_RENDERBUFFER`.
samples	number of samples to be used with the renderbuffer object's storage. Must be less than `GL_MAX_SAMPLES` (`glRenderbufferStorageMultisample` only)
internalformat	must be a format that can be used as a color buffer, depth buffer, or stencil buffer. The supported formats are listed in Tables 12-1 and 12-2.
width	width of the renderbuffer in pixels; must be less than or equal to `GL_MAX_RENDERBUFFER_SIZE`.
height	height of the renderbuffer in pixels; must be less than or equal to `GL_MAX_RENDERBUFFER_SIZE`.

be values that are smaller than the maximum renderbuffer size supported by the implementation. The minimum size value that must be supported by all OpenGL ES implementations is 1. The actual maximum size supported by the implementation can be queried using the following code:

```
GLint maxRenderbufferSize = 0;
glGetIntegerv(GL_MAX_RENDERBUFFER_SIZE, &maxRenderbufferSize);
```

The *`internalformat`* argument specifies the format that the application would like to use to store pixels in the renderbuffer object. Table 12-1 lists the renderbuffer formats to store a color-renderable buffer, and Table 12-2 lists the formats to store a depth-renderable or stencil-renderable buffer.

The renderbuffer object can be attached to the color, depth, or stencil attachment of the framebuffer object without the renderbuffer's storage format and dimensions being specified. The renderbuffer's storage format and dimensions can be specified before or after the renderbuffer object has been attached to the framebuffer object. This information will, however, need to be correctly specified before the framebuffer object and renderbuffer attachment can be used for rendering.

Multisample Renderbuffers

Multisample renderbuffers enable the application to render to off-screen framebuffers with multisample anti-aliasing. The multisample renderbuffers cannot be directly bound to textures, but they can be resolved to single-sample textures using the newly introduced framebuffer blit (described later in this chapter).

As described in the previous section, to create a multisample renderbuffer, you use the `glRenderbufferStorageMultisample` API.

Renderbuffer Formats

Table 12-1 lists the renderbuffer formats to store a color-renderable buffer, and Table 12-2 lists the renderbuffer formats to store a depth-renderable or stencil-renderable buffer.

Table 12-1 Renderbuffer Formats for Color-Renderable Buffer

Internal Format	Red Bits	Green Bits	Blue Bits	Alpha Bits
GL_R8	8	—	—	—
GL_R8UI	ui8	—	—	—
GL_R8I	i8	—	—	—
GL_R16UI	ui16	—	—	—
GL_R16I	i16	—	—	—
GL_R32UI	ui32	—	—	—
GL_R32I	i32	—	—	—

(continues)

Table 12-1 Renderbuffer Formats for Color-Renderable Buffer *(continued)*

Internal Format	Red Bits	Green Bits	Blue Bits	Alpha Bits
GL_RG8	8	8	—	—
GL_RG8UI	ui8	ui8	—	—
GL_RG8I	i8	i8	—	—
GL_RG16UI	ui16	ui16	—	—
GL_RG16I	i16	i16	—	—
GL_RG32UI	ui32	ui32	—	—
GL_RG32I	i32	i32	—	—
GL_RGB8	8	8	8	—
GL_RGB565	5	6	5	—
GL_RGBA8	8	8	8	8
GL_SRGB8_ALPHA8	8	8	8	8
GL_RGB5_A1	5	5	5	1
GL_RGBA4	4	4	4	4
GL_RGB10_A2	10	10	10	2
GL_RGBA8UI	ui8	ui8	ui8	ui8
GL_RGBA8I	i8	i8	i8	i8
GL_RGB10_A2UI	ui10	ui10	ui10	ui2
GL_RGBA16UI	ui16	ui16	ui16	ui16
GL_RGBA16I	i16	i16	i16	i16
GL_RGBA32UI	ui32	ui32	ui32	ui32
GL_RGBA32I	i32	i32	i32	i32

i denotes an integer; ui denotes an unsigned integer type.

Table 12-2 Renderbuffer Formats for Depth-Renderable and Stencil-Renderable Buffer

Internal Format	Depth Bits	Stencil Bits
`GL_DEPTH_COMPONENT16`	16	—
`GL_DEPTH_COMPONENT24`	24	—
`GL_DEPTH_COMPONENT32F`	f32	—
`GL_DEPTH24_STENCIL8`	24	8
`GL_DEPTH32F_STENCIL8`	f32	8
`GL_STENCIL_INDEX8`	—	8

`f` denotes a float type.

Using Framebuffer Objects

We describe how to use framebuffer objects to render to an off-screen buffer (i.e., renderbuffer) or to render to a texture. Before we can use a framebuffer object and specify its attachments, we need to make it the current framebuffer object. The `glBindFramebuffer` command is used to set the current framebuffer object.

```
void   glBindFramebuffer(GLenum target,   GLuint framebuffer)
```

target	must be set to `GL_READ_FRAMEBUFFER`, `GL_DRAW_FRAMEBUFFER`, or `GL_FRAMEBUFFER`
framebuffer	framebuffer object name

Note that `glGenFramebuffers` is not required to assign a framebuffer object name before it is bound using `glBindFramebuffer`. An application can specify an unused framebuffer object name to `glBindFramebuffer`. However, we do recommend that OpenGL ES applications call `glGenFramebuffers` and use framebuffer object names returned by `glGenFramebuffers` instead of specifying their own buffer object names.

On some OpenGL ES 3.0 implementations, the first time a framebuffer object name is bound by calling `glBindFramebuffer`, the framebuffer object is allocated with the appropriate default state. If the allocation is successful, this allocated object is bound as the current framebuffer object for the rendering context.

The following state is associated with a framebuffer object:

- Color attachment point—The attachment point for the color buffer.
- Depth attachment point—The attachment point for the depth buffer.
- Stencil attachment point—The attachment point for the stencil buffer.
- Framebuffer completeness status—Whether the framebuffer is in a complete state and can be rendered to.

For each attachment point, the following information is specified:

- Object type—Specifies the type of object that is associated with the attachment point. This can be `GL_RENDERBUFFER` if a renderbuffer object is attached or `GL_TEXTURE` if a texture object is attached. The default value is `GL_NONE`.
- Object name—Specifies the name of the object attached. This can be either the renderbuffer object name or the texture object name. The default value is 0.
- Texture level—If a texture object is attached, then this specifies the mip level of the texture associated with the attachment point. The default value is 0.
- Texture cubemap face—If a texture object is attached and the texture is a cubemap, then this specifies which one of the six cubemap faces is to be used as the attachment point. The default value is `GL_TEXTURE_CUBE_MAP_POSITIVE_X`.
- Texture layer—Specifies the 2D slice of the 3D texture to be used as the attachment point. The default value is 0.

`glBindFramebuffer` can also be used to bind to an existing framebuffer object (i.e., an object that has been assigned and used before and, therefore, has valid state associated with it). No changes are made to the state of the newly bound framebuffer object.

Once a framebuffer object has been bound, the color, depth, and stencil attachments of the currently bound framebuffer object can be set to a renderbuffer object or a texture. As shown in Figure 12-1, the color attachment can be set to a renderbuffer that stores color values, or to a mip level of a 2D texture or a cubemap face, or to a layer of a 2D array textures, or to a mip level of a 2D slice in a 3D texture. The depth attachment can be set to a renderbuffer that stores depth values or packed depth and stencil values, to a mip level of a 2D depth texture, or to a depth cubemap face. The stencil attachment must be set to a renderbuffer that stores stencil values or packed depth and stencil values.

Attaching a Renderbuffer as a Framebuffer Attachment

The `glFramebufferRenderbuffer` command is used to attach a renderbuffer object to a framebuffer attachment point.

```
void   glFramebufferRenderbuffer(GLenum target,
                                 GLenum attachment,
                                 GLenum renderbuffertarget,
                                 GLuint renderbuffer)
```

target	must be set to `GL_READ_FRAMEBUFFER`, `GL_DRAW_FRAMEBUFFER`, or `GL_FRAMEBUFFER`

attachment	must be one of the following enums:
	`GL_COLOR_ATTACHMENTi`
	`GL_DEPTH_ATTACHMENT`
	`GL_STENCIL_ATTACHMENT`
	`GL_DEPTH_STENCIL_ATTACHMENT`

renderbuffertarget	must be set to `GL_RENDERBUFFER`
renderbuffer	the renderbuffer object that should be used as attachment; the *renderbuffer* must be either zero or the name of an existing renderbuffer object

If `glFramebufferRenderbuffer` is called with *renderbuffer* not equal to zero, this renderbuffer object will be used as the new color, depth, or stencil attachment point as specified by the value of the `attachment` argument.

The attachment point's state will be modified to

- Object type = `GL_RENDERBUFFER`
- Object name = `renderbuffer`
- Texture level and texture layer = 0
- Texture cubemap face = `GL_NONE`

The newly attached renderbuffer object's state or contents of its buffer do not change.

If `glFramebufferRenderbuffer` is called with *`renderbuffer`* equal to zero, then the color, depth, or stencil buffer as specified by `attachment` is detached and reset to zero.

Attaching a 2D Texture as a Framebuffer Attachment

The `glFramebufferTexture2D` command is used to attach a mip level of a 2D texture or a cubemap face to a framebuffer attachment point. It can be used to attach a texture as a color, depth, or stencil attachment.

```
void   glFramebufferTexture2D(GLenum   target,
                              GLenum   attachment,
                              GLenum   textarget,
                              GLuint   texture,
                              Glint    level)
```

target	must be set to `GL_READ_FRAMEBUFFER`, `GL_DRAW_FRAMEBUFFER`, or `GL_FRAMEBUFFER`

attachment	must be one of the following enums:
	`GL_COLOR_ATTACHMENTi`
	`GL_DEPTH_ATTACHMENT`
	`GL_STENCIL_ATTACHMENT`
	`GL_DEPTH_STENCIL_ATTACHMENT`

textarget	specifies the texture target; this is the value specified in the *`target`* argument in `glTexImage2D`
texture	specifies the texture object
level	specifies the mip level of texture image

If `glFramebufferTexture2D` is called with *`texture`* not equal to zero, then the color, depth, or stencil attachment will be set to `texture`. If `glFramebufferTexture2D` generates an error, no change is made to the state of the framebuffer.

The attachment point's state will be modified to

- Object type = `GL_TEXTURE`
- Object name = `texture`
- Texture level = `level`
- Texture cubemap face = valid if the texture attachment is a cubemap and is one of the following values:

  `GL_TEXTURE_CUBE_MAP_POSITIVE_X`

  `GL_TEXTURE_CUBE_MAP_POSITIVE_Y`

  `GL_TEXTURE_CUBE_MAP_POSITIVE_Z`

  `GL_TEXTURE_CUBE_MAP_NEGATIVE_X`

  `GL_TEXTURE_CUBE_MAP_NEGATIVE_Y`

  `GL_TEXTURE_CUBE_MAP_NEGATIVE_Z`
- Texture layer = `0`

The newly attached texture object's state or contents of its image are not modified by `glFramebufferTexture2D`. Note that the texture object's state and image can be modified after it has been attached to a framebuffer object.

If `glFramebufferTexture2D` is called with *`texture`* equal to zero, then the color, depth, or stencil attachment is detached and reset to zero.

Attaching an Image of a 3D Texture as a Framebuffer Attachment

The `glFramebufferTextureLayer` command is used to attach a 2D slice and a specific mip level of a 3D texture or a level of 2D array textures to a framebuffer attachment point. Refer to Chapter 9, "Texturing," for a detailed description of how 3D textures work.

```
void   glFramebufferTextureLayer(GLenum   target,
                                 GLenum   attachment,
                                 GLuint   texture,
                                 GLint    level,
                                 GLint    layer)
```

target	must be set to `GL_READ_FRAMEBUFFER`, `GL_DRAW_FRAMEBUFFER`, or `GL_FRAMEBUFFER`.

attachment	must be one of the following enums:
	`GL_COLOR_ATTACHMENTi`
	`GL_DEPTH_ATTACHMENT`
	`GL_STENCIL_ATTACHMENT`
	`GL_DEPTH_STENCIL_ATTACHMENT`

texture	specifies the texture object.
level	specifies the mip level of the texture image.
layer	specifies the layer of texture image. If *texture* is `GL_TEXTURE_3D`, then *level* must be greater than or equal to zero and less than or equal to log2 of the value of `GL_MAX_3D_TEXTURE_SIZE`. If *texture* is `GL_TEXTURE_2D_ARRAY`, then *level* must be greater than or equal to zero and no larger than log2 of the value `GL_MAX_TEXTURE_SIZE`.

The newly attached texture object's state or contents of its image are not modified by `glFramebufferTextureLayer`. Note that the texture object's state and image can be modified after it has been attached to a framebuffer object.

The attachment point's state will be modified to

- Object type = `GL_TEXTURE`
- Object name = `texture`
- Texture level = `level`
- Texture cubemap face = `GL_NONE`
- Texture layer = `0`

If `glFramebufferTextureLayer` is called with *texture* equal to zero, then the attachment is detached and reset to zero.

One interesting question arises: What happens if we are rendering into a texture and at the same time use this texture object as a texture in a fragment shader? Will the OpenGL ES implementation generate an error when such a situation arises? In some cases, it is possible for the OpenGL ES implementation to determine if a texture object is being used as a texture input and a framebuffer attachment into which we are currently drawing. `glDrawArrays` and `glDrawElements` could then generate an error. To ensure that `glDrawArrays` and `glDrawElements` can be executed as rapidly as possible, however, these checks are not performed. Instead of generating an error, in this case rendering results are undefined. It is the application's responsibility to make sure that this situation does not occur.

Checking for Framebuffer Completeness

A framebuffer object needs to be defined as *complete* before it can be used as a rendering target. If the currently bound framebuffer object is not complete, OpenGL ES commands that draw primitives or read pixels will fail and generate an appropriate error that indicates the reason the framebuffer is incomplete.

The rules for a framebuffer object to be considered complete are as follows:

- Make sure that the color, depth, and stencil attachments are valid. A color attachment is valid if it is zero (i.e., there is no attachment) or if it is a color-renderable renderbuffer object or a texture object with one of the formats listed in Table 12-1. A depth attachment is valid if it is zero or is a depth-renderable renderbuffer object or a depth texture with one of the formats listed in Table 12-2 with depth buffer bits. A stencil attachment is valid if it is zero or is a stencil-renderable renderbuffer object with one of the formats listed in Table 12-2 with stencil buffer bits. There is a minimum of one valid attachment. A framebuffer is not complete if it has no attachments, as there is nothing to draw into or read from.
- Valid attachments associated with a framebuffer object must have the same width and height.
- If depth and stencil attachments exist, they must be the same image.
- The value of `GL_RENDERBUFFER_SAMPLES` is the same for all renderbuffer attachments. If the attachments are a combination of renderbuffers and textures, the value of `GL_RENDERBUFFER_SAMPLES` is zero.

The `glCheckFramebufferStatus` command can be used to verify that a framebuffer object is complete.

GLenum	**glCheckFramebufferStatus**(GLenum *target*)
target	must be set to `GL_READ_FRAMEBUFFER`, `GL_DRAW_FRAMEBUFFER`, or `GL_FRAMEBUFFER`

`glCheckFramebufferStatus` returns zero if *target* is not equal to `GL_FRAMEBUFFER`. If *target* is equal to `GL_FRAMEBUFFER`, one of the following enums is returned:

- `GL_FRAMEBUFFER_COMPLETE`—Framebuffer is complete.
- `GL_FRAMEBUFFER_UNDEFINED`—If *target* is the default framebuffer but it does not exist.
- `GL_FRAMEBUFFER_INCOMPLETE_ATTACHMENT`—The framebuffer attachment points are not complete. This might be due to the fact that the required attachment is zero or is not a valid texture or renderbuffer object.
- `GL_FRAMEBUFFER_INCOMPLETE_MISSING_ATTACHMENT`—No valid attachments in the framebuffer.
- `GL_FRAMEBUFFER_UNSUPPORTED`—The combination of internal formats used by attachments in the framebuffer results in a nonrenderable target.
- `GL_FRAMEBUFFER_INCOMPLETE_MULTISAMPLE`—`GL_RENDERBUFFER_SAMPLES` is not the same for all renderbuffer attachments or `GL_RENDERBUFFER_SAMPLES` is non-zero when the attachments are a combination of renderbuffers and textures.

If the currently bound framebuffer object is not complete, attempts to use that object for reading and writing pixels will fail. In turn, calls to draw primitives, such as `glDrawArrays` and `glDrawElements`, and commands that read the framebuffer, such as `glReadPixels`, `glCopyTeximage2D`, `glCopyTexSubImage2D`, and `glCopyTexSubImage3D`, will generate a `GL_INVALID_FRAMEBUFFER_OPERATION` error.

Framebuffer Blits

Framebuffer blits allow for efficient copying of a rectangle of pixel values from one framebuffer (i.e., read framebuffer) to another framebuffer (i.e., draw framebuffer). One key application of framebuffer blits is to resolve a multisample renderbuffer to a texture (with a framebuffer object that has a texture bound for the color attachment).

You can perform this operation using the following command:

```
void   glBlitFramebuffer(GLint srcX0, GLint srcY0,
                         GLint srcX1, GLint srcY1,
                         GLint dstX0, GLint dstY0,
                         GLint dstX1, GLint dstY1,
                         GLbitfield mask, GLenum filter)
```

srcX0, srcY0, srcX1, srcY1	specify the bound of the source rectangle within the read buffer
dstX0, dstY0, dstX1, dstY1	specify the bound of the destination rectangle within the write buffer
mask	specifies the bit-wise or of the flags indicating which buffers are to be copied; consists of `GL_COLOR_BUFFER_BIT` `GL_DEPTH_BUFFER_BIT` `GL_STENCIL_BUFFER_BIT` `GL_DEPTH_STENCIL_ATTACHMENT`
filter	specifies the interpolation to be applied if the image is stretched; must be `GL_NEAREST` or `GL_LINEAR`

Example 12-1 (as part of the `Chapter_11/MRTs` example) illustrates how to use framebuffer blits to copy four color buffers from a framebuffer object into four quadrants of the window for the default framebuffer.

Example 12-1 Copying Pixels Using Framebuffer Blits

```
void BlitTextures ( ESContext *esContext )
{
   UserData *userData = esContext->userData;

   // set the default framebuffer for writing
   glBindFramebuffer ( GL_DRAW_FRAMEBUFFER,
                       defaultFramebuffer );

   // set the fbo with four color attachments for reading
   glBindFramebuffer ( GL_READ_FRAMEBUFFER, userData->fbo );
```

(continues)

Example 12-1 Copying Pixels Using Framebuffer Blits *(continued)*

```
   // Copy the output red buffer to lower-left quadrant
   glReadBuffer ( GL_COLOR_ATTACHMENT0 );
   glBlitFramebuffer ( 0, 0,
                       esContext->width, esContext->height,
                       0, 0,
                       esContext->width/2, esContext->height/2,
                       GL_COLOR_BUFFER_BIT, GL_LINEAR );

   // Copy the output green buffer to lower-right quadrant
   glReadBuffer ( GL_COLOR_ATTACHMENT1 );
   glBlitFramebuffer ( 0, 0,
                       esContext->width, esContext->height,
                       esContext->width/2, 0,
                       esContext->width, esContext->height/2,
                       GL_COLOR_BUFFER_BIT, GL_LINEAR );

   // Copy the output blue buffer to upper-left quadrant
   glReadBuffer ( GL_COLOR_ATTACHMENT2 );
   glBlitFramebuffer ( 0, 0,
                       esContext->width, esContext->height,
                       0, esContext->height/2,
                       esContext->width/2, esContext->height,
                       GL_COLOR_BUFFER_BIT, GL_LINEAR );

   // Copy the output gray buffer to upper-right quadrant
   glReadBuffer ( GL_COLOR_ATTACHMENT3 );
   glBlitFramebuffer ( 0, 0,
                       esContext->width, esContext->height,
                       esContext->width/2, esContext->height/2,
                       esContext->width, esContext->height,
                       GL_COLOR_BUFFER_BIT, GL_LINEAR );
}
```

Framebuffer Invalidation

Framebuffer invalidation gives the application a mechanism to inform the driver that the contents of the framebuffer are no longer needed. This allows the driver to take several optimization steps: (1) skip unnecessary restoration of the contents of the tiles in tile-based rendering (TBR) architecture for further rendering to a framebuffer, (2) skip unnecessary data copying between GPUs in multi-GPU systems, or (3) skip flushing certain caches in some implementations to improve performance. This functionality is very important to achieve peak performance in many applications, especially those that perform significant amounts of off-screen rendering.

Let us review the design of TBR GPUs to understand why framebuffer invalidation is important for such GPUs. TBR GPUs are commonly employed on mobile devices to minimize the amount of data transferred between the GPU and system memory and thereby reduce one of the biggest consumers of power, memory bandwidth. This is done by adding a fast on-chip memory that can hold a small amount of pixel data. The framebuffer is then divided into many tiles. For each tile, primitives are rendered into the on-chip memory, and then the results are copied to the system memory once completed. Because only a minimal amount of data per pixel (the final pixel result) will be copied to the system memory, this approach saves memory bandwidth between the GPU and system memory.

With framebuffer invalidation, the GPU can remove contents of the framebuffer that are no longer required so as to reduce the amount of contents to be held per frame. In addition, the GPU may remove unnecessary data transfer from the on-chip memory to the system memory if the tile data is no longer valid. Because the memory bandwidth requirement between the GPU and system memory can be reduced significantly, this leads to reduced power consumption and improved performance.

The `glInvalidateFramebuffer` and `glInvalidateSubFramebuffer` commands are used to invalidate the entire framebuffer or a pixel subregion of the framebuffer.

```
void   glInvalidateFramebuffer(GLenum target,
                               GLsizei numAttachments,
                               const GLenum *attachments)

void   glInvalidateSubFramebuffer(GLenum target,
                               GLsizei numAttachments,
                               const GLenum *attachments,
                               GLint x, GLint y,
                               GLsizei width, GLsizei height)
```

target	must be set to `GL_READ_FRAMEBUFFER`, `GL_DRAW_FRAMEBUFFER`, or `GL_FRAMEBUFFER`
numAttachments	number of attachments in the *attachments* list
attachments	pointer to an array of *numAttachments* attachments
x, y	specify the lower-left origin of the pixel rectangle to invalidate (lower-left corner is 0,0) (`glInvalidateSubFramebuffer` only)

width	specifies the width of the pixel rectangle to invalidate (`glInvalidateSubFramebuffer` only)
height	specifies the height of the pixel rectangle to invalidate (`glInvalidateSubFramebuffer` only)

Deleting Framebuffer and Renderbuffer Objects

After the application has finished using renderbuffer objects, they can be deleted. Deleting renderbuffer and framebuffer objects is very similar to deleting texture objects.

Renderbuffer objects are deleted using the `glDeleteRenderbuffers` API.

```
void   glDeleteRenderbuffers(GLsizei n,
                             GLuint *renderbuffers)
```

n	number of renderbuffer object names to delete
renderbuffers	pointer to an array of *n* renderbuffer object names to be deleted

`glDeleteRenderbuffers` deletes the renderbuffer objects specified in `renderbuffers`. Once a renderbuffer object is deleted, it has no state associated with it and is marked as unused; it can then later be reused as a new renderbuffer object. When deleting a renderbuffer object that is also the currently bound renderbuffer object, the renderbuffer object is deleted and the current renderbuffer binding is reset to zero. If the renderbuffer object names specified in `renderbuffers` are invalid or zero, they are ignored (i.e., no error will be generated). Further, if the renderbuffer is attached to the currently bound framebuffer object, it is first detached from the framebuffer and only then deleted.

Framebuffer objects are deleted using the `glDeleteFramebuffers` API.

```
void   glDeleteFramebuffers(GLsizei n,
                            GLuint *framebuffers)
```

n	number of framebuffer object names to delete
framebuffers	pointer to an array of *n* framebuffer object names to be deleted

`glDeleteFramebuffers` deletes the framebuffer objects specified in `framebuffers`. Once a framebuffer object is deleted, it has no state associated with it and is marked as unused; it can then later be reused as a new framebuffer object. When deleting a framebuffer object that is also the currently bound framebuffer object, the framebuffer object is deleted and the current framebuffer binding is reset to zero. If the framebuffer object names specified in `framebuffers` are invalid or zero, they are ignored and no error will be generated.

Deleting Renderbuffer Objects That Are Used as Framebuffer Attachments

What happens if a renderbuffer object being deleted is used as an attachment in a framebuffer object? If the renderbuffer object to be deleted is used as an attachment in the currently bound framebuffer object, `glDeleteRenderbuffers` will reset the attachment to zero. If the renderbuffer object to be deleted is used as an attachment in framebuffer objects that are not currently bound, then `glDeleteRenderbuffers` will not reset these attachments to zero. It is the responsibility of the application to detach these deleted renderbuffer objects from the appropriate framebuffer objects.

Reading Pixels and Framebuffer Objects

The `glReadPixels` command reads pixels from the color buffer and returns them in a user-allocated buffer. The color buffer that will be read from is the color buffer allocated by the window system–provided framebuffer or the color attachment of the currently bound framebuffer object. When a non-zero buffer object is bound to `GL_PIXEL_PACK_BUFFER` using `glBindBuffer`, the `glReadPixels` command can return immediately and invoke DMA transfer to read pixels from the framebuffer and write the data into the pixel buffer object.

Several combinations of *`format`* and *`type`* arguments in `glReadPixels` are supported: a *`format`* of `GL_RGBA`, `GL_RGBA_INTEGER`, or implementation-specific values returned by querying `GL_IMPLEMENTATION_COLOR_READ_FORMAT`; and a *`type`* of `GL_UNSIGNED_BYTE`, `GL_UNSIGNED_INT`, `GL_INT`, `GL_FLOAT`, or implementation-specific values returned by querying `GL_IMPLEMENTATION_COLOR_READ_TYPE`. The implementation-specific format and type returned will depend on the format and type of the currently attached color buffer. These values can change if the currently bound framebuffer changes. They must be queried whenever the currently bound framebuffer object changes to determine the correct implementation-specific format and type values that must be passed to `glReadPixels`.

Examples

Let's now look at some examples that demonstrate how to use framebuffer objects. Example 12-2 demonstrates how to render to texture using framebuffer objects. In this example, we draw to a texture using a framebuffer object. We then use this texture to draw a quad to the window system–provided framebuffer (i.e., the screen). Figure 12-2 shows the generated image.

Example 12-2 Render to Texture

```
GLuint framebuffer;
GLuint depthRenderbuffer;
GLuint texture;
GLint texWidth = 256, texHeight = 256;
GLint maxRenderbufferSize;

glGetIntegerv ( GL_MAX_RENDERBUFFER_SIZE, &maxRenderbufferSize);

// check if GL_MAX_RENDERBUFFER_SIZE is >= texWidth and texHeight

if ( ( maxRenderbufferSize <= texWidth ) ||
     ( maxRenderbufferSize <= texHeight ) )
{
   // cannot use framebuffer objects, as we need to create
   // a depth buffer as a renderbuffer object
   // return with appropriate error
}

// generate the framebuffer, renderbuffer, and texture object names
glGenFramebuffers ( 1, &framebuffer );
glGenRenderbuffers ( 1, &depthRenderbuffer );
glGenTextures ( 1, &texture );

// bind texture and load the texture mip level 0
// texels are RGB565
// no texels need to be specified as we are going to draw into
// the texture
glBindTexture ( GL_TEXTURE_2D, texture );
glTexImage2D ( GL_TEXTURE_2D, 0, GL_RGB, texWidth, texHeight, 0,
               GL_RGB, GL_UNSIGNED_SHORT_5_6_5, NULL );

glTexParameteri ( GL_TEXTURE_2D,  GL_TEXTURE_WRAP_S,
                                  GL_CLAMP_TO_EDGE );
glTexParameteri ( GL_TEXTURE_2D,  GL_TEXTURE_WRAP_T,
                                  GL_CLAMP_TO_EDGE );
glTexParameteri ( GL_TEXTURE_2D,  GL_TEXTURE_MAG_FILTER,
                                  GL_LINEAR );
```

Example 12-2 Render to Texture *(continued)*

```
glTexParameteri ( GL_TEXTURE_2D,  GL_TEXTURE_MIN_FILTER,
                                  GL_LINEAR);

// bind renderbuffer and create a 16-bit depth buffer
// width and height of renderbuffer = width and height of
// the texture
glBindRenderbuffer ( GL_RENDERBUFFER, depthRenderbuffer );
glRenderbufferStorage ( GL_RENDERBUFFER, GL_DEPTH_COMPONENT16,
                        texWidth, texHeight );

// bind the framebuffer
glBindFramebuffer ( GL_FRAMEBUFFER, framebuffer );

// specify texture as color attachment
glFramebufferTexture2D ( GL_FRAMEBUFFER, GL_COLOR_ATTACHMENT0,
                         GL_TEXTURE_2D, texture, 0 );

// specify depth_renderbuffer as depth attachment
glFramebufferRenderbuffer ( GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT,
                            GL_RENDERBUFFER, depthRenderbuffer);

// check for framebuffer complete
status = glCheckFramebufferStatus ( GL_FRAMEBUFFER );
if ( status == GL_FRAMEBUFFER_COMPLETE )
{
   // render to texture using FBO
   // clear color and depth buffer
   glClearColor ( 0.0f, 0.0f, 0.0f, 1.0f );
   glClear ( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );

   // Load uniforms for vertex and fragment shaders
   // used to render to FBO. The vertex shader is the
   // ES 1.1 vertex shader described in Example 8-8 in
   // Chapter 8. The fragment shader outputs the color
   // computed by the vertex shader as fragment color and
   // is described in Example 1-2 in Chapter 1.
   set_fbo_texture_shader_and_uniforms( );

   // drawing commands to the framebuffer object draw_teapot();

   // render to window system-provided framebuffer
   glBindFramebuffer ( GL_FRAMEBUFFER, 0 );
   // Use texture to draw to window system-provided framebuffer.
   // We draw a quad that is the size of the viewport.
   //
   // The vertex shader outputs the vertex position and texture
   // coordinates passed as inputs.
```

(continues)

Example 12-2 Render to Texture *(continued)*

```
   //
   // The fragment shader uses the texture coordinate to sample
   // the texture and uses this as the per-fragment color value.
   set_screen_shader_and_uniforms ( );
   draw_screen_quad ( );
}

// clean up
glDeleteRenderbuffers ( 1, &depthRenderbuffer );
glDeleteFramebuffers ( 1, &framebuffer);
glDeleteTextures ( 1, &texture );
```

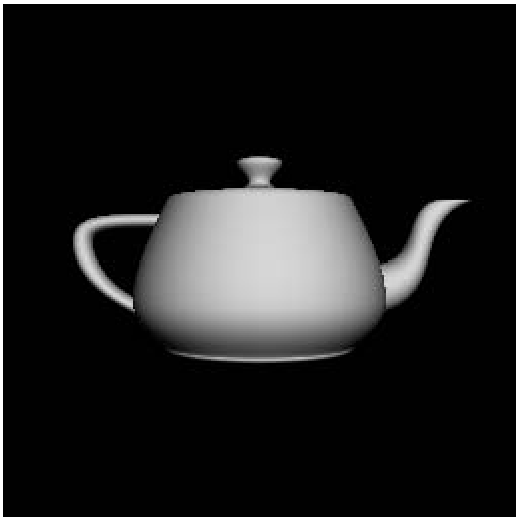

Figure 12-2 Render to Color Texture

In Example 12-2, we create the `framebuffer`, `texture`, and `depthRenderbuffer` objects using the appropriate `glGen***` commands. The `framebuffer` object uses a color attachment that is a texture object (`texture`) and a depth attachment that is a renderbuffer object (`depthRenderbuffer`).

Before we create these objects, we query the maximum renderbuffer size (`GL_MAX_RENDERBUFFER_SIZE`) to verify that the maximum renderbuffer size supported by the implementation is less than or equal to the width and height of texture that will be used as a color attachment. This step ensures that we can create a depth renderbuffer successfully and use it as the depth attachment in `framebuffer`.

After the objects have been created, we call `glBindTexture(texture)` to make the texture the currently bound texture object. The texture mip level is then specified using `glTexImage2D`. Note that the `pixels` argument is `NULL`: We are rendering to the entire texture region, so there is no reason to specify any input data (this data will be overwritten).

The `depthRenderbuffer` object is bound using `glBindRenderbuffer`, and `glRenderbufferStorage` is called to allocate storage for a 16-bit depth buffer.

The `framebuffer` object is bound using `glBindFramebuffer`. `texture` is attached as a color attachment to `framebuffer`, and `depthRenderbuffer` is attached as a depth attachment to `framebuffer`.

We next check the framebuffer status to see if it is complete before we begin drawing into `framebuffer`. Once framebuffer rendering is complete, we reset the currently bound framebuffer to the window system–provided framebuffer by calling `glBindFramebuffer(GL_FRAMEBUFFER, 0)`. We can now use `texture`, which was used as a render target in `framebuffer`, to draw to the window system–provided framebuffer.

In Example 12-2, the depth buffer attachment to `framebuffer` was a renderbuffer object. In Example 12-3, we consider how to use a depth texture as a depth buffer attachment to `framebuffer`. Applications can render to the depth texture used as a framebuffer attachment from the light source. The rendered depth texture can then be used as a shadow map to calculate the percentage in shadow for each fragment. Figure 12-3 shows the generated image.

Example 12-3 Render to Depth Texture

```
#define COLOR_TEXTURE   0
#define DEPTH_TEXTURE   1

GLuint framebuffer;
GLuint textures[2];
GLint  texWidth = 256, texHeight = 256;

// generate the framebuffer and texture object names
glGenFramebuffers ( 1, &framebuffer );
glGenTextures ( 2, textures );

// bind color texture and load the texture mip level 0
// texels are RGB565
// no texels need to specified as we are going to draw into
// the texture
```

(continues)

Example 12-3 Render to Depth Texture *(continued)*

```
glBindTexture ( GL_TEXTURE_2D, textures[COLOR_TEXTURE] );
glTexImage2D ( GL_TEXTURE_2D, 0, GL_RGB, texWidth, texHeight, 0,
               GL_RGB, GL_UNSIGNED_SHORT_5_6_5, NULL );

glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
                  GL_CLAMP_TO_EDGE );
glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
                  GL_CLAMP_TO_EDGE );
glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                  GL_LINEAR );
glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                  GL_LINEAR );

// bind depth texture and load the texture mip level 0
// no texels need to specified as we are going to draw into
// the texture
glBindTexture ( GL_TEXTURE_2D, textures[DEPTH_TEXTURE] );
glTexImage2D ( GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT, texWidth,
               texHeight, 0, GL_DEPTH_COMPONENT,
               GL_UNSIGNED_SHORT, NULL );

glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
                  GL_CLAMP_TO_EDGE );
glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
                  GL_CLAMP_TO_EDGE );
glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                  GL_NEAREST );
glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                  GL_NEAREST );

// bind the framebuffer
glBindFramebuffer ( GL_FRAMEBUFFER, framebuffer );

// specify texture as color attachment
glFramebufferTexture2D ( GL_FRAMEBUFFER, GL_COLOR_ATTACHMENT0,
                         GL_TEXTURE_2D, textures[COLOR_TEXTURE],
                         0 );

// specify texture as depth attachment
glFramebufferTexture2D ( GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT,
                         GL_TEXTURE_2D, textures[DEPTH_TEXTURE],
                         0 );

// check for framebuffer complete
status = glCheckFramebufferStatus ( GL_FRAMEBUFFER );
if ( status == GL_FRAMEBUFFER_COMPLETE )
{
   // render to color and depth textures using FBO
   // clear color and depth buffers
```

Example 12-3 Render to Depth Texture *(continued)*

```
   glClearColor ( 0.0f, 0.0f, 0.0f, 1.0f );
   glClear ( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );

   // Load uniforms for vertex and fragment shaders
   // used to render to FBO. The vertex shader is the
   // ES 1.1 vertex shader described in Example 8-8 in
   // Chapter 8. The fragment shader outputs the color
   // computed by vertex shader as fragment color and
   // is described in Example 1-2 in Chapter 1.
   set_fbo_texture_shader_and_uniforms( );

   // drawing commands to the framebuffer object
   draw_teapot( );

   // render to window system-provided framebuffer
   glBindFramebuffer ( GL_FRAMEBUFFER, 0 );

   // Use depth texture to draw to window system framebuffer.
   // We draw a quad that is the size of the viewport.
   //
   // The vertex shader outputs the vertex position and texture
   // coordinates passed as inputs.
   //
   // The fragment shader uses the texture coordinate to sample
   // the texture and uses this as the per-fragment color value.
   set_screen_shader_and_uniforms( );
   draw_screen_quad( );
}

// clean up
glDeleteFramebuffers ( 1, &framebuffer );
glDeleteTextures ( 2, textures );
```

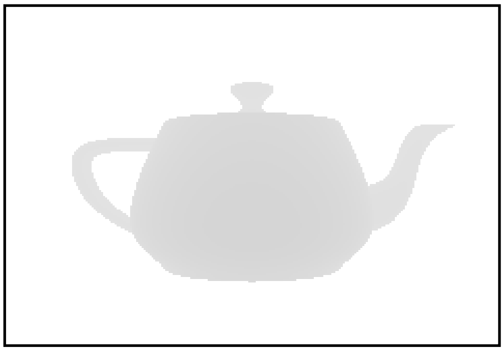

Figure 12-3 Render to Depth Texture

Note: The width and height of the off-screen renderbuffers do not have to be a power of 2.

Performance Tips and Tricks

Here, we discuss some performance tips that developers should carefully consider when using framebuffer objects:

- Avoid frequent switching between rendering to the window system–provided framebuffer and rendering to framebuffer objects. This is an issue for handheld OpenGL ES 3.0 implementations, as many of these implementations use a tile-based rendering architecture. With a tile-based rendering architecture, dedicated internal memory is used to store the color, depth, and stencil values for a tile (i.e., region) of the framebuffer. The internal memory is used as it is much more efficient in terms of power utilization, and it has better memory latency and bandwidth compared with going to external memory. After rendering to a tile is completed, the tile is written out to device (or system) memory. Every time you switch from one rendering target to another, the appropriate texture and renderbuffer attachments will need to be rendered, saved, and restored. This can become quite expensive. The best method would be to render to the appropriate framebuffers in the scene first, and then render to the window system–provided framebuffer, followed by execution of the `eglSwapBuffers` command to swap the display buffer.
- Don't create and destroy framebuffer and renderbuffer objects (or any other large data objects for that matter) per frame.
- Try to avoid modifying textures (using `glTexImage2D`, `glTexSubImage2D`, `glCopyTeximage2D`, and so on) that are attachments to framebuffer objects used as rendering targets.
- Set the `pixels` argument in `glTexImage2D` and `glTexImage3D` to `NULL` if the entire texture image will be rendered, as the original data will not be used anyway. Use `glInvalidateFramebuffer` to clear the texture image before drawing to the texture if you expect the image to have any predefined pixel values in it.
- Share depth and stencil renderbuffers as attachments used by framebuffer objects wherever possible to keep the memory footprint requirement to a minimum. We recognize that this recommendation has limited use, as the width and height of these buffers have to be the same. In a future version of OpenGL ES, the rule that the width and height of various attachments of a framebuffer object must be equal might be relaxed, making sharing easier.

Summary

In this chapter, you learned about the use of framebuffer objects for rendering to off-screen surfaces. There are several uses of framebuffer objects, the most common of which is for rendering to a texture. You learned how to specify color, depth, and stencil attachments to a framebuffer object and how to copy and invalidate pixels in the framebuffer, and then saw some examples that demonstrated rendering to a framebuffer object. Understanding framebuffer objects is critical for implementing many advanced effects, such as reflections, shadow maps, and postprocessing. Next, you will learn about sync objects and fences—the mechanisms to synchronize the application and GPU execution.

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Chapter 13

Sync Objects and Fences

OpenGL ES 3.0 provides a mechanism for the application to wait until a set of OpenGL ES operations have finished executing on the GPU. You can synchronize GL operations among multiple graphics contexts and threads, which can be important in many advanced graphics applications. For example, you may want to wait for transform feedback results before using those results in your applications.

In this chapter, we discuss the flush command, the finish command, and sync objects and fences, including why they are useful and how to use them to synchronize operations in the graphics pipeline. Finally, we conclude with an example of using sync objects and fences.

Flush and Finish

The OpenGL ES 3.0 API inherits the OpenGL client–server model. The application, or client, issues commands, and these commands are processed by the OpenGL ES implementation or server. In OpenGL, the client and the server can reside on different machines over a network. OpenGL ES also allows the client and server to reside on different machines but because OpenGL ES targets handheld and embedded platforms, the client and server will typically be on the same device.

In the client–server model, the commands issued by the client do not necessarily get sent to the server immediately. If the client and server are operating over a network, it will be very inefficient to send individual commands over the network. Instead, the commands can be buffered on the client side and then issued to the server at a later point in time. To support this approach, a mechanism is needed that lets the client know when the server has completed execution of previously submitted commands. Consider another example where multiple OpenGL ES contexts (each current to a different thread) are sharing objects. To synchronize correctly between these contexts, it is important that commands from context A be issued to the server before commands from context B, which depends on OpenGL ES state modified by context A. The `glFlush` command is used to flush any pending commands in the current OpenGL ES context and issue them to the server. Note that `glFlush` only issues the commands to the server; it does not wait for them to complete. If the client requires that the commands be completed, the `glFinish` command should be used. We do not recommend using `glFinish` unless absolutely necessary. Because `glFinish` does not return until all queued commands in the context have been completely processed by the server, calling `glFinish` can adversely impact performance by forcing the client and the server to synchronize their operations.

Why Use a Sync Object?

OpenGL ES 3.0 introduces a new feature, called a fence, that provides a way for the application to inform the GPU to wait until a set of OpenGL ES operations have finished executing before queuing up more for execution. You can insert a fence command into the GL command stream and associate it with a sync object to be waited on.

If we compare using sync objects to the `glFinish` command, sync objects are more efficient, as you can wait on partial completions of the GL command stream. By comparison, calling the `glFinish` command may reduce the performance of your applications, as this command will empty the graphics pipeline.

Creating and Deleting a Sync Object

To insert a fence command to the GL command stream and create a sync object, you can call the following function:

```
GLsync   glFenceSync(GLenum condition, GLbitfield flags)
```

condition	specifies the condition that must be met to signal the sync object; must be `GL_SYNC_GPU_COMMANDS_COMPLETE`
flags	specifies a bit-wise combination of flags to control the behavior of the sync object; must be zero presently

When a sync object is first created, its status is unsignaled. After the specified condition is satisfied by the fence command, then its status becomes signaled. Because sync objects cannot be reused, you must create one sync object for each synchronization operation.

To delete a sync object, you can call the following function:

```
GLvoid   glDeleteSync(GLsync sync)
```

sync	specifies the sync object to be deleted

The deletion operation does not occur immediately, as the sync object will be deleted only when no other operation is waiting for it. Thus you can call the `glDeleteSync` command right after waiting for the sync object, which is described next.

Waiting for and Signaling a Sync Object

You can block the client and wait for a sync object to be signaled with the following call:

```
GLenum   glClientWaitSync(GLsync sync, GLbitfield flags,
                          GLuint64 timeout)
```

sync	specifies the sync object to wait on for its status
flags	specifies a bitfield controlling the command flushing behavior; may be `GL_SYNC_FLUSH_COMMANDS_BIT`
timeout	specifies the timeout in nanoseconds to wait for the sync object to be signaled

If the sync object is already at a signaled state, the `glClientWaitSync` command will return immediately. Otherwise, the call will block and wait up to *`timeout`* nanoseconds for the sync object to be signaled.

The `glClientWaitSync` function can return the following values:

- `GL_ALREADY_SIGNALED`: the sync object was already at the signaled state when the function was called.
- `GL_TIMEOUT_EXPIRED`: the sync object did not become signaled after *`timeout`* nanoseconds passed.
- `GL_CONDITION_SATISFIED`: the sync object was signaled before the timeout expired.
- `GL_WAIT_FAILED`: an error occurred.

The `glWaitSync` function is similar to the `glClientWaitSync` function, except that the function returns immediately and blocks the GPU until the sync object is signaled.

```
void   glWaitSync(GLsync sync, GLbitfield flags,
                  GLuint64 timeout)
```

`sync`	specifies the sync object to wait on for its status.
`flags`	specifies a bitfield controlling the command flushing behavior; must be zero.
`timeout`	specifies the timeout in nanoseconds that the server should wait before continuing; must be `GL_TIMEOUT_IGNORED`.

Example

Example 13-1 shows an example of inserting a fence command after transform feedback buffers are created (see the `EmitParticles` function implementation) and blocking the GPU to wait on the transform feedback results before drawing them (see the `Draw` function implementation). The `EmitParticles` function and `Draw` function are executed by two separate CPU threads.

This code segment is a part of the particle system with transform feedback example that will be described in more detail in Chapter 14, "Advanced Programming with OpenGL ES 3.0."

Example 13-1 Inserting a Fence Command and Waiting for Its Result in Transform Feedback Example

```
void EmitParticles ( ESContext *esContext, float deltaTime )
{
   // Many codes skipped ...

   // Emit particles using transform feedback
   glBeginTransformFeedback ( GL_POINTS );
      glDrawArrays ( GL_POINTS, 0, NUM_PARTICLES );
   glEndTransformFeedback ( );

   // Create a sync object to ensure transform feedback results
   // are completed before the draw that uses them
   userData->emitSync =
      glFenceSync ( GL_SYNC_GPU_COMMANDS_COMPLETE, 0 );

   // Many codes skipped ...
}

void Draw ( ESContext *esContext )
{
   UserData *userData = ( UserData* ) esContext->userData;

   // Block the GL server until transform feedback results
   // are completed
   glWaitSync ( userData->emitSync, 0, GL_TIMEOUT_IGNORED );
   glDeleteSync ( userData->emitSync );

   // Many codes skipped ...

   glDrawArrays ( GL_POINTS, 0, NUM_PARTICLES );
}
```

Summary

In this chapter, you learned about efficient primitives for synchronizing within the host application and GPU execution in OpenGL ES 3.0. We discussed how to use the sync objects and fences. In the next chapter, you will see many advanced rendering examples that tie together all the concepts you have learned so far throughout the book.

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Chapter 14

Advanced Programming with OpenGL ES 3.0

In this chapter, we put together many of the techniques you have learned throughout this book to discuss some advanced uses of OpenGL ES 3.0. A large number of advanced rendering techniques can be accomplished with the programmable flexibility of OpenGL ES 3.0. In this chapter, we cover the following techniques:

- Per-fragment lighting
- Environment mapping
- Particle system with point sprites
- Particle system with transform feedback
- Image postprocessing
- Projective texturing
- Noise using a 3D texture
- Procedural textures
- Terrain rendering with vertex texture fetch
- Shadows using a depth texture

Per-Fragment Lighting

In Chapter 8, "Vertex Shaders," we covered the lighting equations that can be used in the vertex shader to calculate per-vertex lighting. Commonly, to achieve higher-quality lighting, we seek to evaluate the lighting equations on a per-fragment basis. In this section, we provide an example of evaluating ambient, diffuse, and specular lighting on a per-fragment basis. This example is a PVRShaman workspace that can be found in `Chapter_14/PVR_PerFragmentLighting`, as pictured in Figure 14-1. Several of the examples in this chapter make use of PVRShaman, a shader development integrated development environment (IDE) that is part of the Imagination Technologies PowerVR SDK (downloadable from http://powervrinsider.com/).

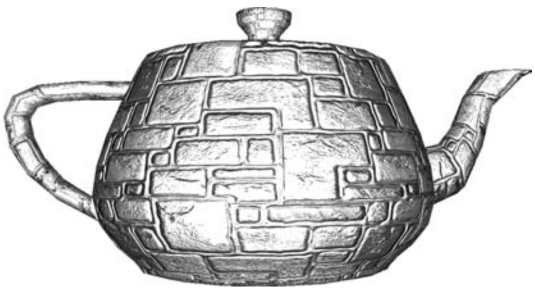

Figure 14-1 Per-Fragment Lighting Example

Lighting with a Normal Map

Before we get into the details of the shaders used in the PVRShaman workspace, we need to discuss the general approach that is used in the example. The simplest way to do lighting per-fragment would be to use the interpolated vertex normal in the fragment shader and then move the lighting computations into the fragment shader. However, for the diffuse term, this would really not yield much better results than doing the lighting on a per-vertex basis. There would be the advantage that the normal vector could be renormalized, which would remove artifacts due to linear interpolation, but the overall quality would be only minimally better. To really take advantage of the ability to do computations on a per-fragment basis, we need to use a normal map to store per-texel normals—a technique that can provide significantly more detail.

A normal map is a 2D texture that stores a normal vector at each texel. The red channel represents the *x* component, the green channel the *y* component, and the blue channel the *z* component. For a normal map stored as `GL_RGB8` with `GL_UNSIGNED_BYTE` data, the values will all be in the range [0, 1]. To represent a normal, these values need to be scaled and biased in the shader to remap to [–1, 1]. The following block of fragment shader code shows how you would go about fetching from a normal map:

```
// Fetch the tangent space normal from normal map
vec3 normal = texture(s_bumpMap, v_texcoord).xyz;

// Scale and bias from [0, 1] to [-1, 1] and normalize
normal = normalize(normal * 2.0 - 1.0);
```

As you can see, this small bit of shader code will fetch the color value from a texture map and then multiply the results by 2 and subtract 1. The result is that the values are rescaled into the [–1, 1] range from the [0, 1] range. We could actually avoid this scale and bias in the shader code by using a signed texture format such as `GL_RGB8_SNORM`, but for the purposes of demonstration we are showing how to use a normal map stored in an unsigned format. In addition, if the data in your normal map are not normalized, you will need to normalize the results in the fragment shader. This step can be skipped if your normal map contains all unit vectors.

The other significant issue to tackle with per-fragment lighting has to do with the space in which the normals in the texture are stored. To minimize computations in the fragment shader, we do not want to have to transform the result of the normal fetched from the normal map. One way to accomplish this would be to store world-space normals in your normal map. That is, the normal vectors in the normal map would each represent a world-space normal vector. Then, the light and direction vectors could be transformed into world space in the vertex shader and could be directly used with the value fetched from the normal map. However, some significant issues arise when storing normal maps in world space. Most importantly, the object must be assumed to be static because no transformation can happen on the object. In addition, the same surface oriented in different directions in space would not be able to share the same texels in the normal map, which can result in much larger maps.

A better solution than using world-space normal maps is to store normal maps in tangent space. The idea behind tangent space is that we define a space for each vertex using three coordinate axes: the normal, binormal, and tangent. The normals stored in the texture map are then all stored in this tangent space. Then, when we want to compute any lighting equations, we transform our incoming lighting vectors into the tangent space and those light vectors can then be used directly with the values in the normal map. The tangent space is typically computed as a preprocess and the binormal and tangent are added to the vertex attribute data. This work is done automatically by PVRShaman, which computes a tangent space for any model that has a vertex normal and texture coordinates.

Lighting Shaders

Once we have tangent space normal maps and tangent space vectors set up, we can proceed with per-fragment lighting. First, let's look at the vertex shader in Example 14-1.

Example 14-1 Per-Fragment Lighting Vertex Shader

```
#version 300 es
uniform mat4 u_matViewInverse;
uniform mat4 u_matViewProjection;
uniform vec3 u_lightPosition;
uniform vec3 u_eyePosition;

in vec4 a_vertex;
in vec2 a_texcoord0;
in vec3 a_normal;
in vec3 a_binormal;
in vec3 a_tangent;

out vec2 v_texcoord;
out vec3 v_viewDirection;
out vec3 v_lightDirection;

void main( void )
{
   // Transform eye vector into world space
   vec3 eyePositionWorld =
      (u_matViewInverse * vec4(u_eyePosition, 1.0)).xyz;

   // Compute world-space direction vector
   vec3 viewDirectionWorld = eyePositionWorld - a_vertex.xyz;

   // Transform light position into world space
   vec3 lightPositionWorld =
      (u_matViewInverse * vec4(u_lightPosition, 1.0)).xyz;

   // Compute world-space light direction vector
   vec3 lightDirectionWorld = lightPositionWorld - a_vertex.xyz;

   // Create the tangent matrix
   mat3 tangentMat = mat3( a_tangent,
                           a_binormal,
                           a_normal );

   // Transform the view and light vectors into tangent space
   v_viewDirection = viewDirectionWorld * tangentMat;
   v_lightDirection = lightDirectionWorld * tangentMat;

   // Transform output position
   gl_Position = u_matViewProjection * a_vertex;
```

Example 14-1 Per-Fragment Lighting Vertex Shader *(continued)*

```
   // Pass through texture coordinate
   v_texcoord = a_texcoord0.xy;

}
```

Note that the vertex shader inputs and uniforms are set up automatically by PVRShaman by setting semantics in the `PerFragmentLighting.pfx` file. We have two uniform matrices that we need as input to the vertex shader: `u_matViewInverse` and `u_matViewProjection`. The `u_matViewInverse` matrix contains the inverse of the view matrix. This matrix is used to transform the light vector and the eye vector (which are in view space) into world space. The first four statements in `main` perform this transformation and compute the light vector and view vector in world space. The next step in the shader is to create a tangent matrix. The tangent space for the vertex is stored in three vertex attributes: `a_normal`, `a_binormal`, and `a_tangent`. These three vectors define the three coordinate axes of the tangent space for each vertex. We construct a 3 × 3 matrix out of these vectors to form the tangent matrix `tangentMat`.

The next step is to transform the view and direction vectors into tangent space by multiplying them by the `tangentMat` matrix. Remember, our purpose here is to get the view and direction vectors into the same space as the normals in the tangent-space normal map. By doing this transformation in the vertex shader, we avoid performing any transformations in the fragment shader. Finally, we compute the final output position and place it in `gl_Position` and pass the texture coordinate along to the fragment shader in `v_texcoord`.

Now we have the view and direction vector in view space and a texture coordinate passed as out variables to the fragment shader. The next step is to actually light the fragments using the fragment shader, as shown in Example 14-2.

Example 14-2 Per-Fragment Lighting Fragment Shader

```
#version 300 es
precision mediump float;

uniform vec4 u_ambient;
uniform vec4 u_specular;
uniform vec4 u_diffuse;
uniform float u_specularPower;
```

(continues)

Example 14-2 Per-Fragment Lighting Fragment Shader *(continued)*

```
uniform sampler2D s_baseMap;
uniform sampler2D s_bumpMap;

in vec2 v_texcoord;
in vec3 v_viewDirection;
in vec3 v_lightDirection;

layout(location = 0) out vec4 fragColor;
void main( void )
{
  // Fetch base map color
  vec4 baseColor = texture(s_baseMap, v_texcoord);

  // Fetch the tangent space normal from normal map
  vec3 normal = texture(s_bumpMap, v_texcoord).xyz;

  // Scale and bias from [0, 1] to [-1, 1] and
  // normalize
  normal = normalize(normal * 2.0 - 1.0);

  // Normalize the light direction and view
  // direction
  vec3 lightDirection = normalize(v_lightDirection);
  vec3 viewDirection = normalize(v_viewDirection);

  // Compute N.L
  float nDotL = dot(normal, lightDirection);

  // Compute reflection vector
  vec3 reflection = (2.0 * normal * nDotL) -
     lightDirection;

  // Compute R.V
  float rDotV =
     max(0.0, dot(reflection, viewDirection));

  // Compute ambient term
  vec4 ambient = u_ambient * baseColor;

  // Compute diffuse term
  vec4 diffuse = u_diffuse * nDotL * baseColor;

  // Compute specular term
  vec4 specular = u_specular *
     pow(rDotV, u_specularPower);

  // Output final color
  fragColor = ambient + diffuse + specular;
}
```

The first part of the fragment shader consists of a series of uniform declarations for the ambient, diffuse, and specular colors. These values are stored in the uniform variables `u_ambient`, `u_diffuse`, and `u_specular`, respectively. The shader is also configured with two samplers, `s_baseMap` and `s_bumpMap`, which are bound to a base color map and the normal map, respectively.

The first part of the fragment shader fetches the base color from the base map and the normal values from the normal map. As described earlier, the normal vector fetched from the texture map is scaled and biased and then normalized so that it is a unit vector with components in the [–1, 1] range. Next, the light vector and view vector are normalized and stored in `lightDirection` and `viewDirection`. Normalization is necessary because of the way fragment shader input variables are interpolated across a primitive. The fragment shader input variables are linearly interpolated across the primitive. When linear interpolation is done between two vectors, the results can become denormalized during interpolation. To compensate for this artifact, the vectors must be normalized in the fragment shader.

Lighting Equations

At this point in the fragment shader, we now have a normal, light vector, and direction vector all normalized and in the same space. This gives us the inputs needed to compute the lighting equations. The lighting computations performed in this shader are as follows:

$$Ambient = k_{Ambient} \times C_{Base}$$

$$Diffuse = k_{Diffuse} \times N \bullet L \times C_{Base}$$

$$Specular = k_{Specular} \times \mathrm{pow}(\max(R \bullet V, 0.0), k_{Specular\ Power}$$

The k constants for ambient, diffuse, and specular colors come from the `u_ambient`, `u_diffuse`, and `u_specular` uniform variables. The C_{Base} is the base color fetched from the base texture map. The dot product of the light vector and the normal vector, $N \bullet L$, is computed and stored in the `nDotL` variable in the shader. This value is used to compute the diffuse lighting term. Finally, the specular computation requires R, which is the reflection vector computed from the equation

$$R = 2 \times N \times (N \bullet L) - L$$

Notice that the reflection vector also requires $N \bullet L$, so the computation used for the diffuse lighting term can be reused in the reflection vector computation. Finally, the lighting terms are stored in the `ambient`, `diffuse`, and `specular` variables in the shader. These results are summed and finally stored in the `fragColor` output variable. The result is a per-fragment lit object with normal data coming from the normal map.

Many variations are possible on per-fragment lighting. One common technique is to store the specular exponent in a texture along with a specular mask value. This allows the specular lighting to vary across a surface. The main purpose of this example is to give you an idea of the types of computations that are typically done for per-fragment lighting. The use of tangent space, along with the computation of the lighting equations in the fragment shader, is typical of many modern games. Of course, it is also possible to add more lights, more material information, and much more.

Environment Mapping

The next rendering technique we cover—related to the previous technique—is performing environment mapping using a cubemap. The example we cover is the PVRShaman workspace `Chapter_14/PVR_EnvironmentMapping`. The results are shown in Figure 14-2.

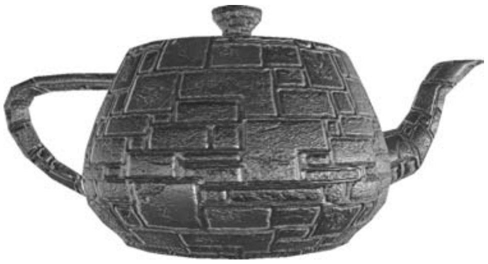

Figure 14-2 Environment Mapping Example

The concept behind environment mapping is to render the reflection of the environment on an object. In Chapter 9, "Texturing," we introduced cubemaps, which are commonly used to store environment maps. In the PVRShaman example workspace, the environment of a mountain scene is stored in a cubemap. The way such cubemaps can be generated is by positioning a camera at the center of a scene and rendering along each of the positive and negative major axis directions using a 90-degree field of view. For reflections that change dynamically, we can render such a cubemap using a framebuffer object dynamically for each frame. For a static environment, this process can be done as a preprocess and the results stored in a static cubemap.

The vertex shader for the environment mapping example is provided in Example 14-3.

Example 14-3 Environment Mapping Vertex Shader

```
#version 300 es
uniform mat4 u_matViewInverse;
uniform mat4 u_matViewProjection;
uniform vec3 u_lightPosition;

in vec4 a_vertex;
in vec2 a_texcoord0;
in vec3 a_normal;
in vec3 a_binormal;
in vec3 a_tangent;

out vec2 v_texcoord;
out vec3 v_lightDirection;
out vec3 v_normal;
out vec3 v_binormal;
out vec3 v_tangent;

void main( void )
{
   // Transform light position into world space
   vec3 lightPositionWorld =
     (u_matViewInverse * vec4(u_lightPosition, 1.0)).xyz;

   // Compute world-space light direction vector
   vec3 lightDirectionWorld = lightPositionWorld - a_vertex.xyz;

   // Pass the world-space light vector to the fragment shader
   v_lightDirection = lightDirectionWorld;

   // Transform output position
   gl_Position = u_matViewProjection * a_vertex;

   // Pass through other attributes
   v_texcoord = a_texcoord0.xy;
   v_normal = a_normal;
   v_binormal = a_binormal;
   v_tangent = a_tangent;
}
```

The vertex shader in this example is very similar to the previous per-fragment lighting example. The primary difference is that rather than transforming the light direction vector into tangent space, we keep the light vector in world space. The reason we must do this is because we ultimately want to fetch from the cubemap using a world-space reflection vector. As such, rather than transforming the light vectors into tangent space, we will transform the normal vector from tangent space into world space. To do so, the vertex shader passes the normal, binormal, and tangent as varyings into the fragment shader so that a tangent matrix can be constructed.

The fragment shader listing for the environment mapping sample is provided in Example 14-4.

Example 14-4 Environment Mapping Fragment Shader

```
#version 300 es
precision mediump float;

uniform vec4 u_ambient;
uniform vec4 u_specular;
uniform vec4 u_diffuse;
uniform float u_specularPower;

uniform sampler2D s_baseMap;
uniform sampler2D s_bumpMap;
uniform samplerCube s_envMap;

in vec2 v_texcoord;
in vec3 v_lightDirection;
in vec3 v_normal;
in vec3 v_binormal;
in vec3 v_tangent;

layout(location = 0) out vec4 fragColor;

void main( void )
{
   // Fetch base map color
   vec4 baseColor = texture( s_baseMap, v_texcoord );

   // Fetch the tangent space normal from normal map
   vec3 normal = texture( s_bumpMap, v_texcoord ).xyz;

   // Scale and bias from [0, 1] to [-1, 1]
   normal = normal * 2.0 - 1.0;

   // Construct a matrix to transform from tangent to
   // world space
   mat3 tangentToWorldMat = mat3( v_tangent,
                                  v_binormal,
                                  v_normal );

   // Transform normal to world space and normalize
   normal = normalize( tangentToWorldMat * normal );

   // Normalize the light direction
   vec3 lightDirection = normalize( v_lightDirection );
```

Example 14-4 Environment Mapping Fragment Shader *(continued)*

```
   // Compute N.L
   float nDotL = dot( normal, lightDirection );

   // Compute reflection vector
   vec3 reflection = ( 2.0 * normal * nDotL ) – lightDirection;

   // Use the reflection vector to fetch from the environment
   // map
   vec4 envColor = texture( s_envMap, reflection );

   // Output final color
   fragColor = 0.25 * baseColor + envColor;
}
```

In the fragment shader, you will notice that the normal vector is fetched from the normal map in the same way as in the per-fragment lighting example. The difference in this example is that rather than leaving the normal vector in tangent space, the fragment shader transforms the normal vector into world space. This is done by constructing the `tangentToWorld` matrix out of the `v_tangent`, `v_binormal`, and `v_normal` varying vectors and then multiplying the fetched normal vector by this new matrix. The reflection vector is then calculated using the light direction vector and normal, both in world space. The result of the computation is a reflection vector that is in world space, exactly what we need to fetch from the cubemap as an environment map. This vector is used to fetch into the environment map using the `texture` function with the `reflection` vector as a texture coordinate. Finally, the resultant `fragColor` is written as a combination of the base map color and the environment map color. The base color is attenuated by 0.25 for the purposes of this example so that the environment map is clearly visible.

This example demonstrates the basics of environment mapping. The same basic technique can be used to produce a large variety of effects. For example, the reflection may be attenuated using a fresnel term to more accurately model the reflection of light on a given material. As mentioned earlier, another common technique is to dynamically render a scene into a cubemap so that the environment reflection varies as an object moves through a scene and the scene itself changes. Using the basic technique shown here, you can extend the technique to accomplish more advanced reflection effects.

Particle System with Point Sprites

The next example we cover is rendering a particle explosion using point sprites. This example demonstrates how to animate a particle in a vertex shader and how to render particles using point sprites. The example we cover is the sample program in `Chapter_14/ParticleSystem`, the results of which are pictured in Figure 14-3.

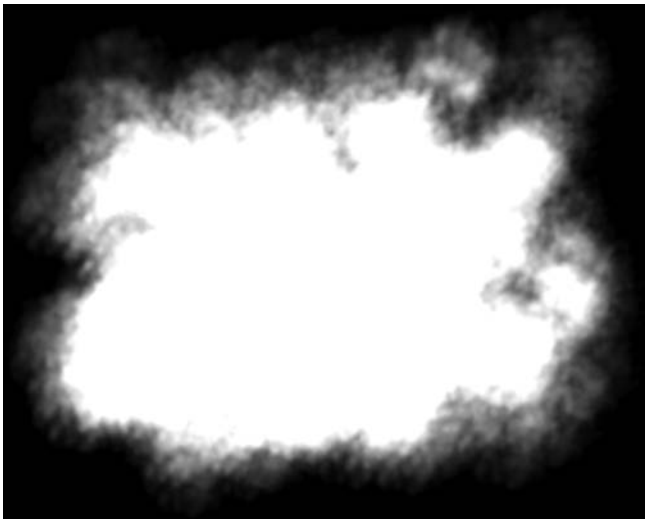

Figure 14-3 Particle System Sample

Particle System Setup

Before diving into the code for this example, it's helpful to cover at a high level the approach this sample uses. One of the goals here is to show how to render a particle explosion without having any dynamic vertex data modified by the CPU. That is, with the exception of uniform variables, there are no changes to any of the vertex data as the explosion animates. To accomplish this goal, a number of inputs are fed into the shaders.

At initialization time, the program initializes the following values in a vertex array, one for each particle, based on a random value:

- **Lifetime**—The lifetime of a particle in seconds.
- **Start position**—The start position of a particle in the explosion.
- **End position**—The final position of a particle in the explosion (the particles are animated by linearly interpolating between the start and end position).

In addition, each explosion has several global settings that are passed in as uniforms:

- **Center position**—The center of the explosion (the per-vertex positions are offset from this center).
- **Color**—An overall color for the explosion.
- **Time**—The current time in seconds.

Particle System Vertex Shader

With this information, the vertex and fragment shaders are completely responsible for the motion, fading, and rendering of the particles. Let's begin by looking at the vertex shader code for the sample in Example 14-5.

Example 14-5 Particle System Vertex Shader

```
#version 300 es
uniform float u_time;
uniform vec3 u_centerPosition;
layout(location = 0) in float a_lifetime;
layout(location = 1) in vec3 a_startPosition;
layout(location = 2) in vec3 a_endPosition;
out float v_lifetime;
void main()
{
  if ( u_time <= a_lifetime )
  {
    gl_Position.xyz = a_startPosition +
                     (u_time * a_endPosition);
    gl_Position.xyz += u_centerPosition;
    gl_Position.w = 1.0;
  }
  else
  {
     gl_Position = vec4( -1000, -1000, 0, 0 );
  }
  v_lifetime = 1.0 - ( u_time / a_lifetime );
  v_lifetime = clamp ( v_lifetime, 0.0, 1.0 );
  gl_PointSize = ( v_lifetime * v_lifetime ) * 40.0;
}
```

The first input to the vertex shader is the uniform variable `u_time`. This variable is set to the current elapsed time in seconds by the application. The value is reset to 0.0 when the time exceeds the length of a single explosion. The next input to the vertex shader is the uniform variable `u_centerPosition`. This variable is set to the center location of the explosion at the start of a new explosion. The setup code for `u_time` and `u_centerPosition` appears in the `Update` function in the C code of the example program, which is provided in Example 14-6.

Example 14-6 Update Function for Particle System Sample

```
void Update (ESContext *esContext, float deltaTime)
{
   UserData *userData = esContext->userData;

   userData->time += deltaTime;

   glUseProgram ( userData->programObject );

   if(userData->time >= 1.0f)
   {
      float centerPos[3];
      float color[4] ;

      userData->time = 0.0f;

      // Pick a new start location and color
      centerPos[0] = ((float)(rand() % 10000)/10000.0f)-0.5f;
      centerPos[1] = ((float)(rand() % 10000)/10000.0f)-0.5f;
      centerPos[2] = ((float)(rand() % 10000)/10000.0f)-0.5f;

      glUniform3fv(userData->centerPositionLoc, 1,
      &centerPos[0]);

      // Random color
      color[0] = ((float)(rand() % 10000) / 20000.0f) + 0.5f;
      color[1] = ((float)(rand() % 10000) / 20000.0f) + 0.5f;
      color[2] = ((float)(rand() % 10000) / 20000.0f) + 0.5f;
      color[3] = 0.5;

      glUniform4fv(userData->colorLoc, 1, &color[0]);
   }
   // Load uniform time variable
   glUniform1f(userData->timeLoc, userData->time);
}
```

As you can see, the `Update` function resets the time after 1 second elapses and then sets up a new center location and time for another explosion. The function also keeps the `u_time` variable up-to-date in each frame.

The vertex inputs to the vertex shader are the particle lifetime, particle start position, and end position. These variables are all initialized to randomly seeded values in the `Init` function in the program. The body of the vertex shader first checks whether a particle's lifetime has expired. If so, the `gl_Position` variable is set to the value (–1000, –1000), which is just a quick way of forcing the point to be off the screen. Because the point will be clipped, all of the subsequent processing for the expired point sprites can be skipped. If the particle is still alive, its position is set to be a linear interpolated value between the start and end positions. Next, the vertex shader passes the remaining lifetime of the particle down into the fragment shader in the varying variable `v_lifetime`. The lifetime will be used in the fragment shader to fade the particle as it ends its life. The final piece of the vertex shader causes the point size to be based on the remaining lifetime of the particle by setting the `gl_Pointsize` built-in variable. This has the effect of scaling the particles down as they reach the end of their life.

Particle System Fragment Shader

The fragment shader code for the example program is provided in Example 14-7.

Example 14-7 Particle System Fragment Shader

```
#version 300 es
precision mediump float;
uniform vec4 u_color;
in float v_lifetime;
layout(location = 0) out vec4 fragColor;
uniform sampler2D s_texture;
void main()
{
  vec4 texColor;
  texColor = texture( s_texture, gl_PointCoord );
  fragColor = vec4( u_color ) * texColor;
  fragColor.a *= v_lifetime;
}
```

The first input to the fragment shader is the `u_color` uniform variable, which is set at the beginning of each explosion by the `Update` function. Next, the `v_lifetime` input variable set by the vertex shader is declared in the fragment shader. In addition, a sampler is declared to which a 2D texture image of smoke is bound.

The fragment shader itself is relatively simple. The texture fetch uses the `gl_PointCoord` variable as a texture coordinate. This special variable for point sprites is set to fixed values for the corners of the point sprite (this process was described in Chapter 7, "Primitive Assembly and

Rasterization," in the discussion of drawing primitives). One could also extend the fragment shader to rotate the point sprite coordinates if rotation of the sprite was required. This requires extra fragment shader instructions, but increases the flexibility of the point sprite.

The texture color is attenuated by the `u_color` variable, and the alpha value is attenuated by the particle lifetime. The application also enables alpha blending with the following blend function:

```
glEnable ( GL_BLEND );
glBlendFunc ( GL_SRC_ALPHA, GL_ONE );
```

As a consequence of this code, the alpha produced in the fragment shader is modulated with the fragment color. This value is then added into whatever values are stored in the destination of the fragment. The result is an additive blend effect for the particle system. Note that various particle effects will use different alpha blending modes to accomplish the desired effect.

The code to actually draw the particles is shown in Example 14-8.

Example 14-8 Draw Function for Particle System Sample

```
void Draw ( ESContext *esContext )
{
   UserData *userData = esContext->userData;

   // Set the viewport
   glViewport ( 0, 0, esContext->width, esContext->height );

   // Clear the color buffer
   glClear ( GL_COLOR_BUFFER_BIT );

   // Use the program object
   glUseProgram ( userData->programObject );

   // Load the vertex attributes
   glVertexAttribPointer ( ATTRIBUTE_LIFETIME_LOC, 1,
                           GL_FLOAT, GL_FALSE,
                           PARTICLE_SIZE * sizeof(GLfloat),
                           userData->particleData );

   glVertexAttribPointer ( ATTRIBUTE_ENDPOSITION_LOC, 3,
                           GL_FLOAT, GL_FALSE,
                           PARTICLE_SIZE * sizeof(GLfloat),
                           &userData->particleData[1] );

   glVertexAttribPointer ( ATTRIBUTE_STARTPOSITION_LOC, 3,
                           GL_FLOAT, GL_FALSE,
                           PARTICLE_SIZE * sizeof(GLfloat),
                           &userData->particleData[4] );
```

Example 14-8 Draw Function for Particle System Sample *(continued)*

```
   glEnableVertexAttribArray ( ATTRIBUTE_LIFETIME_LOC );
   glEnableVertexAttribArray ( ATTRIBUTE_ENDPOSITION_LOC );
   glEnableVertexAttribArray ( ATTRIBUTE_STARTPOSITION_LOC );

   // Blend particles
   glEnable ( GL_BLEND );
   glBlendFunc ( GL_SRC_ALPHA, GL_ONE );

   // Bind the texture
   glActiveTexture ( GL_TEXTURE0 );
   glBindTexture ( GL_TEXTURE_2D, userData->textureId );

   // Set the sampler texture unit to 0
   glUniform1i ( userData->samplerLoc, 0 );

   glDrawArrays( GL_POINTS, 0, NUM_PARTICLES );
}
```

The `Draw` function begins by setting the viewport and clearing the screen. It then selects the program object to use and loads the vertex data using `glVertexAttribPointer`. Note that because the values of the vertex array never change, this example could have used vertex buffer objects rather than client-side vertex arrays. In general, this approach is recommended for any vertex data that does not change because it reduces the vertex bandwidth used. Vertex buffer objects were not used in this example merely to keep the code a bit simpler. After setting the vertex arrays, the function enables the blend function, binds the smoke texture, and then uses `glDrawArrays` to draw the particles.

Unlike with triangles, there is no connectivity for point sprites, so using `glDrawElements` does not really provide any advantage for rendering point sprites in this example. However, often particle systems need to be sorted by depth from back to front to achieve proper alpha blending results. In such cases, one potential approach is to sort the element array to modify the draw order. This technique is very efficient, because it requires minimal bandwidth across the bus per frame (only the index data need be changed, and they are almost always smaller than the vertex data).

This example has demonstrated a number of techniques that can be useful in rendering particle systems using point sprites. The particles were animated entirely on the GPU using the vertex shader. The sizes of the particles were attenuated based on particle lifetime using the `gl_PointSize` variable. In addition, the point sprites were rendered with a texture using the `gl_PointCoord` built-in texture coordinate variable. These are the fundamental elements needed to implement a particle system using OpenGL ES 3.0.

Particle System Using Transform Feedback

The previous example demonstrated one technique for animating a particle system in the vertex shader. Although it included an efficient method for animating particles, the result was severely limited compared to a traditional particle system. In a typical CPU-based particle system, particles are emitted with different initial parameters such as position, velocity, and acceleration and the paths are animated over the particle's lifetime. In the previous example, all of the particles were emitted simultaneously and the paths were limited to a linear interpolation between the start and end positions.

We can build a much more general-purpose GPU-based particle system by using the *transform feedback* feature of OpenGL ES 3.0. To review, transform feedback allows the outputs of the vertex shader to be stored in a buffer object. As a consequence, we can implement a particle emitter completely in a vertex shader on the GPU, store its output into a buffer object, and then use that buffer object with another shader to draw the particles. In general, transform feedback allows you to implement render to vertex buffer (sometimes referred to by the shorthand R2VB), which means that a wide range of algorithms can be moved from the CPU to the GPU.

The example we cover in this section is found in `Chapter_14/ParticleSystemTransformFeedback`. It demonstrates emitting particles for a fountain using transform feedback, as shown in Figure 14-4.

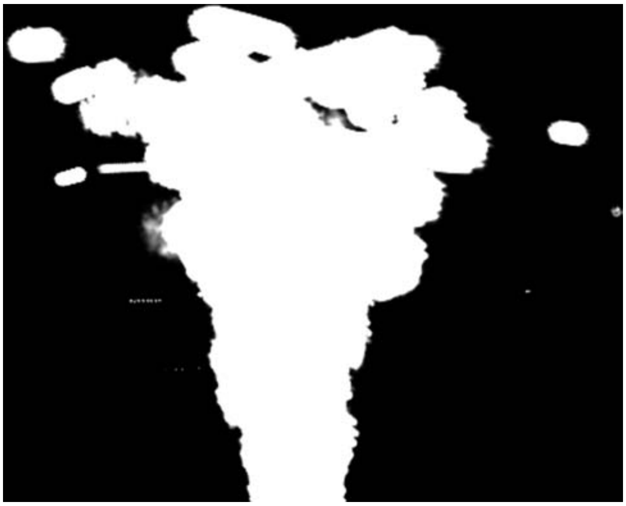

Figure 14-4 Particle System with Transform Feedback

Particle System Rendering Algorithm

This section provides a high-level overview of how the transform feedback-based particle system works. At initialization time, two buffer objects are allocated to hold the particle data. The algorithm ping-pongs (switches back and forth) between the two buffers, each time switching which buffer is the input or output for particle emission. Each particle contains the following information: position, velocity, size, current time, and lifetime.

The particle system is updated with transform feedback and then rendered in the following steps:

- In each frame, one of the particle VBOs is selected as the input and bound as a `GL_ARRAY_BUFFER`. The output is bound as a `GL_TRANSFORM_FEEDBACK_BUFFER`.
- `GL_RASTERIZER_DISCARD` is enabled so that no fragments are drawn.
- The particle emission shader is executed using point primitives (each particle is one point). The vertex shader outputs new particles to the transform feedback buffer and copies existing particles to the transform feedback buffer unchanged.
- `GL_RASTERIZER_DISCARD` is disabled, so that the application can draw the particles.
- The buffer that was rendered to for transform feedback is now bound as a `GL_ARRAY_BUFFER`. Another vertex/fragment shader is bound to draw the particles.
- The particles are rendered to the framebuffer.
- In the next frame, the input/output buffer objects are swapped and the same process continues.

Particle Emission with Transform Feedback

Example 14-9 shows the vertex shader that is used for emitting particles. All of the output variables in this shader are written to a transform feedback buffer object. Whenever a particle's lifetime has expired, the shader will make it a potential candidate for emission as a new active particle. If a new particle is generated, the shader uses a `randomValue` function (shown in the vertex shader code in Example 14-9) that generates a random value to initialize the new particle's velocity and size. The random number generation is based on using a 3D noise texture and using the `gl_VertexID` built-in variable to select a unique texture coordinate for each particle. The details of creating and using a 3D Noise texture are described in the *Noise Using a 3D Texture* section later in this chapter.

Example 14-9 Particle Emission Vertex Shader

```
#version 300 es
#define NUM_PARTICLES           200
#define ATTRIBUTE_POSITION      0
#define ATTRIBUTE_VELOCITY      1
#define ATTRIBUTE_SIZE          2
#define ATTRIBUTE_CURTIME       3
#define ATTRIBUTE_LIFETIME      4

uniform float     u_time;
uniform float     u_emissionRate;
uniform sampler3D s_noiseTex;

layout(location = ATTRIBUTE_POSITION) in vec2  a_position;
layout(location = ATTRIBUTE_VELOCITY) in vec2  a_velocity;
layout(location = ATTRIBUTE_SIZE)     in float a_size;
layout(location = ATTRIBUTE_CURTIME)  in float a_curtime;
layout(location = ATTRIBUTE_LIFETIME) in float a_lifetime;

out vec2  v_position;
out vec2  v_velocity;
out float v_size;
out float v_curtime;
out float v_lifetime;

float randomValue( inout float seed )
{
  float vertexId = float( gl_VertexID ) /
                   float( NUM_PARTICLES );
  vec3 texCoord = vec3( u_time, vertexId, seed );
  seed += 0.1;
  return texture( s_noiseTex, texCoord ).r;
}

void main()
{
  float seed = u_time;
  float lifetime = a_curtime - u_time;
  if( lifetime <= 0.0 && randomValue(seed) < u_emissionRate )
  {
    // Generate a new particle seeded with random values for
    // velocity and size
    v_position = vec2( 0.0, -1.0 );
    v_velocity = vec2( randomValue(seed) * 2.0 - 1.00,
                       randomValue(seed) * 0.4 + 2.0 );
```

Example 14-9 Particle Emission Vertex Shader *(continued)*

```
    v_size = randomValue(seed) * 20.0 + 60.0;
    v_curtime = u_time;
    v_lifetime = 2.0;
  }
  else
  {
    // This particle has not changed; just copy it to the
    // output
    v_position = a_position;
    v_velocity = a_velocity;
    v_size = a_size;
    v_curtime = a_curtime;
    v_lifetime = a_lifetime;
  }
}
```

To use the transform feedback feature with this vertex shader, the output variables must be tagged as being used for transform feedback before linking the program object. This is done in the `InitEmitParticles` function in the example code, where the following snippet shows how the program object is set up for transform feedback:

```
char* feedbackVaryings[5] =
{
   "v_position",
   "v_velocity",
   "v_size",
   "v_curtime",
   "v_lifetime"
};

// Set the vertex shader outputs as transform
// feedback varyings
glTransformFeedbackVaryings ( userData->emitProgramObject, 5,
                              feedbackVaryings,
                              GL_INTERLEAVED_ATTRIBS );

// Link program must occur after calling
// glTransformFeedbackVaryings
glLinkProgram( userData->emitProgramObject );
```

The call to `glTransformFeedbackVaryings` ensures that the passed-in output variables are used for transform feedback. The `GL_INTERLEAVED_ATTRIBS` parameter specifies that the output variables will be interleaved in the output buffer object. The order and layout of the variables must match the expected layout of the buffer object. In this case, our vertex structure is defined as follows:

```
typedef struct
{
   float position[2];
   float velocity[2];
   float size;
   float curtime;
   float lifetime;
} Particle;
```

This structure definition matches the order and type of the varyings that are passed in to `glTransformFeedbackVaryings`.

The code used to emit the particles is provided in the `EmitParticles` function shown in Example 14-10.

Example 14-10 Emit Particles with Transform Feedback

```
void EmitParticles ( ESContext *esContext, float deltaTime )
{
   UserData userData = (UserData) esContext->userData;
      GLuint srcVBO =
   userData->particleVBOs[ userData->curSrcIndex ];
      GLuint dstVBO =
   userData->particleVBOs[(userData->curSrcIndex+1) % 2];

   glUseProgram( userData->emitProgramObject );

   // glVertexAttribPointer and glEnableVeretxAttribArray
   // setup
   SetupVertexAttributes(esContext, srcVBO);

   // Set transform feedback buffer
   glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, dstVBO);

   // Turn off rasterization; we are not drawing
   glEnable(GL_RASTERIZER_DISCARD);

   // Set uniforms
   glUniform1f(userData->emitTimeLoc, userData->time);
   glUniform1f(userData->emitEmissionRateLoc, EMISSION_RATE);

   // Bind the 3D noise texture
   glActiveTexture(GL_TEXTURE0);
   glBindTexture(GL_TEXTURE_3D, userData->noiseTextureId);
   glUniform1i(userData->emitNoiseSamplerLoc, 0);
```

Example 14-10 Emit Particles with Transform Feedback *(continued)*

```
   // Emit particles using transform feedback
   glBeginTransformFeedback(GL_POINTS);
      glDrawArrays(GL_POINTS, 0, NUM_PARTICLES);
   glEndTransformFeedback();

   // Create a sync object to ensure transform feedback
   // results are completed before the draw that uses them
   userData->emitSync = glFenceSync(
                         GL_SYNC_GPU_COMMANDS_COMPLETE, 0 );

   // Restore state
   glDisable(GL_RASTERIZER_DISCARD);
   glUseProgram(0);
   glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, 0);
   glBindTexture(GL_TEXTURE_3D, 0);

   // Ping-pong the buffers
   userData->curSrcIndex = ( userData->curSrcIndex + 1 ) % 2;
}
```

The destination buffer object is bound to the `GL_TRANSFORM_FEEDBACK_BUFFER` target using `glBindBufferBase`. Rasterization is disabled by enabling `GL_RASTERIZER_DISCARD` because we will not actually draw any fragments; instead, we simply want to execute the vertex shader and output to the transform feedback buffer. Finally, before the `glDrawArrays` call, we enable transform feedback rendering by calling `glBeginTransformFeedback(GL_POINTS)`. Subsequent calls to `glDrawArrays` using `GL_POINTS` will then be recorded in the transform feedback buffer until `glEndTransformFeedback` is called. To ensure transform feedback results are completed before the draw call that uses them, we create a sync object and insert a fence command immediately after the `glEndTransformFeedback` is called. Prior to the draw call execution, we will wait on the sync object using the `glWaitSync` call. After executing the draw call and restoring state, we ping-pong between the buffers so that the next time `EmitShaders` is called, it will use the previous frame's transform feedback output as the input.

Rendering the Particles

After emitting the transform feedback buffer, that buffer is bound as a vertex buffer object from which to render the particles. The vertex shader used for particle rendering with point sprites is provided in Example 14-11.

Example 14-11 Particle Rendering Vertex Shader

```
#version 300 es
#define ATTRIBUTE_POSITION      0
#define ATTRIBUTE_VELOCITY      1
#define ATTRIBUTE_SIZE          2
#define ATTRIBUTE_CURTIME       3
#define ATTRIBUTE_LIFETIME      4
layout(location = ATTRIBUTE_POSITION) in vec2 a_position;
layout(location = ATTRIBUTE_VELOCITY) in vec2 a_velocity;
layout(location = ATTRIBUTE_SIZE) in float a_size;
layout(location = ATTRIBUTE_CURTIME) in float a_curtime;
layout(location = ATTRIBUTE_LIFETIME) in float a_lifetime;

uniform float u_time;
uniform vec2 u_acceleration;

void main()
{
  float deltaTime = u_time - a_curtime;
  if ( deltaTime <= a_lifetime )
  {
    vec2 velocity = a_velocity + deltaTime * u_acceleration;
    vec2 position = a_position + deltaTime * velocity;
    gl_Position = vec4( position, 0.0, 1.0 );
    gl_PointSize = a_size * ( 1.0 - deltaTime / a_lifetime );
  }
  else
  {
    gl_Position = vec4( -1000, -1000, 0, 0 );
    gl_PointSize = 0.0;
  }
}
```

This vertex shader uses the transform feedback outputs as input variables. The current age of each particle is computed based on the timestamp that was stored at particle creation for each particle in the `a_curtime` attribute. The particle's velocity and position are updated based on this time. Additionally, the size of the particle is attenuated over the particle's life.

This example has demonstrated how to generate and render a particle system entirely on the GPU. While the particle emitter and rendering were relatively simple here, the same basic model can be used to create more complex particle systems with more involved physics and properties. The primary takeaway message is that transform feedback allows us to generate new vertex data on the GPU without the need for any CPU code. This powerful feature can be used for many algorithms that require generating vertex data on the GPU.

Image Postprocessing

The next example covered in this chapter involves image postprocessing. Using a combination of framebuffer objects and shaders, it is possible to perform a wide variety of image postprocessing techniques. The first example presented here is the simple blur effect in the PVRShaman workspace in `Chapter_14/PVR_PostProcess`, results of which are pictured in Figure 14-5.

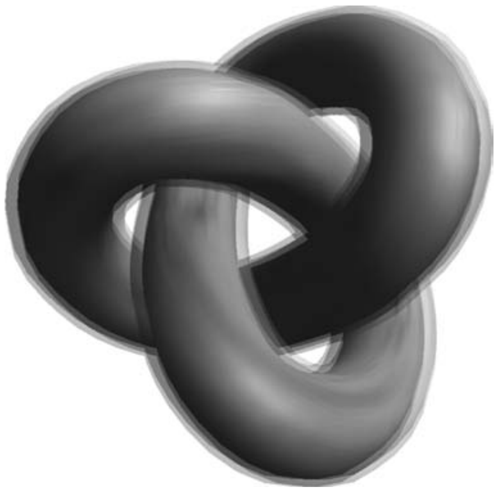

Figure 14-5 Image Postprocessing Example

Render-to-Texture Setup

This example renders a textured knot into a framebuffer object and then uses the color attachment as a texture in a subsequent pass. A full-screen quad is drawn to the screen using the rendered texture as a source. A fragment shader is run over the full-screen quad, which performs a blur filter. In general, many types of postprocessing techniques can be accomplished using this pattern:

1. Render the scene into an off-screen framebuffer object (FBO).
2. Bind the FBO texture as a source and render a full-screen quad to the screen.
3. Execute a fragment shader that performs filtering across the quad.

Some algorithms require performing multiple passes over an image; others require more complicated inputs. However, the general idea is to use a fragment shader over a full-screen quad that performs a postprocessing algorithm.

Blur Fragment Shader

The fragment shader used on the full-screen quad in the blurring example is provided in Example 14-12.

Example 14-12 Blur Fragment Shader

```
#version 300 es
precision mediump float;
uniform sampler2D renderTexture;
uniform float u_blurStep;
in vec2 v_texCoord;
layout(location = 0) out vec4 outColor;
void main(void)
{
   vec4 sample0,
        sample1,
        sample2,
        sample3;

   float fStep = u_blurStep / 100.0;

   sample0 = texture2D ( renderTexture,
      vec2 ( v_texCoord.x - fStep, v_texCoord.y - fStep ) );
   sample1 = texture2D ( renderTexture,
      vec2 ( v_texCoord.x + fStep, v_texCoord.y + fStep ) );
   sample2 = texture2D ( renderTexture,
      vec2 ( v_texCoord.x + fStep, v_texCoord.y - fStep ) );
   sample3 = texture2D ( renderTexture,
      vec2 ( v_texCoord.x - fStep, v_texCoord.y + fStep) );

   outColor = (sample0 + sample1 + sample2 + sample3) / 4.0;
}
```

This shader begins by computing the `fStep` variable, which is based on the `u_blurstep` uniform variable. The `fStep` variable is used to determine how much to offset the texture coordinate when fetching samples from the image. A total of four different samples are taken from the image and then averaged together at the end of the shader. The `fStep` variable is used to offset the texture coordinate in four directions such that four samples in each diagonal direction from the center are taken. The larger the value of `fStep`, the more the image is blurred. One possible optimization to this shader would be to compute the offset texture coordinates in the vertex shader and pass them into varyings in the fragment shader. This approach would reduce the amount of computation done per fragment.

Light Bloom

Now that we have looked at a simple image postprocessing technique, let's consider a slightly more complicated one. Using the blurring technique we introduced in the previous example, we can implement an effect known as *light bloom*. Light bloom is what happens when the eye views a bright light contrasted with a darker surface—that is, the light color bleeds into the darker surface. As you can see from the screenshot in Figure 14-6, the car model color bleeds over the background. The algorithm works as follows:

1. Clear an off-screen render target (`rt0`) and draw the object in black.
2. Blur the off-screen render target (`rt0`) into another render target (`rt1`) using a blur step of 1.0.
3. Blur the off-screen render target (`rt1`) back into the original render target (`rt0`) using a blur step of 2.0.

Note: For more blur, repeat steps 2 and 3 for the amount of blur, increasing the blur step each time.

4. Render the object to the back buffer.
5. Blend the final render target with the back buffer.

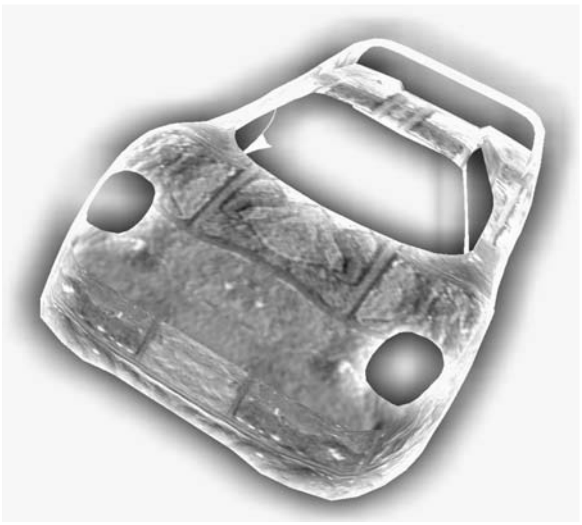

Figure 14-6 Light Bloom Effect

The process this algorithm uses is illustrated in Figure 14-7, which shows each of the steps that goes into producing the final image. As you can see in this figure, the object is first rendered in black to the render target. That render target is then blurred into a second render target in the next pass. The blurred render target is then blurred again, with an expanded blur kernel going back into the original render target. At the end, that blurred render target is blended with the original scene. The amount of bloom can be increased by ping-ponging the blur targets over and over. The shader code for the blur steps is the same as in the previous example; the only difference is that the blur step is being increased for each pass.

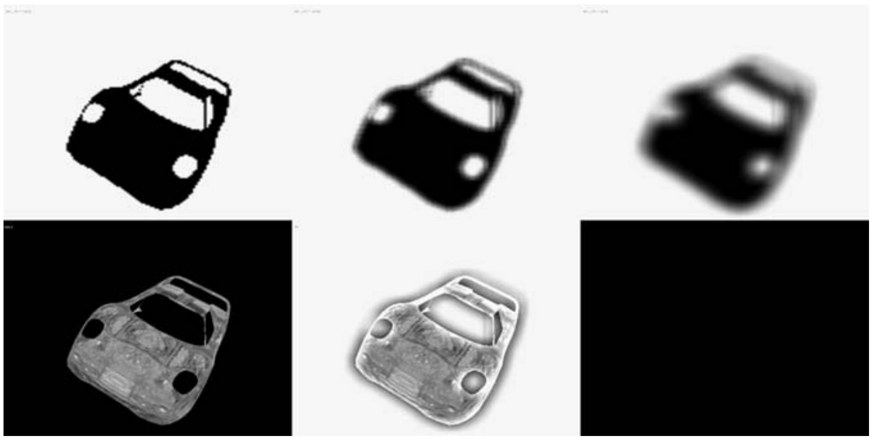

Figure 14-7 Light Bloom Stages

A large variety of other image postprocessing algorithms can be performed using a combination of FBOs and shaders. Some other common techniques include tone mapping, selective blurring, distortion, screen transitions, and depth of field. Using the techniques shown here, you can start to implement other postprocessing algorithms using shaders.

Projective Texturing

A technique that is used to produce many effects, such as shadow mapping and reflections, is projective texturing. To introduce the topic of projective texturing, we provide an example of rendering a projective spotlight. Most of the complexity in using projective texturing derives from the mathematics that goes into calculating the projective texture coordinates. The method shown here could also be used to produce texture coordinates for shadow mapping or reflections. The example offered here is found in the projective spotlight PVRShaman workspace in `Chapter_14/PVR_ProjectiveSpotlight`, the results of which are pictured in Figure 14-8.

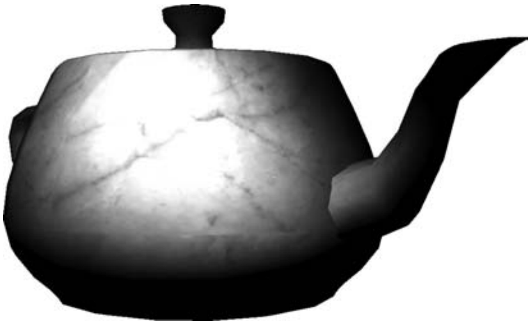

Figure 14-8 Projective Spotlight Example

Projective Texturing Basics

The example uses the 2D texture image pictured in Figure 14-9 and applies it to the surface of a teapot using projective texturing. Projective spotlights were a very common technique used to emulate per-pixel spotlight falloff before shaders were introduced to GPUs. Projective spotlights can still provide an attractive solution because of their high level of efficiency. Applying the projective texture takes just a single texture fetch instruction in the fragment shader and some setup in the vertex shader. In addition, the 2D texture image that is projected can contain really any picture, so many different effects can be achieved.

What, exactly, do we mean by projective texturing? At its most basic, projective texturing is the use of a 3D texture coordinate to look up into a 2D texture image. The (*s*, *t*) coordinates are divided by the (*r*) coordinate such that a texel is fetched using (*s/r*, *t/r*). The OpenGL ES Shading Language provides a special built-in function to do projective texturing called `textureProj`.

```
vec4  textureProj(sampler2D sampler, vec3 coord
                  [, float bias])
```

sampler	a sampler bound to a texture unit specifying the texture to fetch from.
coord	a 3D texture coordinate used to fetch from the texture map. The (*x*, *y*) arguments are divided by (*z*) such that the fetch occurs at (*x/z*, *y/z*).
bias	an optional LOD bias to apply.

Figure 14-9 2D Texture Projected onto Object

The idea behind projective lighting is to transform the position of an object into the projective view space of a light. The projective light space position, after application of a scale and bias, can then be used as a projective texture coordinate. The vertex shader in the PVRShaman example workspace does the work of transforming the position into the projective view space of a light.

Matrices for Projective Texturing

There are three matrices that we need to transform the position into projective view space of the light and get a projective texture coordinate:

- **Light projection**—projection matrix of the light source using the field of view, aspect ratio, and near and far planes of the light.
- **Light view**—The view matrix of the light source. This would be constructed just as if the light were a camera.
- **Bias matrix**—A matrix that transforms the light-space projected position into a 3D projective texture coordinate.

The light projection matrix would be constructed just like any other projection matrix, using the light's parameters for field of view (*FOV*), aspect ratio (*aspect*), and near (*zNear*) and far plane (*zFar*) distances.

$$\begin{pmatrix} \dfrac{\cot\left(\dfrac{FOV}{2}\right)}{aaspect} & 0 & 0 & 0 \\ 0 & \cot\left(\dfrac{FOV}{2}\right) & 0 & 0 \\ 0 & 0 & \dfrac{zFar + zNear}{zNear - zFar} & \dfrac{2 \times zFar + zNear}{zNear - zFar} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

The light view matrix is constructed by using the three primary axis directions that define the light's view axes and the light's position. We refer to the axes as the right, up, and look vectors.

$$\begin{pmatrix} right.x & up.x & look.x & 0 \\ right.y & up.y & look.y & 0 \\ right.z & up.z & look.z & 0 \\ dot(right,-lightPos) & dot(up,-lightPos) & dot(look,-lightPos) & 1 \end{pmatrix}$$

After transforming the object's position by the view and projection matrices, we must then turn the coordinates into projective texture coordinates. This is accomplished by using a 3 × 3 bias matrix on the (*x*, *y*, *z*) components of the position in projective light space. The bias matrix does a linear transformation to go from the [–1, 1] range to the [0, 1] range. Having the coordinates in the [0, 1] range is necessary for the values to be used as texture coordinates.

$$\begin{pmatrix} 0.5 & 0.0 & 0.0 \\ 0.0 & -0.5 & 0.0 \\ 0.5 & 0.5 & 1.0 \end{pmatrix}$$

Typically, the matrix to transform the position into a projective texture coordinate would be computed on the CPU by concatenating the projection, view, and bias matrices together (using a 4 × 4 version of the bias matrix). The result would then be loaded into a single uniform matrix that could transform the position in the vertex shader. However, in the example, we perform this computation in the vertex shader for illustrative purposes.

Projective Spotlight Shaders

Now that we have covered the basic mathematics, we can examine the vertex shader in Example 14-13.

Example 14-13 Projective Texturing Vertex Shader

```
#version 300 es
uniform float u_time_0_X;
uniform mat4 u_matProjection;
uniform mat4 u_matViewProjection;
in vec4 a_vertex;
in vec2 a_texCoord0;
in vec3 a_normal;

out vec2 v_texCoord;
out vec3 v_projTexCoord;
out vec3 v_normal;
out vec3 v_lightDir;

void main( void )
{
  gl_Position = u_matViewProjection * a_vertex;
  v_texCoord = a_texCoord0.xy;

  // Compute a light position based on time
  vec3 lightPos;
  lightPos.x = cos(u_time_0_X);
  lightPos.z = sin(u_time_0_X);
  lightPos.xz = 200.0 * normalize(lightPos.xz);
  lightPos.y = 200.0;

  // Compute the light coordinate axes
  vec3 look = -normalize( lightPos );
  vec3 right = cross( vec3( 0.0, 0.0, 1.0), look );
  vec3 up = cross( look, right );

  // Create a view matrix for the light
  mat4 lightView = mat4( right, dot( right, -lightPos ),
                         up,    dot( up, -lightPos ),
                         look,  dot( look, -lightPos),
                         0.0, 0.0, 0.0, 1.0 );

  // Transform position into light view space
  vec4 objPosLight = a_vertex * lightView;

  // Transform position into projective light view space
  objPosLight = u_matProjection * objPosLight;
```

Example 14-13 Projective Texturing Vertex Shader *(continued)*

```
  // Create bias matrix
  mat3 biasMatrix = mat3( 0.5,  0.0, 0.5,
                          0.0, -0.5, 0.5,
                          0.0,  0.0, 1.0 );
  // Compute projective texture coordinates
  v_projTexCoord = objPosLight.xyz * biasMatrix;

  v_lightDir = normalize(a_vertex.xyz - lightPos);
  v_normal = a_normal;
}
```

The first operation this shader does is to transform the position by the `u_matViewProjection` matrix and output the texture coordinate for the base map to the `v_texCoord` output variable. Next, the shader computes a position for the light based on time. This bit of the code can really be ignored, but it was added to animate the light in the vertex shader. In a typical application, this step would be done on the CPU and not in the shader.

Based on the position of the light, the vertex shader then computes the three coordinate axis vectors for the light and places the results into the `look`, `right`, and `up` variables. Those vectors are used to create a view matrix for the light in the `lightView` variable using the equations previously described. The input position for the object is then transformed by the `lightView` matrix, which transforms the position into light space. The next step is to use the perspective matrix to transform the light space position into projected light space. Rather than creating a new perspective matrix for the light, this example uses the `u_matProjection` matrix for the camera. Typically, a real application would want to create its own projection matrix for the light based on how big the cone angle and falloff distance are.

Once the position is transformed into projective light space, a `biasMatrix` is created to transform the position into a projective texture coordinate. The final projective texture coordinate is stored in the `vec3` output variable `v_projTexCoord`. In addition, the vertex shader passes the light direction and normal vectors into the fragment shader in the `v_lightDir` and `v_normal` variables. These vectors will be used to determine whether a fragment is facing the light source so as to mask off the projective texture for fragments facing away from the light.

The fragment shader performs the actual projective texture fetch that applies the projective spotlight texture to the surface (Example 14-14).

Example 14-14 Projective Texturing Fragment Shader

```
#version 300 es
precision mediump float;

uniform sampler2D baseMap;
uniform sampler2D spotLight;
in vec2 v_texCoord;
in vec3 v_projTexCoord;
in vec3 v_normal;
in vec3 v_lightDir;
out vec4 outColor;

void main( void )
{
    // Projective fetch of spotlight
    vec4 spotLightColor =
       textureProj( spotLight, v_projTexCoord );

    // Base map
    vec4 baseColor = texture( baseMap, v_texCoord );

    // Compute N.L
    float nDotL = max( 0.0, -dot( v_normal, v_lightDir ) );

    outColor = spotLightColor * baseColor * 2.0 * nDotL;
}
```

The first operation that the fragment shader performs is the projective texture fetch using `textureProj`. As you can see, the projective texture coordinate that was computed during the vertex shader and passed in the input variable `v_projTexCoord` is used to perform the projective texture fetch. The wrap modes for the projective texture are set to `GL_CLAMP_TO_EDGE` and the minification/magnification filters are both set to `GL_LINEAR`. The fragment shader then fetches the color from the base map using the `v_texCoord` variable. Next, the shader computes the dot product of the light direction and the normal vector; this result is used to attenuate the final color so that the projective spotlight is not applied to fragments that are facing away from the light. Finally, all of the components are multiplied together (and scaled by 2.0 to increase the brightness). This gives us the final image of the teapot lit by the projective spotlight (refer back to Figure 14-7).

As mentioned at the beginning of this section, the key takeaway lesson from this example is the set of computations that go into computing a projective texture coordinate. The computation shown here is the exact same computation that you would use to produce a coordinate to fetch from a shadow map. Similarly, rendering reflections with projective texturing requires that you transform the position into the projective view space of the reflection camera. You would do the same thing we have done here, but substitute the light matrices for the reflection camera matrices. Projective texturing is a very powerful tool in creating advanced effects, and you should now understand the basics of how to use it.

Noise Using a 3D Texture

The next rendering technique we cover is using a 3D texture for noise. In Chapter 9, "Texturing," we introduced the basics of 3D textures. As you will recall, a 3D texture is essentially a stack of 2D texture slices representing a 3D volume. 3D textures have many possible uses, one of which is the representation of noise. In this section, we show an example of using a 3D volume of noise to create a wispy fog effect. This example builds on the linear fog example from Chapter 10, "Fragment Shaders." The example is found in `Chapter_14/Noise3D`, the results of which are shown in Figure 14-10.

Figure 14-10 Fog Distorted by 3D Noise Texture

Generating Noise

The application of noise is a very common technique that plays a role in a large variety of 3D effects. The OpenGL Shading Language (*not* OpenGL ES Shading Language) included functions for computing noise in one, two, three, and four dimensions. These functions return a pseudorandom continuous noise value that is repeatable based on the input value. Unfortunately, the functions are expensive to implement. Most programmable GPUs did not implement noise functions natively in hardware, which meant the noise computations had to be implemented using shader instructions (or worse, in software on the CPU). It takes a lot of shader instructions to implement these noise functions, so the performance was too slow to be used in most real-time fragment shaders. Recognizing this problem, the OpenGL ES working group decided to drop noise from the OpenGL ES Shading Language (although vendors are still free to expose it through an extension).

Although computing noise in the fragment shader is prohibitively expensive, we can work around the problem using a 3D texture. It is possible to easily produce acceptable-quality noise by precomputing the noise and placing the results in a 3D texture. A number of algorithms can be used to generate noise. The list of references and links described at the end of this chapter can be used to obtain more information about the various noise algorithms. Here, we discuss a specific algorithm that generates a lattice-based gradient noise. Ken Perlin's noise function (Perlin, 1985) is a lattice-based gradient noise and a widely used method for generating noise. For example, a lattice-based gradient noise is implemented by the *noise* function in the Renderman shading language.

The gradient noise algorithm takes a 3D coordinate as input and returns a floating-point noise value. To generate this noise value given an input (*x*, *y*, z), we map the *x*, *y*, and *z* values to appropriate integer locations in a lattice. The number of cells in a lattice is programmable and for our implementation is set to 256 cells. For each cell in the lattice, we need to generate and store a pseudorandom gradient vector. Example 14-15 describes how these gradient vectors are generated.

Example 14-15 Generating Gradient Vectors

```
// permTable describes a random permutation of
// 8-bit values from 0 to 255
static unsigned char permTable[256] = {
   0xE1, 0x9B, 0xD2, 0x6C, 0xAF, 0xC7, 0xDD, 0x90,
   0xCB, 0x74, 0x46, 0xD5, 0x45, 0x9E, 0x21, 0xFC,
   0x05, 0x52, 0xAD, 0x85, 0xDE, 0x8B, 0xAE, 0x1B,
   0x09, 0x47, 0x5A, 0xF6, 0x4B, 0x82, 0x5B, 0xBF,
   0xA9, 0x8A, 0x02, 0x97, 0xC2, 0xEB, 0x51, 0x07,
   0x19, 0x71, 0xE4, 0x9F, 0xCD, 0xFD, 0x86, 0x8E,
   0xF8, 0x41, 0xE0, 0xD9, 0x16, 0x79, 0xE5, 0x3F,
   0x59, 0x67, 0x60, 0x68, 0x9C, 0x11, 0xC9, 0x81,
   0x24, 0x08, 0xA5, 0x6E, 0xED, 0x75, 0xE7, 0x38,
   0x84, 0xD3, 0x98, 0x14, 0xB5, 0x6F, 0xEF, 0xDA,
   0xAA, 0xA3, 0x33, 0xAC, 0x9D, 0x2F, 0x50, 0xD4,
   0xB0, 0xFA, 0x57, 0x31, 0x63, 0xF2, 0x88, 0xBD,
   0xA2, 0x73, 0x2C, 0x2B, 0x7C, 0x5E, 0x96, 0x10,
   0x8D, 0xF7, 0x20, 0x0A, 0xC6, 0xDF, 0xFF, 0x48,
   0x35, 0x83, 0x54, 0x39, 0xDC, 0xC5, 0x3A, 0x32,
   0xD0, 0x0B, 0xF1, 0x1C, 0x03, 0xC0, 0x3E, 0xCA,
   0x12, 0xD7, 0x99, 0x18, 0x4C, 0x29, 0x0F, 0xB3,
   0x27, 0x2E, 0x37, 0x06, 0x80, 0xA7, 0x17, 0xBC,
   0x6A, 0x22, 0xBB, 0x8C, 0xA4, 0x49, 0x70, 0xB6,
```

Example 14-15 Generating Gradient Vectors *(continued)*

```
   0xF4, 0xC3, 0xE3, 0x0D, 0x23, 0x4D, 0xC4, 0xB9,
   0x1A, 0xC8, 0xE2, 0x77, 0x1F, 0x7B, 0xA8, 0x7D,
   0xF9, 0x44, 0xB7, 0xE6, 0xB1, 0x87, 0xA0, 0xB4,
   0x0C, 0x01, 0xF3, 0x94, 0x66, 0xA6, 0x26, 0xEE,
   0xFB, 0x25, 0xF0, 0x7E, 0x40, 0x4A, 0xA1, 0x28,
   0xB8, 0x95, 0xAB, 0xB2, 0x65, 0x42, 0x1D, 0x3B,
   0x92, 0x3D, 0xFE, 0x6B, 0x2A, 0x56, 0x9A, 0x04,
   0xEC, 0xE8, 0x78, 0x15, 0xE9, 0xD1, 0x2D, 0x62,
   0xC1, 0x72, 0x4E, 0x13, 0xCE, 0x0E, 0x76, 0x7F,
   0x30, 0x4F, 0x93, 0x55, 0x1E, 0xCF, 0xDB, 0x36,
   0x58, 0xEA, 0xBE, 0x7A, 0x5F, 0x43, 0x8F, 0x6D,
   0x89, 0xD6, 0x91, 0x5D, 0x5C, 0x64, 0xF5, 0x00,
   0xD8, 0xBA, 0x3C, 0x53, 0x69, 0x61, 0xCC, 0x34,
};

#define NOISE_TABLE_MASK   255

// lattice gradients 3D noise
static float gradientTable[256*3];

#define FLOOR(x)  ((int)(x) - ((x) < 0 && (x) != (int)(x)))
#define smoothstep(t) (t * t * (3.0f - 2.0f * t))
#define lerp(t, a, b) (a + t * (b - a))

void initNoiseTable()
{
   int            i;
   float          a;
   float          x, y, z, r, theta;
   float          gradients[256*3];
   unsigned int   *p, *psrc;

   srandom(0);
   // build gradient table for 3D noise
   for (i=0; i<256; i++)
   {
      /*
      * calculate 1 - 2 * random number
      */
      a = (random() % 32768) / 32768.0f;
      z = (1.0f - 2.0f * a);

      r = sqrtf(1.0f - z * z);    // r is radius of circle

      a = (random() % 32768) / 32768.0f;
      theta = (2.0f * (float)M_PI * a);
      x = (r * cosf(a));
      y = (r * sinf(a));
```

(continues)

Example 14-15 Generating Gradient Vectors *(continued)*

```
      gradients[i*3] = x;
      gradients[i*3+1] = y;
      gradients[i*3+2] = z;
   }

   // use the index in the permutation table to load the
   // gradient values from gradients to gradientTable
   p = (unsigned int *)gradientTable;
   psrc = (unsigned int *)gradients;
   for (i=0; i<256; i++)
   {
      int indx = permTable[i];
      p[i*3] = psrc[indx*3];
      p[i*3+1] = psrc[indx*3+1];
      p[i*3+2] = psrc[indx*3+2];
   }
}
```

Example 14-16 shows how the gradient noise is calculated using the pseudorandom gradient vectors and an input 3D coordinate.

Example 14-16 3D Noise

```
//
// generate the value of gradient noise for a given lattice
// point
//
// (ix, iy, iz) specifies the 3D lattice position
// (fx, fy, fz) specifies the fractional part
//
static float
glattice3D(int ix, int iy, int iz, float fx, float fy,
float fz)
{
   float   *g;
   int      indx, y, z;

   z = permTable[iz & NOISE_TABLE_MASK];
   y = permTable[(iy + z) & NOISE_TABLE_MASK];
   indx = (ix + y) & NOISE_TABLE_MASK;
   g = &gradientTable[indx*3];

   return (g[0]*fx + g[1]*fy + g[2]*fz);
}

//
// generate the 3D noise value
```

Example 14-16 3D Noise *(continued)*

```
// f describes input (x, y, z) position for which the noise value
// needs to be computed. noise3D returns the scalar noise value
//
float
noise3D(float *f)
{
   int   ix, iy, iz;
   float   fx0, fx1, fy0, fy1, fz0, fz1;
   float   wx, wy, wz;
   float   vx0, vx1, vy0, vy1, vz0, vz1;

   ix = FLOOR(f[0]);
   fx0 = f[0] - ix;
   fx1 = fx0 - 1;
   wx = smoothstep(fx0);

   iy = FLOOR(f[1]);
   fy0 = f[1] - iy;
   fy1 = fy0 - 1;
   wy = smoothstep(fy0);

   iz = FLOOR(f[2]);
   fz0 = f[2] - iz;
   fz1 = fz0 - 1;
   wz = smoothstep(fz0);

   vx0 = glattice3D(ix, iy, iz, fx0, fy0, fz0);
   vx1 = glattice3D(ix+1, iy, iz, fx1, fy0, fz0);
   vy0 = lerp(wx, vx0, vx1);
   vx0 = glattice3D(ix, iy+1, iz, fx0, fy1, fz0);
   vx1 = glattice3D(ix+1, iy+1, iz, fx1, fy1, fz0);
   vy1 = lerp(wx, vx0, vx1);
   vz0 = lerp(wy, vy0, vy1);

   vx0 = glattice3D(ix, iy, iz+1, fx0, fy0, fz1);
   vx1 = glattice3D(ix+1, iy, iz+1, fx1, fy0, fz1);
   vy0 = lerp(wx, vx0, vx1);
   vx0 = glattice3D(ix, iy+1, iz+1, fx0, fy1, fz1);
   vx1 = glattice3D(ix+1, iy+1, iz+1, fx1, fy1, fz1);
   vy1 = lerp(wx, vx0, vx1);
   vz1 = lerp(wy, vy0, vy1);

   return lerp(wz, vz0, vz1);;
}
```

The `noise3D` function returns a value between –1.0 and 1.0. The value of gradient noise is always 0 at the integer lattice points. For points in between, trilinear interpolation of gradient values across the eight integer lattice points that surround the point is used to generate the scalar noise value. Figure 14-11 shows a 2D slice of the gradient noise using the preceding algorithm.

Figure 14-11 2D Slice of Gradient Noise

Using Noise

Once we have created a 3D noise volume, it is very easy to use it to produce a variety of effects. In the case of the wispy fog effect, the idea is simple: Scroll the 3D noise texture in all three dimensions based on time and use the value from the texture to distort the fog factor. Let's take a look at the fragment shader in Example 14-17.

Example 14-17 Noise-Distorted Fog Fragment Shader

```
#version 300 es
precision mediump float;
uniform sampler3D s_noiseTex;
uniform float u_fogMaxDist;
uniform float u_fogMinDist;
uniform vec4 u_fogColor;
uniform float u_time;
in vec4 v_color;
in vec2 v_texCoord;
in vec4 v_eyePos;
layout(location = 0) out vec4 outColor;

float computeLinearFogFactor()
```

Example 14-17 Noise-Distorted Fog Fragment Shader *(continued)*

```
{
  float factor;
  // Compute linear fog equation
  float dist = distance( v_eyePos,
                 vec4( 0.0, 0.0, 0.0, 1.0 ) );
  factor = (u_fogMaxDist - dist) /
           (u_fogMaxDist - u_fogMinDist );
  // Clamp in the [0, 1] range
  factor = clamp( factor, 0.0, 1.0 );
  return factor;
}

void main( void )
{
  float fogFactor = computeLinearFogFactor();
  vec3 noiseCoord =
     vec3( v_texCoord.xy + u_time, u_time );
  fogFactor -=
     texture(s_noiseTex, noiseCoord).r * 0.25;
  fogFactor = clamp(fogFactor, 0.0, 1.0);
  vec4 baseColor = v_color;
  outColor = baseColor * fogFactor +
            u_fogColor * (1.0 - fogFactor);
}
```

This shader is very similar to our linear fog example in Chapter 10, "Fragment Shaders." The primary difference is that the linear fog factor is distorted by the 3D noise texture. The shader computes a 3D texture coordinate based on time and places it in `noiseCoord`. The `u_time` uniform variable is tied to the current time and is updated each frame. The 3D texture is set up with *s, t*, and *r* wrap modes of `GL_MIRRORED_REPEAT` so that the noise volume scrolls smoothly on the surface. The (*s*, *t*) coordinates are based on the coordinates for the base texture and scroll in both directions. The *r*-coordinate is based purely on time; thus it is continuously scrolled.

The 3D texture is a single-channel `(GL_R8)` texture, so only the red component of the texture is used (the green and blue channels have the same value as the red channel). The value fetched from the volume is subtracted from the computed `fogFactor` and then used to linearly interpolate between the fog color and base color. The result is a wispy fog that appears to roll in from a distance. Its speed can be increased easily by applying a scale to the `u_time` variable when scrolling the 3D texture coordinates.

You can achieve a number of different effects by using a 3D texture to represent noise. For example, you can use noise to represent dust in a light volume, add a more natural appearance to a procedural texture, and simulate water waves. Applying a 3D texture is a great way to economize on performance, yet still achieve high-quality visual effects. It is unlikely that you can expect handheld devices to compute noise functions in the fragment shader and have enough performance to run at a high frame rate. As such, having a precomputed noise volume will be a very valuable trick to have in your toolkit for creating effects.

Procedural Texturing

The next topic we cover is the generation of procedural textures. Textures are typically described as a 2D image, a cubemap, or a 3D image. These images store color or depth values. Built-in functions defined in the OpenGL ES Shading Language take a texture coordinate, a texture object referred to as a sampler, and return a color or depth value. Procedural texturing refers to textures that are described as a procedure instead of as an image. The procedure describes the algorithm that will generate a texture color or depth value given a set of inputs.

The following are some of the benefits of procedural textures:

- They provide much more compact representation than a stored texture image. All you need to store is the code that describes the procedural texture, which will typically be much smaller in size than a stored image.
- Procedural textures, unlike stored images, have no fixed resolution. As a consequence, they can be applied to the surface without loss of detail. Thus we will not see problematic issues such as reduced detail as we zoom onto a surface that uses a procedural texture. We will, however, encounter these issues when using a stored texture image because of its fixed resolution.

The disadvantages of procedural textures are as follows:

- Although the procedural texture might have a smaller footprint than a stored texture, it might take a lot more cycles to execute the procedural texture versus doing a lookup in the stored texture. With procedural textures, you are dealing with instruction bandwidth, versus memory bandwidth for stored textures. Both the instruction and memory bandwidth are at a premium on handheld devices, and a developer must carefully choose which approach to take.
- Procedural textures can lead to serious aliasing artifacts. Although most of these artifacts can be resolved, they result in additional instructions to the procedural texture code, which can impact the performance of a shader.

The decision whether to use a procedural texture or a stored texture should be based on careful analysis of the performance and memory bandwidth requirements of each.

A Procedural Texture Example

We now look at a simple example that demonstrates procedural textures. We are familiar with how to use a checkerboard texture image to draw a checkerboard pattern on an object. We now look at a procedural texture implementation that renders a checkerboard pattern on an object. The example we cover is the Checker.pod PVRShaman workspace in `Chapter_14/PVR_ProceduralTextures`. Examples 14-18 and 14-19 describe the vertex and fragment shaders that implement the checkerboard texture procedurally.

Example 14-18 Checker Vertex Shader

```
#version 300 es
uniform mat4 mvp_matrix; // combined model-view
                         // + projection matrix

in vec4 a_position; //     input vertex position
in vec2 a_st;       //     input texture coordinate
out vec2 v_st;      //     output texture coordinate

void main()
{
   v_st = a_st;
   gl_Position = mvp_matrix * a_position;
}
```

The vertex shader code in Example 14-18 is really straightforward. It transforms the position using the combined model–view and projection matrix and passes the texture coordinate (`a_st`) to the fragment shader as a varying variable (`v_st`).

The fragment shader code in Example 14-19 uses the `v_st` texture coordinate to draw the texture pattern. Although easy to understand, the fragment shader might yield poor performance because of the multiple conditional checks done on values that can differ over fragments being executed in parallel. This can diminish performance, as the number of vertices or fragments executed in parallel by the GPU is reduced. Example 14-20 is a version of the fragment shader that omits any conditional checks.

Figure 14-12 shows the checkerboard image rendered using the fragment shader in Example 14-17 with `u_frequency` = 10.

Example 14-19 Checker Fragment Shader with Conditional Checks

```
#version 300 es
precision mediump float;

// frequency of the checkerboard pattern
uniform int u_frequency;

in vec2 v_st;
layout(location = 0) out vec4 outColor;

void main()
{
   vec2 tcmod = mod(v_st * float(u_frequency), 1.0);

   if(tcmod.s < 0.5)
   {
      if(tcmod.t < 0.5)
         outColor = vec4(1.0);
      else
         outColor = vec4(0.0);
   }
   else
   {
      if(tcmod.t < 0.5)
         outColor = vec4(0.0);
      else
         outColor = vec4(1.0);
   }
}
```

Example 14-20 Checker Fragment Shader without Conditional Checks

```
#version 300 es
precision mediump float;

// frequency of the checkerboard pattern
uniform int u_frequency;

in vec2 v_st;
layout(location = 0) out vec4 outColor;

void
main()
{
  vec2 texcoord = mod(floor(v_st * float(u_frequency * 2)),2.0);
  float delta = abs(texcoord.x - texcoord.y);
  outColor = mix(vec4(1.0), vec4(0.0), delta);
}
```

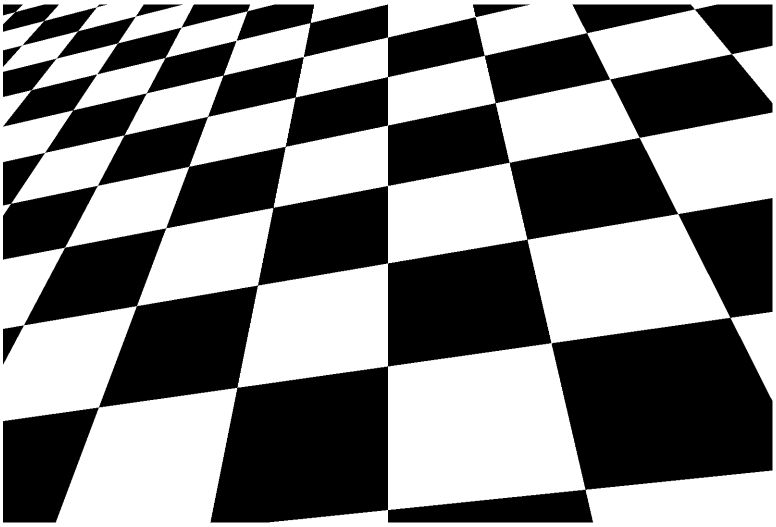
Figure 14-12 Checkerboard Procedural Texture

As you can see, this was really easy to implement. We do see quite a bit of aliasing, which is never acceptable. With a texture checkerboard image, aliasing issues are overcome by using mipmapping and applying preferably a trilinear or bilinear filter. We now look at how to render an anti-aliased checkerboard pattern.

Anti-Aliasing of Procedural Textures

In *Advanced RenderMan: Creating CGI for Motion Pictures*, Anthony Apodaca and Larry Gritz give a very thorough explanation of how to implement analytic anti-aliasing of procedural textures. We use the techniques described in this book to implement our anti-aliased checker fragment shader. Example 14-21 describes the anti-aliased checker fragment shader code from the CheckerAA.rfx PVR_Shaman workspace in `Chapter_14/PVR_ProceduralTextures`.

Example 14-21 Anti-Aliased Checker Fragment Shader

```
#version 300 es
precision mediump float;

uniform int u_frequency;
in vec2 v_st;
layout(location = 0) out vec4 outColor;
```

(continues)

Example 14-21 Anti-Aliased Checker Fragment Shader *(continued)*

```
void main()
{
   vec4    color;
   vec4    color0 = vec4(0.0);
   vec4    color1 = vec4(1.0);
   vec2    st_width;
   vec2    fuzz;
   vec2    check_pos;
   float   fuzz_max;

   // calculate the filter width
   st_width = fwidth(v_st);
   fuzz = st_width * float(u_frequency) * 2.0;
   fuzz_max = max(fuzz.s, fuzz.t);

   // get the place in the pattern where we are sampling
   check_pos = fract(v_st * float(u_frequency));

   if (fuzz_max <= 0.5)
   {
      // if the filter width is small enough, compute
      // the pattern color by performing a smooth interpolation
      // between the computed color and the average color
      vec2 p = smoothstep(vec2(0.5), fuzz + vec2(0.5),
        check_pos) + (1.0 - smoothstep(vec2(0.0), fuzz,
        check_pos));

      color = mix(color0, color1,
                    p.x * p.y + (1.0 - p.x) * (1.0 - p.y));
      color = mix(color, (color0 + color1)/2.0,
         smoothstep(0.125, 0.5, fuzz_max));
   }
   else
   {
      // filter is too wide; just use the average color
      color = (color0 + color1)/2.0;
   }
   outColor = color;
}
```

Figure 14-13 shows the checkerboard image rendered using the anti-aliased fragment shader in Example 14-18 with `u_frequency` = 10.

To anti-alias the checkerboard procedural texture, we need to estimate the average value of the texture over an area covered by the pixel. Given a function `g(v)` that represents a procedural texture, we need to calculate

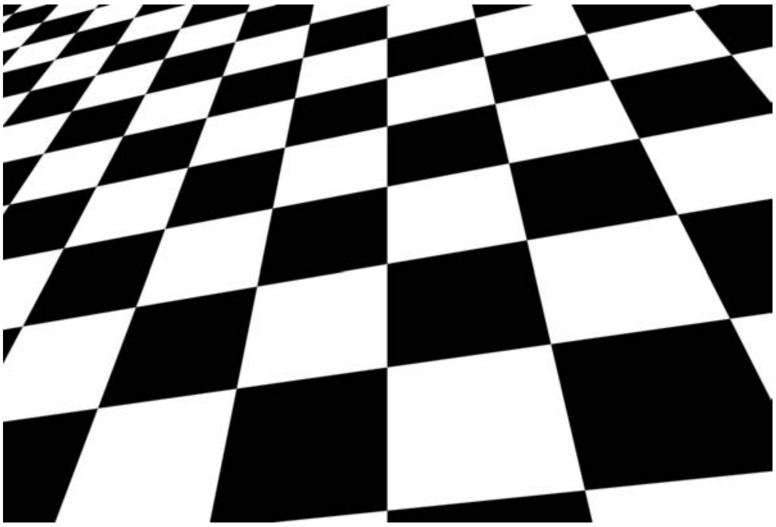

Figure 14-13 Anti-aliased Checkerboard Procedural Texture

the average value of `(v)` of the region covered by this pixel. To determine this region, we need to know the rate of change of `g(v)`. The OpenGL ES Shading Language 3.00 contains derivative functions we can use to compute the rate of change of `g(v)` in `x` and `y` using the functions `dFdx` and `dFdy`. The rate of change, called the gradient vector, is given by `[dFdx(g(v)), dFdy(g(v))]`. The magnitude of the gradient vector is computed as `sqrt ((dFdx(g(v))2 + dFdx(g(v))2)`. This value can also be approximated by `abs(dFdx(g(v)))+abs(dFdy(g(v)))`. The function `fwidth` can be used to compute the magnitude of this gradient vector. This approach works well if `g(v)` is a scalar expression. If `g(v)` is a point, however, we need to compute the cross-product of `dFdx(g(v))` and `dFdy(g(v))`. In the case of the checkerboard texture example, we need to compute the magnitude of the `v_st.x` and `v_st.y` scalar expressions and, therefore, the function `fwidth` can be used to compute the filter widths for `v_st.x` and `v_st.y`.

Let `w` be the filter width computed by `fwidth`. We need to know two additional things about the procedural texture:

- The smallest value of filter width `k` such that the procedural texture `g(v)` will not show any aliasing artifacts for filter widths less than `k/2`.
- The average value of the procedural texture `g(v)` over very large widths.

If `w < k/2`, we should not see any aliasing artifacts. If `w > k/2` (i.e., the filter width is too large), aliasing will occur. We use the average value of `g(v)` in this case. For other values of `w`, we use a `smoothstep` to fade between the true function and average values. The full definition of the `smoothstep` built-in function is provided in Appendix B.

This discussion should have provided you with good insight into how to use procedural textures and how to resolve aliasing artifacts that become apparent when you are using procedural textures. The generation of procedural textures for many different applications is a very broad subject. The following list of references is a good place to start if you are interested in finding more information about procedural texture generation.

Further Reading on Procedural Textures

1. Anthony A. Apodaca and Larry Gritz. *Advanced Renderman: Creating CGI for Motion Pictures* (Morgan Kaufmann, 1999).
2. David S. Ebert, F. Kenton Musgrave, Darwyn Peachey, Ken Perlin, and Steven Worley. *Texturing and Modeling: A Procedural Approach*, 3rd ed. (Morgan Kaufmann, 2002).
3. K. Perlin. An image synthesizer. *Computer Graphics* (SIGGRAPH 1985 Proceedings, pp. 287–296, July 1985).
4. K. Perlin. Improving noise. *Computer Graphics* (SIGGRAPH 2002 Proceedings, pp. 681–682).
5. K. Perlin. Making noise. noisemachine.com/talkl/.
6. Pixar. The Renderman interface specification, version 3.2. July 2000. renderman.pixar.com/products/rispec/index.htm.
7. Randi J. Rost. *OpenGL Shading Language*, 2nd ed. (Addison-Wesley Professional, 2006).

Rendering Terrain with Vertex Texture Fetch

The next topic we cover is rendering terrain with the vertex texture fetch feature in OpenGL ES 3.0. In this example, we show how to render a terrain using a height map, as shown in Figure 14-14.

Our terrain rendering example consists of two steps:

1. Generate a square grid for the terrain base.
2. Compute a vertex normal and fetch height values from the height map in the vertex shader.

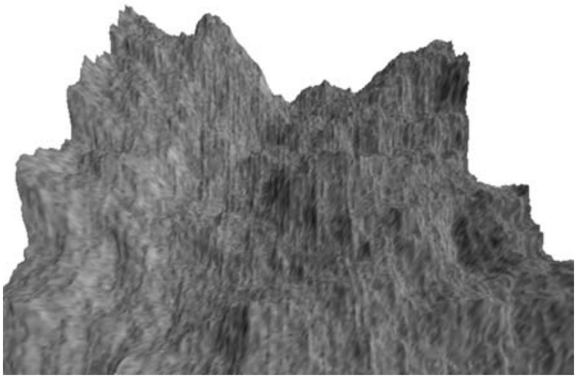

Figure 14-14 Terrain Rendered with Vertex Texture Fetch

Generating a Square Terrain Grid

The code in Example 14-22 generates a square triangle grid that we use as the base terrain.

Example 14-22 Terrain Rendering Flat Grid Generation

```
int ESUTIL_API esGenSquareGrid ( int size, GLfloat **vertices,
                                 GLuint **indices )
{
   int i, j;
   int numIndices = (size-1) * (size-1) * 2 * 3;

   // Allocate memory for buffers
   if ( vertices != NULL )
   {
      int numVertices = size * size;
      float stepSize = (float) size - 1;
      *vertices = malloc ( sizeof(GLfloat) * 3 * numVertices );

      for ( i = 0; i < size; ++i ) // row
      {
         for ( j = 0; j < size; ++j ) // column
         {
            (*vertices)[ 3 * (j + i*size)     ] = i / stepSize;
            (*vertices)[ 3 * (j + i*size) + 1 ] = j / stepSize;
            (*vertices)[ 3 * (j + i*size) + 2 ] = 0.0f;
         }
      }
   }
```

(continues)

Example 14-22 Terrain Rendering Flat Grid Generation *(continued)*

```
   // Generate the indices
   if ( indices != NULL )
   {
      *indices = malloc ( sizeof(GLuint) * numIndices );

      for ( i = 0; i < size - 1; ++i )
      {
         for ( j = 0; j < size - 1; ++j )
         {
            // two triangles per quad
            (*indices)[ 6*(j+i*(size-1))   ] = j+(i)  *(size)   ;
            (*indices)[ 6*(j+i*(size-1))+1 ] = j+(i)  *(size)+1 ;
            (*indices)[ 6*(j+i*(size-1))+2 ] = j+(i+1)*(size)+1 ;

            (*indices)[ 6*(j+i*(size-1))+3 ] = j+(i)  *(size)   ;
            (*indices)[ 6*(j+i*(size-1))+4 ] = j+(i+1)*(size)+1 ;
            (*indices)[ 6*(j+i*(size-1))+5 ] = j+(i+1)*(size)   ;
         }
      }
   }

   return numIndices;
}
```

First, we generate the vertex position as a regularly spaced *xy*-coordinate in the [0, 1] range. The same *xy*-value can also be used as the vertex texture coordinate to look up the height value from the height map.

Second, we generate a list of indices for `GL_TRIANGLES`. A better method is to generate a list of indices for `GL_TRIANGLE_STRIP`, as you can improve the rendering performance by improving the vertex cache locality in the GPU.

Computing Vertex Normal and Fetching Height Value in Vertex Shader

Example 14-23 shows how to compute vertex normals and fetch height values from a height map in a vertex shader.

Example 14-23 Terrain Rendering Vertex Shader

```
#version 300 es
uniform mat4 u_mvpMatrix;
uniform vec3 u_lightDirection;
layout(location = 0) in vec4 a_position;
```

Example 14-23 Terrain Rendering Vertex Shader *(continued)*

```
uniform sampler2D s_texture;
out vec4 v_color;
void main()
{
   // compute vertex normal from height map
   float hxl = textureOffset( s_texture,
                  a_position.xy, ivec2(-1,  0) ).w;
   float hxr = textureOffset( s_texture,
                  a_position.xy, ivec2( 1,  0) ).w;
   float hyl = textureOffset( s_texture,
                  a_position.xy, ivec2( 0, -1) ).w;
   float hyr = textureOffset( s_texture,
                  a_position.xy, ivec2( 0,  1) ).w;
   vec3 u = normalize( vec3(0.05, 0.0, hxr-hxl) );
   vec3 v = normalize( vec3(0.0, 0.05, hyr-hyl) );
   vec3 normal = cross( u, v );

   // compute diffuse lighting
   float diffuse = dot( normal, u_lightDirection );
   v_color = vec4( vec3(diffuse), 1.0 );

   // get vertex position from height map
   float h = texture ( s_texture, a_position.xy ).w;
   vec4 v_position = vec4 ( a_position.xy,
                            h/2.5,
                            a_position.w );
   gl_Position = u_mvpMatrix * v_position;
}
```

The example provided in the `Chapter_14/TerrainRendering` folder shows a simple way of rendering terrain using a height map. If you are interested in finding out more about this topic, you can find many advanced techniques for efficiently rendering a large terrain model using the following list of references.

Further Reading on Large Terrain Rendering

1. Marc Duchaineau et al. *ROAMing Terrain: Real-Time Optimally Adapting Meshes* (IEEE Visualization, 1997).
2. Peter Lindstorm et al. *Real-Time Continuous Level of Detail Rendering of Height Fields* (Proceedings of SIGGRAPH, 1996).
3. Frank Losasso and Hugues Hoppe. *Geometry Clipmaps: Terrain Rendering Using Nested Regular Grids,* ACM Trans. Graphics (SIGGRAPH, 2004).

4. Krzystof Niski, Budirijanto Purnomo, and Jonathan Cohen. *Multi-grained Level of Detail Using Hierarchical Seamless Texture Atlases* (ACM SIGGRAPH I3D, 2007).
5. Filip Strugar. Continuous distance-dependent level of detail for rendering heightmaps (*Journal of Graphics, GPU and Game Tools*, vol. 14, issue 4, 2009).

Shadows Using a Depth Texture

The next topic we cover is rendering shadows using a depth texture in OpenGL ES 3.0 using a two-rendering-pass algorithm:

1. In the first rendering pass, we draw the scene from the point of view of the light. We record the fragment depth value into a texture.
2. In the second rendering pass, we render the scene from the point of view of the eye position. In the fragment shader, we perform a depth test that determines whether the fragment is in the shadow by sampling the depth texture.

In addition, we use the percentage closer filtering (PCF) technique to sample the depth texture to generate soft shadows.

The result of executing the shadow rendering example from `Chapter_14/Shadows` is shown in Figure 14-15.

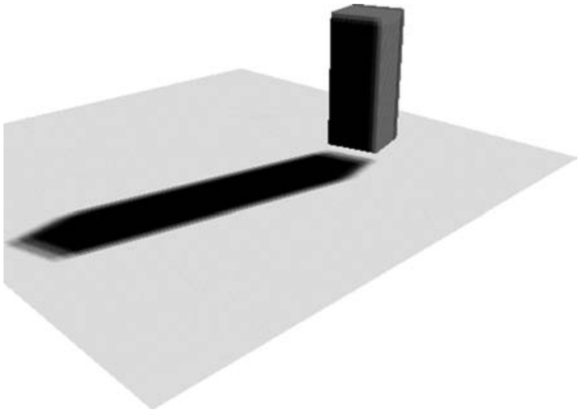

Figure 14-15 Shadow Rendering with a Depth Texture and 6 × 6 PCF

Rendering from the Light Position Into a Depth Texture

We render the scene from the point of view of the light into a depth texture using the following steps:

1. Set up a MVP matrix using the light position.

   Example 14-24 shows the MVP transformation matrix generated by concatenating orthographic projection, model, and view transformation matrices.

Example 14-24 Set up a MVP Matrix from the Light Position

```
// Generate an orthographic projection matrix
esMatrixLoadIdentity ( &ortho );
esOrtho ( &ortho, -10, 10, -10, 10, -30, 30 );

// Generate a model matrix
esMatrixLoadIdentity ( &model );

esTranslate ( &model, -2.0f, -2.0f, 0.0f );
esScale ( &model, 10.0f, 10.0f, 10.0f );
esRotate ( &model, 90.0f, 1.0f, 0.0f, 0.0f );

// Generate a view-matrix transformation
// from the light position
esMatrixLookAt ( &view,
                 userData->lightPosition[0],
                 userData->lightPosition[1],
                 userData->lightPosition[2],
                 0.0f, 0.0f, 0.0f,
                 0.0f, 1.0f, 0.0f );

esMatrixMultiply ( &modelview, &model, &view );

// Compute the final MVP
esMatrixMultiply ( &userData->groundMvpLightMatrix,
                   &modelview, &ortho );
```

2. Create a depth texture and attach it to a framebuffer object.

   Example 14-25 shows how to create a 1024 × 1024 16-bit depth texture to store the shadow map. The shadow map is set with a `GL_LINEAR` texture filter. When it is used with a `sampler2Dshadow` sampler type, we gain a hardware-based PCF, as the hardware will perform four depth comparisons in a single tap. We then show how to render into a framebuffer object with a depth texture attachment (recall that this topic was discussed in Chapter 12, "Framebuffer Objects").

Example 14-25 Create a Depth Texture and Attach It to a Framebuffer Object

```
int InitShadowMap ( ESContext *esContext )
{
   UserData userData = (UserData) esContext->userData;
   GLenum none = GL_NONE;

   // use 1K x 1K texture for shadow map
   userData->shadowMapTextureWidth = 1024;
   userData->shadowMapTextureHeight = 1024;

   glGenTextures ( 1, &userData->shadowMapTextureId );
   glBindTexture ( GL_TEXTURE_2D, userData->shadowMapTextureId);
   glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                     GL_NEAREST );
   glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                     GL_LINEAR );
   glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
                     GL_CLAMP_TO_EDGE );
   glTexParameteri ( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
                     GL_CLAMP_TO_EDGE );

   // set up hardware comparison
   glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
                    GL_COMPARE_REF_TO_TEXTURE );
   glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_COMPARE_FUNC,
                    GL_LEQUAL );

   glTexImage2D ( GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT16,
                  userData->shadowMapTextureWidth,
                  userData->shadowMapTextureHeight,
                  0, GL_DEPTH_COMPONENT, GL_UNSIGNED_SHORT,
                  NULL );

   glBindTexture ( GL_TEXTURE_2D, 0 );

   GLint defaultFramebuffer = 0;
   glGetIntegerv ( GL_FRAMEBUFFER_BINDING,
                   &defaultFramebuffer );

   // set up fbo
   glGenFramebuffers ( 1, &userData->shadowMapBufferId );
   glBindFramebuffer ( GL_FRAMEBUFFER,
                       userData->shadowMapBufferId );

   glDrawBuffers ( 1, &none );

   glFramebufferTexture2D ( GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT,
                            GL_TEXTURE_2D,
                            userData->shadowMapTextureId, 0 );
```

Example 14-25 Create a Depth Texture and Attach It to a Framebuffer Object *(continued)*

```
   glActiveTexture ( GL_TEXTURE0 );
   glBindTexture ( GL_TEXTURE_2D, userData->shadowMapTextureId);

   if ( GL_FRAMEBUFFER_COMPLETE !=
           glCheckFramebufferStatus ( GL_FRAMEBUFFER ) )
   {
      return FALSE;
   }

   glBindFramebuffer ( GL_FRAMEBUFFER, defaultFramebuffer );

   return TRUE;
}
```

3. Render the scene using a pass-through vertex and fragment shader.

   Example 14-26 provides the vertex and fragment shaders used to render the scene to the depth texture from the point of view of the light. Both shaders are very simple, as we need simply to record the fragment depth value into the shadow map texture.

Example 14-26 Rendering to Depth Texture Shaders

```
// vertex shader
#version 300 es
uniform mat4 u_mvpLightMatrix;
layout(location = 0) in vec4 a_position;
out vec4 v_color;
void main()
{
   gl_Position = u_mvpLightMatrix * a_position;
}

// fragment shader
#version 300 es
precision lowp float;
void main()
{
}
```

To use these shaders, in the host code prior to rendering the scene, we clear the depth buffer and disable color rendering. To avoid the creation of a shadow rendering artifact due to a precision problem, we can use a polygon offset command to increase the depth values written to the texture.

```
// clear depth buffer
glClear( GL_DEPTH_BUFFER_BIT );

// disable color rendering; only write to depth buffer
glColorMask ( GL_FALSE, GL_FALSE, GL_FALSE, GL_FALSE );

// reduce shadow rendering artifact
glEnable ( GL_POLYGON_OFFSET_FILL );
glPolygonOffset( 4.0f, 100.0f );
```

Rendering from the Eye Position with the Depth Texture

We render the scene from the point of view of the light into a depth texture using the following steps:

1. Set up a MVP matrix using the eye position.

   The MVP matrix setup consists of the same code as in Example 14-24, with the exception that we create the view transformation matrix by passing the eye position to the `esMatrixLookAt` call as follows:

   ```
   // create a view-matrix transformation
   esMatrixLookAt ( &view,
                    userData->eyePosition[0],
                    userData->eyePosition[1],
                    userData->eyePosition[2],
                    0.0f, 0.0f, 0.0f,
                    0.0f, 1.0f, 0.0f );
   ```

2. Render the scene using the shadow map created in the first rendering pass.

Example 14-27 shows the vertex and fragment shaders that we use to render the scene from the eye position.

Example 14-27 Rendering from the Eye Position Shaders

```
// vertex shader
#version 300 es
uniform mat4 u_mvpMatrix;
uniform mat4 u_mvpLightMatrix;
layout(location = 0) in vec4 a_position;
layout(location = 1) in vec4 a_color;
out vec4 v_color;
out vec4 v_shadowCoord;
void main()
```

Example 14-27 Rendering from the Eye Position Shaders *(continued)*

```
{
   v_color = a_color;
   gl_Position = u_mvpMatrix * a_position;
   v_shadowCoord = u_mvpLightMatrix * a_position;

   // transform from [-1,1] to [0,1];
   v_shadowCoord = v_shadowCoord * 0.5 + 0.5;
}

// fragment shader
#version 300 es
precision lowp float;
uniform lowp sampler2DShadow s_shadowMap;
in vec4 v_color;
in vec4 v_shadowCoord;
layout(location = 0) out vec4 outColor;

float lookup ( float x, float y )
{
   float pixelSize = 0.002; // 1/500
   vec4 offset = vec4 ( x * pixelSize * v_shadowCoord.w,
                        y * pixelSize * v_shadowCoord.w,
                        0.0, 0.0 );
   return textureProj ( s_shadowMap, v_shadowCoord + offset );
}

void main()
{
   // 3x3 kernel with 4 taps per sample, effectively 6x6 PCF
   float sum = 0.0;
   float x, y;
   for ( x = -2.0; x <= 2.0; x += 2.0 )
      for ( y = -2.0; y <= 2.0; y += 2.0 )
         sum += lookup ( x, y );

   // divide sum by 9.0
   sum = sum * 0.11;
   outColor = v_color * sum;
}
```

In the vertex shader, we transform the vertex position twice: (1) using the MVP matrix created from the eye position and (2) using the MVP matrix created from the light position. The former result is recorded into `gl_Position`, while the latter result is recorded into `v_shadowCoord`. Note that the `v_shadowCoord` result is exactly the same vertex position result when we render to the shadow map. Armed with this knowledge, we can use the v_shadowCoord as the texture coordinate to sample into the shadow map by first transforming the coordinate from homogeneous coordinate [–1, 1] space into [0, 1] space in the vertex shader. Alternatively, we can avoid performing these calculations in the vertex shader by pre-multiplying the MVP matrix from the light position with the following bias matrix in the host code:

```
0.5, 0.0, 0.0, 0.0,
0.0, 0.5, 0.0, 0.0,
0.0, 0.0, 0.5, 0.0,
0.5, 0.5, 0.5, 1.0
```

In the fragment shader, we check the current fragment to determine whether it is in the shadow by sampling the shadow map using the v_shadowCoord and textureProj call. We perform 3 × 3 kernel filtering to further increase the effect of PCF (effectively 6 × 6 PCF when combined with four hardware depth comparisons per tap). Then we average the shadow map sample result to modulate the fragment color. When the fragment is in shadow, the sample result will be zero and the fragment will be rendered in black.

Summary

This chapter explored how many of the OpenGL ES 3.0 features presented throughout this book can be applied to achieve various rendering techniques. This chapter covered rendering techniques that made use of features including cubemaps, normal maps, point sprites, transform feedback, image postprocessing, projective texturing, framebuffer objects, vertex texture fetch, shadow maps, and many shading techniques. Next, we will return to the API to discuss the functions your application can use to query OpenGL ES 3.0 for information.

Chapter 15

State Queries

OpenGL ES 3.0 maintains "state information" that includes the values of internal variables required for rendering. You'll need to compile and link shader programs, initialize vertex arrays and attribute bindings, specify uniform values, and probably load and bind texture—and that only scratches the surface.

There are also a large number of values that are intrinsic to OpenGL ES 3.0's operation. You might need to determine the maximum size of viewport that is supported or the maximum number of texture units, for example. All of those values can be queried by your application.

This chapter describes the functions your applications can use to obtain values from OpenGL ES 3.0, and the parameters that you can query.

OpenGL ES 3.0 Implementation String Queries

One of the most fundamental queries that you will need to perform in your (well-written) applications is to obtain information about the underlying OpenGL ES 3.0 implementation, such as which version of OpenGL ES is supported, whose implementation it is, and which extensions are available. These characteristics are all returned as ASCII strings from the `glGetString` function.

```
const GLubyte*   glGetString(GLenum name)
const GLubyte*   glGetStringi(GLenum name, GLuint index)
```

name	specifies the parameter to be returned. Can be one of `GL_VENDOR`, `GL_RENDERER`, `GL_VERSION`, `GL_SHADING_LANGUAGE_VERSION`, or `GL_EXTENSIONS`. Must be `GL_EXTENSIONS` for `glGetStringi`.
index	specifies the index of the string to return (`glGetStringi` only).

The `GL_VENDOR` and `GL_RENDERER` queries are formatted for human consumption and have no set format; they are initialized with whatever the implementer felt were useful descriptions.

The `GL_VERSION` query will return a string starting with "OpenGL ES 3.0" for all OpenGL ES 3.0 implementations. The version string can additionally include vendor-specific information after those tokens, and will always have the following format:

```
OpenGL ES <version> <vendor-specific information>
```

with `<version>` being the version number (e.g., 3.0), composed of a major release number, followed by a period and the minor release number, and optionally another period and a tertiary release value (often used by vendors to represent an OpenGL ES 3.0 driver's revision number).

Likewise, the `GL_SHADING_LANGUAGE_VERSION` query will always return a string starting with "OpenGL ES GLSL ES 3.00." This string can also have vendor-specific information appended to it, and will take the following form:

```
OpenGL ES GLSL ES <version> <vendor-specific information>
```

with a similar formatting for the `<version>` value.

Implementations that support OpenGL ES 3.0 must also support OpenGL ES GLSL ES 1.00.

When OpenGL ES is updated to the next version, these version numbers will change accordingly.

Finally, the `GL_EXTENSIONS` query will return a space-separated list of all extensions supported by the implementation, or the `NULL` string if the implementation is not extended.

Querying Implementation-Dependent Limits

Many rendering parameters depend on the underlying capabilities of the OpenGL ES implementation—for example, how many texture units are available to a shader, or what the maximum size for a texture map or aliased point is. Values of those types are queried using one of the functions shown here:

```
void   glGetBooleanv(GLenum pname,   GLboolean *params)
void   glGetFloatv(GLenum pname,     GLfloat *params)
void   glGetIntegerv(GLenum pname,   GLint *params)
void   glGetInteger64v(GLenum pname, GLint64 *params)
```

pname	specifies the implementation-specific parameter to be queried
params	specifies an array of values of the respective type with enough entries to hold the return values for the associated parameter

A number of implementation-dependent parameters can be queried, as listed in Table 15-1.

Table 15-1 Implementation-Dependent State Queries

State Variable	Description	Minimum/ Initial Value	Get Function
GL_MAX_ELEMENT_ INDEX	Maximum element index	$2^{24} - 1$	glGetInteger64v
GL_SUBPIXEL_ BITS	Number of subpixel bits supported	4	glGetIntegerv
GL_MAX_TEXTURE_ SIZE	Maximum size of a texture	2048	glGetIntegerv
GL_MAX_3D_ TEXTURE_SIZE	Maximum size of 3D texture supported	256	glGetIntegerv
GL_MAX_ARRAY_ TEXTURE_LAYERS	Maximum number of texture layers supported	256	glGetIntegerv

(continues)

Table 15-1 Implementation-Dependent State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_MAX_TEXTURE_ LOD_BIAS	Maximum absolute texture level of detail bias supported	2.0	glGetFloatv
GL_MAX_CUBE_ MAP_TEXTURE_ SIZE	Maximum dimension of a cubemap texture	2048	glGetIntegerv
GL_MAX_ RENDERBUFFER_ SIZE	Maximum width and height of renderbuffers supported	2048	glGetIntegerv
GL_MAX_DRAW_ BUFFERS	Maximum active number of draw buffers supported	4	glGetIntegerv
GL_MAX_COLOR_ ATTACHMENTS	Maximum number of color attachments supported	4	glGetIntegerv
GL_MAX_ VIEWPORT_DIMS	Dimensions of the maximum supported viewport size		glGetIntegerv
GL_ALIASED_ POINT_SIZE_RANGE	Range of aliased point sizes	1, 1	glGetFloatv
GL_ALIASED_LINE_ WIDTH_RANGE	Range of aliased line width sizes	1, 1	glGetFloatv
GL_MAX_ELEMENT_ INDICES	Maximum number of glDrawRangeElements indices supported		glGetIntegerv
GL_MAX_ELEMENT_ VERTICES	Maximum number of glDrawRangeElements vertices supported		glGetIntegerv
GL_NUM_ COMPRESSED_ TEXTURE_FORMATS	Number of compressed texture formats supported	10	glGetIntegerv
GL_COMPRESSED_ TEXTURE_FORMATS	Compressed texture formats supported		glGetIntegerv

Table 15-1 Implementation-Dependent State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_NUM_PROGRAM_ BINARY_FORMATS	Number of program binary formats supported	0	glGetIntegerv
GL_PROGRAM_ BINARY_FORMATS	Program binary formats supported		glGetIntegerv
GL_NUM_SHADER_ BINARY_FORMATS	Number of shader binary formats supported	0	glGetIntegerv
GL_SHADER_ BINARY_FORMATS	Shader binary formats supported		glGetIntegerv
GL_MAX_SERVER_ WAIT_TIMEOUT	Maximum glWaitSync timeout interval	0	glGetInteger64v
GL_MAX_VERTEX_ ATTRIBS	Maximum number of vertex attributes supported	16	glGetIntegerv
GL_MAX_VERTEX_ UNIFORM_ COMPONENTS	Maximum number of components for vertex shader uniform variables supported	1024	glGetIntegerv
GL_MAX_VERTEX_ UNIFORM_VECTORS	Maximum number of vectors for vertex shader uniform variables supported	256	glGetIntegerv
GL_MAX_VERTEX_ UNIFORM_BLOCKS	Maximum number of vertex uniform buffers per program supported	12	glGetIntegerv
GL_MAX_VERTEX_ OUTPUT_ COMPONENTS	Maximum number of components of outputs written by a vertex shader supported	64	glGetIntegerv
GL_MAX_VERTEX_ TEXTURE_IMAGE_ UNITS	Maximum number of texture image units accessible by a vertex shader supported	16	glGetIntegerv

(continues)

Table 15-1 Implementation-Dependent State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
`GL_MAX_FRAGMENT_UNIFORM_COMPONENTS`	Maximum number of components for fragment shader uniform variables supported	896	`glGetIntegerv`
`GL_MAX_FRAGMENT_UNIFORM_VECTORS`	Maximum number of vectors for fragment shader uniform variables supported	224	`glGetIntegerv`
`GL_MAX_FRAGMENT_UNIFORM_BLOCKS`	Maximum number of fragment uniform buffers per program supported	12	`glGetIntegerv`
`GL_MAX_FRAGMENT_INPUT_COMPONENTS`	Maximum number of components of inputs read by a fragment shader supported	60	`glGetIntegerv`
`GL_MAX_TEXTURE_IMAGE_UNITS`	Maximum number of texture image units accessible by a fragment shader supported	16	`glGetIntegerv`
`GL_MIN_PROGRAM_TEXEL_OFFSET`	Minimum texel offset allowed in a lookup supported	–8	`glGetIntegerv`
`GL_MAX_PROGRAM_TEXEL_OFFSET`	Maximum texel offset allowed in a lookup supported	7	`glGetIntegerv`
`GL_MAX_UNIFORM_BUFFER_BINDINGS`	Maximum number of uniform buffer bindings supported	24	`glGetIntegerv`
`GL_MAX_UNIFORM_BLOCK_SIZE`	Maximum size of a uniform block supported	16384	`glGetInteger64v`
`GL_UNIFORM_BUFFER_OFFSET_ALIGNMENT`	Minimum required alignment for uniform buffer sizes and offsets supported	1	`glGetIntegerv`

Table 15-1 Implementation-Dependent State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_MAX_COMBINED_UNIFORM_BLOCKS	Maximum number of uniform buffers per program supported	24	glGetIntegerv
GL_MAX_COMBINED_VERTEX_UNIFORM_COMPONENTS	Maximum number of words for vertex shader uniform variables in all uniform blocks supported		glGetInteger64v
GL_MAX_COMBINED_FRAGMENT_UNIFORM_COMPONENTS	Maximum number of words for vertex shader uniform variables in all uniform blocks supported		glGetInteger64v
GL_MAX_VARYING_COMPONENTS	Maximum number of components for output variables supported	60	glGetIntegerv
GL_MAX_VARYING_VECTORS	Maximum number of vectors for output variables supported	15	glGetIntegerv
GL_MAX_COMBINED_TEXTURE_IMAGE_UNITS	Maximum number of accessible texture units supported	32	glGetIntegerv
GL_MAX_TRANSFORM_FEEDBACK_INTERLEAVED_COMPONENTS	Maximum number of components in interleaved mode supported	64	glGetIntegerv
GL_MAX_TRANSFORM_FEEDBACK_SEPARATE_COMPONENTS	Maximum number of components in separate mode supported	4	glGetIntegerv

(continues)

Table 15-1 Implementation-Dependent State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_MAX_ TRANSFORM_ FEEDBACK_ SEPARATE_ATTRIBS	Maximum number of separate attributes that can be captured in transform feedback supported	4	glGetIntegerv
GL_SAMPLE_ BUFFER	Number of multisample buffers	0	glGetIntegerv
GL_SAMPLES	Coverage mask size	0	glGetIntegerv
GL_MAX_SAMPLES	Maximum number of samples supported for multisampling	4	glGetIntegerv
GL_RED_BITS	Number of red bits in current color buffer		glGetIntegerv
GL_GREEN_BITS	Number of green bits in current color buffer		glGetIntegerv
GL_BLUE_BITS	Number of blue bits in current color buffer		glGetIntegerv
GL_ALPHA_BITS	Number of alpha bits in current color buffer		glGetIntegerv
GL_DEPTH_BITS	Number of bits in the current depth buffer		glGetIntegerv
GL_STENCIL_BITS	Number of stencil bits in current stencil buffer		glGetIntegerv
GL_ IMPLEMENTATION_ COLOR_READ_TYPE	Data type for pixel components for pixel read operations		glGetIntegerv
GL_ IMPLEMENTATION_ COLOR_READ_ FORMAT	Pixel format for pixel read operations		glGetIntegerv

Querying OpenGL ES State

Your application can modify many parameters to affect OpenGL ES 3.0's operation. Although it's usually more efficient for an application to track these values when it modifies them, you can retrieve any of the values listed in Table 15-2 from the currently bound context. For each token, the appropriate OpenGL ES 3.0 get function is provided.

Table 15-2 Application-Modifiable OpenGL ES State Queries

State Variable	Description	Minimum/ Initial Value	Get Function
`GL_ARRAY_BUFFER_BINDING`	Currently bound vertex attribute array binding	0	`glGetIntegerv`
`GL_VIEWPORT`	Current size of the viewport		`glGetIntegerv`
`GL_ELEMENT_ARRAY_BUFFER_BINDING`	Currently bound element array binding	0	`glGetIntegerv`
`GL_VERTEX_ARRAY_BINDING`	Currently bound vertex array binding	0	`glGetIntegerv`
`GL_DEPTH_RANGE`	Current depth range values	(0, 1)	`glGetFloatv`
`GL_LINE_WIDTH`	Current line width	1.0	`glGetFloatv`
`GL_POLYGON_OFFSET_FACTOR`	Current polygon offset factor value	0	`glGetFloatv`
`GL_POLYGON_OFFSET_UNITS`	Current polygon offset units value	0	`glGetFloatv`
`GL_CULL_FACE_MODE`	Current face culling mode	`GL_BACK`	`glGetIntegerv`
`GL_FRONT_FACE`	Current front-facing vertex winding mode	`GL_CCW`	`glGetIntegerv`
`GL_SAMPLE_COVERAGE_VALUE`	Current value specified for multisampling sample coverage value	1	`glGetFloatv`

(continues)

Table 15-2 Application-Modifiable OpenGL ES State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_SAMPLE_ COVERAGE_ INVERT	Current multisampling coverage value inversion setting	GL_FALSE	glGetBooleanv
GL_TEXTURE_ BINDING_2D	Current 2D texture binding	0	glGetIntegerv
GL_TEXTURE_ BINDING_CUBE_ MAP	Current cubemap texture binding	0	glGetIntegerv
GL_ACTIVE_ TEXTURE	Current texture unit	0	glGetIntegerv
GL_SAMPLER_ BINDING	Current sampler object bound to active texture unit	0	glGetIntegerv
GL_COLOR_ WRITEMASK	Color buffer writable	GL_TRUE	glGetBooleanv
GL_DEPTH_ WRITEMASK	Depth buffer writable	GL_TRUE	glGetBooleanv
GL_STENCIL_ WRITEMASK	Current write mask for front-facing polygons	1	glGetIntegerv
GL_STENCIL_ BACK_WRITEMASK	Current write mask for back-facing polygons	1	glGetIntegerv
GL_COLOR_ CLEAR_VALUE	Current color buffer clear value	0, 0, 0, 0	glGetFloatv
GL_DEPTH_ CLEAR_VALUE	Current depth buffer clear value	1	glGetIntegerv
GL_STENCIL_ CLEAR_VALUE	Current stencil buffer clear value	0	glGetIntegerv
GL_SCISSOR_BOX	Current offset and dimensions of the scissor box	0, 0, w, h	glGetIntegerv

Table 15-2 Application-Modifiable OpenGL ES State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_STENCIL_FUNC	Current stencil test operator function	GL_ALWAYS	glGetIntegerv
GL_STENCIL_VALUE_MASK	Current stencil test value mask	1s	glGetIntegerv
GL_STENCIL_REF	Current stencil test reference value	0	glGetIntegerv
GL_STENCIL_FAIL	Current operation for stencil test failure	GL_KEEP	glGetIntegerv
GL_STENCIL_PASS_DEPTH_FAIL	Current operation for when the stencil test passes, but the depth test fails	GL_KEEP	glGetIntegerv
GL_STENCIL_PASS_DEPTH_PASS	Current operation when both the stencil and depth tests pass	GL_KEEP	glGetIntegerv
GL_STENCIL_BACK_FUNC	Current back-facing stencil test operator function	GL_ALWAYS	glGetIntegerv
GL_STENCIL_BACK_VALUE_MASK	Current back-facing stencil test value mask	1s	glGetIntegerv
GL_STENCIL_BACK_REF	Current back-facing stencil test reference value	0	glGetIntegerv
GL_STENCIL_BACK_FAIL	Current operation for back-facing stencil test failure	GL_KEEP	glGetIntegerv
GL_STENCIL_BACK_PASS_DEPTH_FAIL	Current operation for when the back-facing stencil test passes, but the depth test fails	GL_KEEP	glGetIntegerv
GL_STENCIL_BACK_PASS_DEPTH_PASS	Current operation when both the back-facing stencil and depth tests pass	GL_KEEP	glGetIntegerv

(continues)

Table 15-2 Application-Modifiable OpenGL ES State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_DEPTH_FUNC	Current depth test comparison function	GL_LESS	glGetIntegerv
GL_BLEND_SRC_ RGB	Current source RGB blending coefficient	GL_ONE	glGetIntegerv
GL_BLEND_SRC_ ALPHA	Current source alpha blending coefficient	GL_ONE	glGetIntegerv
GL_BLEND_DST_ RGB	Current destination RGB blending coefficient	GL_ZERO	glGetIntegerv
GL_BLEND_DST_ ALPHA	Current destination alpha blending coefficient	GL_ZERO	glGetIntegerv
GL_BLEND_ EQUATION	Current blend equation operator	GL_FUNC_ ADD	glGetIntegerv
GL_BLEND_ EQUATION_RGB	Current RGB blend equation operator	GL_FUNC_ ADD	glGetIntegerv
GL_BLEND_ EQUATION_ALPHA	Current alpha blend equation operator	GL_FUNC_ ADD	glGetIntegerv
GL_BLEND_COLOR	Current blend color	0, 0, 0, 0	glGetFloatv
GL_DRAW_ BUFFERi	Current buffers being drawn by the corresponding output color		glGetIntegerv
GL_READ_BUFFER	Current color buffer selected for reading		glGetIntegerv
GL_UNPACK_ IMAGE_HEIGHT	Current image height for pixel unpacking	0	glGetIntegerv
GL_UNPACK_ SKIP_IMAGES	Current number of pixel images skipped before the first pixel for pixel unpacking	0	glGetIntegerv

Table 15-2 Application-Modifiable OpenGL ES State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
`GL_UNPACK_ROW_LENGTH`	Current row length for pixel unpacking	0	`glGetIntegerv`
`GL_UNPACK_SKIP_ROWS`	Current number of rows of pixel locations skipped before the first pixel for pixel unpacking	0	`glGetIntegerv`
`GL_UNPACK_SKIP_PIXELS`	Current number of pixel locations skipped before the first pixel for pixel unpacking	0	`glGetIntegerv`
`GL_UNPACK_ALIGNMENT`	Current byte-boundary alignment for pixel unpacking	4	`glGetIntegerv`
`GL_PACK_ROW_LENGTH`	Current row length for pixel packing	0	`glGetIntegerv`
`GL_PACK_SKIP_ROWS`	Current number of rows of pixel locations skipped before the first pixel for pixel packing	0	`glGetIntegerv`
`GL_PACK_SKIP_PIXELS`	Current number of pixel locations skipped before the first pixel for pixel packing	0	`glGetIntegerv`
`GL_PACK_ALIGNMENT`	Current byte-boundary alignment for pixel packing	4	`glGetIntegerv`
`GL_PIXEL_PACK_BUFFER_BINDING`	Name of buffer object currently bound for pixel packing	0	`glGetIntegerv`
`GL_PIXEL_UNPACK_BUFFER_BINDING`	Name of buffer object currently bound for pixel unpacking	0	`glGetIntegerv`

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Table 15-2 Application-Modifiable OpenGL ES State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
GL_CURRENT_ PROGRAM	Currently bound shader program	0	glGetIntegerv
GL_ RENDERBUFFER_ BINDING	Currently bound renderbuffer	0	glGetIntegerv
GL_TRANSFORM_ FEEDBACK_ BINDING	Buffer object currently bound to generic bind point for transform feedback operations	0	glGetIntegerv
GL_TRANSFORM_ FEEDBACK_ BINDING	Buffer object currently bound to each transform feedback attribute stream	0	glGetIntegeri_v
GL_TRANSFORM_ FEEDBACK_ BUFFER_START	Start offset of binding range for each transform feedback attribute stream	0	glGetInteger64i_v
GL_TRANSFORM_ FEEDBACK_ BUFFER_SIZE	Size of binding range for each transform feedback attribute stream	0	glGetInteger64i_v
GL_TRANSFORM_ FEEDBACK_ PAUSED	Whether transform feedback is currently paused on the object	GL_FALSE	glGetBooleanv
GL_TRANSFORM_ FEEDBACK_ ACTIVE	Whether transform feedback is currently active on the object	GL_FALSE	glGetBooleanv
GL_UNIFORM_ BUFFER_BINDING	Currently bound uniform buffer object for buffer object manipulation	0	glGetIntegerv
GL_UNIFORM_ BUFFER_BINDING	Uniform buffer object currently bound to the specified context binding point	0	glGetIntegeri_v

Table 15-2 Application-Modifiable OpenGL ES State Queries *(continued)*

State Variable	Description	Minimum/ Initial Value	Get Function
`GL_UNIFORM_BUFFER_START`	Start of currently bound uniform buffer region	0	`glGetInteger64i_v`
`GL_UNIFORM_BUFFER_SIZE`	Size of currently bound uniform buffer region	0	`glGetInteger64i_v`
`GL_GENERATE_MIPMAP_HINT`	Mipmap generation hint	`GL_DONT_CARE`	`glGetIntegerv`
`GL_FRAGMENT_SHADER_DERIVATIVE_HINT`	Fragment shader derivative accuracy hint	`GL_DONT_CARE`	`glGetIntegerv`
`GL_READ_FRAMEBUFFER_BINDING`	Currently bound framebuffer for reading	0	`glGetIntegerv`
`GL_DRAW_FRAMEBUFFER_BINDING`	Currently bound framebuffer for drawing	0	`glGetIntegerv`

Hints

OpenGL ES 3.0 uses hints to modify the operation of features, allowing a bias toward either performance or quality. You can specify a preference by calling the following function:

```
void  glHint(GLenum target, GLenum mode)
```

`target`	specifies the hint to be set, and must be either `GL_GENERATE_MIPMAP_HINT` or `GL_FRAGMENT_SHADER_DERIVATIVE_HINT`.
`mode`	specifies the operational mode the feature should use. Valid values are `GL_FASTEST` to specify performance, `GL_NICEST` to favor quality, or `GL_DONT_CARE` to reset any preferences to the implementation default.

The current value of any hint can be retrieved by calling `glGetIntegerv` using the appropriate hint enumerated value.

Entity Name Queries

OpenGL ES 3.0 references numerous entities that you define—textures, shaders, programs, vertex buffers, sampler objects, query objects, sync objects, vertex array objects, transform feedback objects, framebuffers, and renderbuffers—by integer names. You can determine if a name is currently in use (and therefore a valid entity) by calling one of the following functions:

```
GLboolean   glIsTexture(GLuint texture)
GLboolean   glIsShader(GLuint shader)
GLboolean   glIsProgram(GLuint program)
GLboolean   glIsBuffer(GLuint buffer)
GLboolean   glIsSampler(GLuint sampler)
GLboolean   glIsQuery(GLuint query)
GLboolean   glIsSync(GLuint sync)
GLboolean   glIsVertexArray(GLuint array)
GLboolean   glIsTransformFeedback(GLuint transform)
GLboolean   glIsRenderbuffer(GLuint renderbuffer)
GLboolean   glIsFramebuffer(GLuint framebuffer)
```

texture, *shader*, *program*, *buffer*, *sampler*, *query*, *sync*, *array*, *transform*, *renderbuffer*, *framebuffer*	specify the name of the respective entity to determine if the name is in use

Nonprogrammable Operations Control and Queries

Much of OpenGL ES 3.0's rasterization functionality, like blending or back-face culling, is controlled by turning on and off the features you need. The functions controlling the various operations are mentioned here.

`void` **`glEnable`**`(GLenum` *`capability`*`)`	
`capability`	specifies the feature that should be turned on and affects all rendering until the feature is turned off

`void` **`glDisable`**`(GLenum` *`capability`*`)`	
`capability`	specifies the feature that should be turned off

Additionally, you can determine if a feature is in use by calling the following function:

`GLboolean` **`glIsEnabled`**`(GLenum` *`capability`*`)`	
`capability`	specifies which feature should be examined to determine if it's enabled

The capabilities controlled by `glEnable` and `glDisable` are listed in Table 15-3.

Table 15-3 OpenGL ES 3.0 Capabilities Controlled by `glEnable` and `glDisable`

Capability	Description
`GL_CULL_FACE`	Discard polygons whose vertex winding order is opposite of the specified front-facing mode (`GL_CW` or `GL_CCW`, as specified by `glFrontFace`)
`GL_POLYGON_OFFSET_FILL`	Offset the depth value of a fragment to aid in rendering coplanar geometry
`GL_SCISSOR_TEST`	Further restrict rendering to the scissor box

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Table 15-3 OpenGL ES 3.0 Capabilities Controlled by `glEnable` and `glDisable` *(continued)*

Capability	Description
`GL_SAMPLE_COVERAGE`	Use a fragment's computed coverage value in multisampling operations
`GL_SAMPLE_ALPHA_TO_COVERAGE`	Use a fragment's alpha value as its coverage value in multisampling operations
`GL_STENCIL_TEST`	Enable the stencil test
`GL_DEPTH_TEST`	Enable the depth test
`GL_BLEND`	Enable blending
`GL_PRIMITIVE_RESTART_FIXED_INDEX`	Enable primitive restarting
`GL_RASTERIZER_DISCARD`	Enable primitive discard before rasterization
`GL_DITHER`	Enable dithering

Shader and Program State Queries

OpenGL ES 3.0 shaders and programs have a considerable amount of state information that you can retrieve regarding their configuration, and the attributes and uniform variables used by them. Numerous functions are provided for querying the state associated with shaders. To determine the shaders attached to a program, call the following function:

```
void  glGetAttachedShaders(GLuint program, GLsizei maxcount,
                           GLsizei *count, GLuint *shaders)
```

program	specifies the program to query to determine the attached shaders
maxcount	the maximum number of shader names to be returned
count	the actual number of shader names returned
shaders	an array of length *maxcount* used for storing the returned shader names

To retrieve the source code for a shader, call the following function:

```
void  glGetShaderSource(GLuint shader, GLsizei bufsize,
                        GLsizei *length, GLchar *source)
```

shader	specifies the shader to query
bufsize	the number of bytes available in the array source for returning the shader's source
length	the length of the returned shader string
source	specifies an array of `GLchars` to store the shader source to

To retrieve a value associated with a uniform variable at a particular uniform location associated with a shader program, call the following function:

```
void  glGetUniformfv(GLuint program, GLint location,
                     GLfloat *params)
void  glGetUniformiv(GLuint program, GLint location,
                     GLint *params)
```

program	the program to query to retrieve the uniform's value
location	the uniform location associated with the program for which to retrieve the values
params	an array of the appropriate type for storing the uniform variable's values; the associated type of the uniform in the shader determines the number of values returned

Finally, to query the range and precision of OpenGL ES 3.0 shader language types, call the following function:

```
void  glGetShaderPrecisionFormat(GLenum shaderType,
                                 GLenum precisionType,
                                 GLint *range,
                                 GLint *precision)
```

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shaderType	specifies the type of shader, and must be either `GL_VERTEX_SHADER` or `GL_FRAGMENT_SHADER`
precisionType	specifies the precision qualifier type, and must be one of `GL_LOW_FLOAT`, `GL_MEDIUM_FLOAT`, `GL_HIGH_FLOAT`, `GL_LOW_INT`, `GL_MEDIUM_INT`, or `GL_HIGH_INT`
range	a two-element array that returns the minimum and maximum values for *precisionType* as a log base-2 number
precision	returns the precision for *precisionType* as a log base-2 value

Vertex Attribute Queries

State information for vertex attribute arrays can also be retrieved from the current OpenGL ES 3.0 context. To obtain the pointer to the current generic vertex attributes for a specific index, call the following function:

```
void  glGetVertexAttribPointerv(GLuint index, GLenum pname,
                                GLvoid **pointer)
```

index	specifies the index of the generic vertex attribute array
pname	specifies the parameter to be retrieved; must be `GL_VERTEX_ATTRIB_ARRAY_POINTER`
pointer	returns the address of the specified vertex attribute array

The associated state for accessing the data elements in the vertex attribute array, such as value type or stride, can be obtained by calling the following function:

```
void  glGetVertexAttribfv(GLuint index, GLenum pname,
                          GLfloat *params)
void  glGetVertexAttribiv(GLuint index, GLenum pname,
                          GLint *params)
```

index	specifies the index of the generic vertex attribute array.

pname	specifies the parameter to be retrieved; must be one of `GL_VERTEX_ATTRIB_ARRAY_BUFFER_BINDING`, `GL_VERTEX_ATTRIB_ARRAY_ENABLED`, `GL_VERTEX_ATTRIB_ARRAY_SIZE`, `GL_VERTEX_ATTRIB_ARRAY_STRIDE`, `GL_VERTEX_ATTRIB_ARRAY_TYPE`, `GL_VERTEX_ATTRIB_ARRAY_NORMALIZED`, `GL_VERTEX_ATTRIB_ARRAY_INTEGER`, or `GL_VERTEX_ATTRIB_ARRAY_DIVISOR`. `GL_CURRENT_VERTEX_ATTRIB` returns the current vertex attribute as specified by `glEnableVertexAttribArray`, and the other parameters are values specified when the vertex attribute pointer is specified by calling `glVertexAttribPointer`.
params	specifies an array of the appropriate type for storing the returned parameter values.

Texture State Queries

OpenGL ES 3.0 texture objects store a texture's image data, along with settings describing how the texels in the image should be sampled. The texture filter state, which includes the minification and magnification texture filters and texture-coordinate wrap modes, can be queried from the currently bound texture object. The following call retrieves the texture filter settings:

```
void  glGetTexParameterfv(GLenum target, GLenum pname,
                          GLfloat *params)
void  glGetTexParameteriv(GLenum target, GLenum pname,
                          GLint *params)
```

target	specifies the texture target; can either be `GL_TEXTURE_2D`, `GL_TEXTURE_2D_ARRAY`, `GL_TEXTURE_3D`, or `GL_TEXTURE_CUBE_MAP`
pname	specifies the texture filter parameter to be retrieved; may be `GL_TEXTURE_BASE_LEVEL`, `GL_TEXTURE_COMPARE_FUNC`, `GL_TEXTURE_COMPARE_MODE`, `GL_TEXTURE_MAG_FILTER`, `GL_TEXTURE_IMMUTABLE_FORMAT`, `GL_TEXTURE_MAX_LEVEL`, `GL_TEXTURE_MAX_LOD`, `GL_TEXTURE_MIN_FILTER`, `GL_TEXTURE_MIN_LOD`, `GL_TEXTURE_SWIZZLE_R`,

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	`GL_TEXTURE_SWIZZLE_G`, `GL_TEXTURE_SWIZZLE_B`, `GL_TEXTURE_SWIZZLE_A`, `GL_TEXTURE_WRAP_S`, `GL_TEXTURE_SWIZZLE_T`, or `GL_TEXTURE_WRAP_R`
params	specifies an array of the appropriate type for storing the returned parameter values

Sampler Queries

State information for sampler objects can be retrieved from the current OpenGL ES 3.0 context by calling the following function:

```
void  glGetSamplerParameterfv(GLuint sampler, GLenum pname,
                              GLfloat *params)
void  glGetSamplerParameteriv(GLuint sampler, GLenum pname,
                              GLint *params)
```

sampler	specifies the name of a sampler object
pname	specifies the sampler parameter to be retrieved; may be `GL_TEXTURE_MAG_FILTER`, `GL_TEXTURE_MIN_FILTER`, `GL_TEXTURE_MIN_LOD`, `GL_TEXTURE_MAX_LOD`, `GL_TEXTURE_WRAP_S`, `GL_TEXTURE_WRAP_T`, `GL_TEXTURE_WRAP_R`, `GL_TEXTURE_COMPARE_MODE`, or `GL_TEXTURE_COMPARE_FUNC`
params	specifies an array of the appropriate type for storing the returned parameter values

Asynchronous Object Queries

Information about a query object can be retrieved from the current OpenGL ES 3.0 context by calling the following function:

```
void  glGetQueryiv(GLuint target, GLenum pname,
                   GLint *params)
```

target	specifies the query target object; can be `GL_ANY_SAMPLES_PASSED`,

	`GL_ANY_SAMPLES_PASSED_CONSERVATIVE`, or `GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN`
pname	specifies the query object parameter to be retrieved; must be `GL_CURRENT_QUERY`
params	specifies an array of the appropriate type for storing the returned parameter values

The state of a query object can be retrieved by calling the following function:

```
void  glGetQueryObjectuiv(GLuint id, GLenum pname,
                          GLuint *params)
```

id	specifies the name of a query object
pname	specifies the query object parameter to be retrieved; can be `GL_QUERY_RESULT` or `GL_QUERY_RESULT_AVAILABLE`
params	specifies an array of the appropriate type for storing the returned parameter values

Sync Object Queries

The properties of a sync object can be retrieved from the current OpenGL ES 3.0 context by calling the following function:

```
void  glGetSynciv(GLsync sync, GLenum pname,
                  GLsizei bufsize, GLsizei *length,
                  GLint *values)
```

sync	specifies the sync object to query
pname	specifies the parameter to retrieve from the sync object
bufsize	the number of bytes available in the returning *values*
length	the address of the returned number of bytes in *values*
values	specifies the address of an array for the returned parameter

Vertex Buffer Queries

Vertex buffer objects have associated state information describing the state and usage of the buffer. Those parameters can be retrieved by calling the following function:

```
void  glGetBufferParameteriv(GLenum target, GLenum pname,
                             GLint *params)
void  glGetBufferParameter64iv(GLenum target, GLenum pname,
                               GLint64 *params)
```

target	specifies the buffer of the currently bound vertex buffer; must be one of `GL_ARRAY_BUFFER`, `GL_COPY_READ_BUFFER`, `GL_COPY_WRITE_BUFFER`, `GL_ELEMENT_ARRAY_BUFFER`, `GL_PIXEL_PACK_BUFFER`, `GL_PIXEL_UNPACK_BUFFER`, `GL_TRANSFORM_FEEDBACK_BUFFER`, or `GL_UNIFORM_BUFFER`
pname	specifies the buffer parameter to be retrieved; must be one of `GL_BUFFER_SIZE`, `GL_BUFFER_USAGE`, `GL_BUFFER_MAPPED`, `GL_BUFFER_ACCESS_FLAGS`, `GL_BUFFER_MAP_LENGTH`, or `GL_BUFFER_MAP_OFFSET`
params	specifies an integer array for storing the returned parameter values

Additionally, you can retrieve the current pointer address for a mapped buffer by calling the following function:

```
void  glGetBufferPointerv(GLenum target, GLenum pname,
                          GLvoid **params)
```

target	specifies the buffer of the currently bound vertex buffer; must be one of `GL_ARRAY_BUFFER`, `GL_COPY_READ_BUFFER`, `GL_COPY_WRITE_BUFFER`, `GL_ELEMENT_ARRAY_BUFFER`, `GL_PIXEL_PACK_BUFFER`, `GL_PIXEL_UNPACK_BUFFER`, `GL_TRANSFORM_FEEDBACK_BUFFER`, or `GL_UNIFORM_BUFFER`
pname	specifies the parameter to retrieve; must be `GL_BUFFER_MAP_POINTER`
params	specifies a pointer for storing the returned address

Renderbuffer and Framebuffer State Queries

Characteristics of an allocated renderbuffer can be retrieved by calling the following function:

```
void  glGetRenderbufferParameteriv(GLenum target,
                                   GLenum pname,
                                   GLint *params)
```

target	specifies the target for the currently bound renderbuffer; must be GL_RENDERBUFFER
pname	specifies the renderbuffer parameter to retrieve; must be one of GL_RENDERBUFFER_WIDTH, GL_RENDERBUFFER_HEIGHT, GL_RENDERBUFFER_INTERNAL_FORMAT, GL_RENDERBUFFER_RED_SIZE, GL_RENDERBUFFER_GREEN_SIZE, GL_RENDERBUFFER_BLUE_SIZE, GL_RENDERBUFFER_ALPHA_SIZE, GL_RENDERBUFFER_DEPTH_SIZE, GL_RENDERBUFFER_SAMPLES, or GL_RENDERBUFFER_STENCIL_SIZE
params	specifies an integer array for storing the returned parameter values

Likewise, the current attachments to a framebuffer can be queried by calling the following function:

```
void  glGetFramebufferAttachmentParameteriv(GLenum target,
          GLenum attachment,GLenum pname,GLint *params)
```

target	specifies the framebuffer target; must be one of GL_READ_FRAMEBUFFER, GL_WRITE_FRAMEBUFFER, or GL_FRAMEBUFFER
attachment	specifies which attachment point to query; must be one of GL_COLOR_ATTACHMENTi, GL_DEPTH_ATTACHMENT, GL_DEPTH_STENCIL_ATTACHMENT, or GL_STENCIL_ATTACHMENT

(continues)

(continued)

pname	specifies GL_FRAMEBUFFER_ATTACHMENT_OBJECT_TYPE, GL_FRAMEBUFFER_ATTACHMENT_OBJECT_NAME, GL_FRAMEBUFFER_ATTACHMENT_RED_SIZE, GL_FRAMEBUFFER_ATTACHMENT_GREEN_SIZE, GL_FRAMEBUFFER_ATTACHMENT_BLUE_SIZE, GL_FRAMEBUFFER_ATTACHMENT_ALPHA_SIZE, GL_FRAMEBUFFER_ATTACHMENT_DEPTH_SIZE, GL_FRAMEBUFFER_ATTACHMENT_STENCIL_SIZE, GL_FRAMEBUFFER_ATTACHMENT_COMPONENT_TYPE, GL_FRAMEBUFFER_ATTACHMENT_COLOR_ENCODING, GL_FRAMEBUFFER_ATTACHMENT_TEXTURE_LAYER, GL_FRAMEBUFFER_ATTACHMENT_TEXTURE_LEVEL, GL_FRAMEBUFFER_ATTACHMENT_TEXTURE_CUBE_MAP_FACE
params	specifies an integer array for storing the returned parameter values

Summary

As there is a large amount of state information in OpenGL ES 3.0, in this chapter we provided a reference for the various state queries that your applications can make. Next, in the final chapter you will learn how to build the OpenGL ES sample code in this book for various OpenGL ES platforms.

Chapter 16

OpenGL ES Platforms

As of this writing, OpenGL ES 3.0 is available in Android 4.3+, iOS 7 (on the iPhone 5s), Windows, and Linux. We attempted to make the sample code for the book available on as many platforms as possible. We want our readers to be able to choose the OpenGL ES 3.0 platform that is most relevant to them. In this chapter, we cover some specifics of getting up and running while building the sample code with the following platforms:

- Windows (OpenGL ES 3.0 Emulation) with Microsoft Visual Studio
- Ubuntu Linux (OpenGL ES 3.0 Emulation)
- Android 4.3+ NDK (C++)
- Android 4.3+ SDK (Java)
- iOS 7 with Xcode 5

Building for Microsoft Windows with Visual Studio

After downloading the sample code from the book's website (opengles-book.com) and installing CMake v2.8 (http://cmake.org), the next step to build the sample code for Windows is to download an OpenGL ES 3.0 Emulator. Three choices of emulators are currently available:

- Qualcomm Adreno SDK v3.4+, available from http://developer.qualcomm.com/develop/

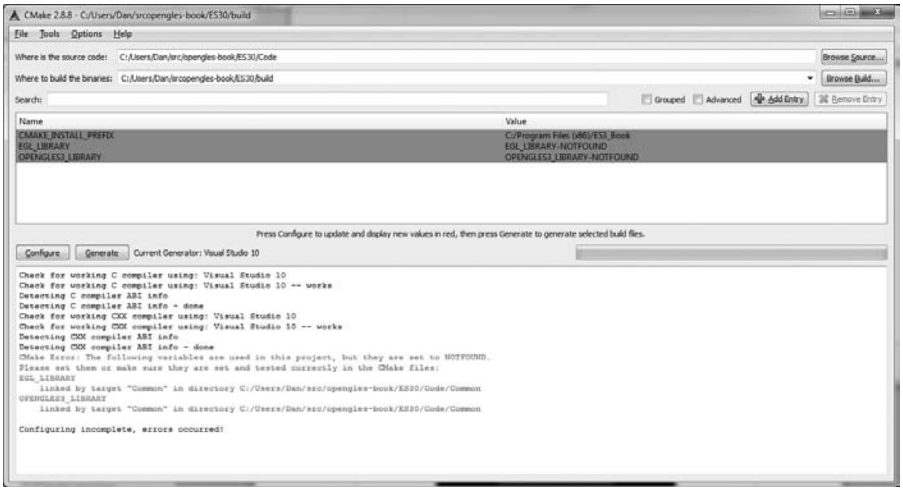
- ARM Mali OpenGL ES 3.0 Emulator, available from http://malideveloper.arm.com/develop-for-mali/tools/opengl-es-3-0-emulator/
- PowerVR Insider SDK v3.2+, available from http://imgtec.com/PowerVR/insider/sdkdownloads/index.asp

Any of these emulators is a suitable choice for using the sample code for this book. We leave it up to you to choose which option best fits with your development needs. If you want to use the PVRShaman workspaces from Chapters 10 and 14, the PowerVR Insider SDK is required. For this section, we chose to use the Qualcomm Adreno SDK v3.4. After downloading and installing your choice of OpenGL ES 3.0 emulator, you can use CMake to generate the Microsoft Visual Studio solution and projects.

Open the cmake-gui and point the GUI to the location where you have downloaded the source code, as shown in Figure 16-1. Create a folder to build the binaries underneath that base directory and set it as the location to build the binaries in the GUI. You can then click Configure and choose the version of Microsoft Visual Studio you are using. CMake will now give an error because the EGL and OpenGLES3 library are not found.

If you are using the Qualcomm Adreno SDK installed to `C:\AdrenoSDK`, you must now set the following variables in the cmake-gui:

- `EGL_LIBRARY: C:/AdrenoSDK/Lib/Win32/OGLES3/libEGL.lib`
- `OPENGLES3_LIBRARY:C:/AdrenoSDK/Lib/Win32/OGLES3/libGLESv2.lib`



Where is the source code: C:/Users/Dan/src/opengles-book/ES30/Code

Where to build the binaries: C:/Users/Dan/srcopengles-book/ES30/build

Search:

Name	Value
CMAKE_INSTALL_PREFIX	C:/Program Files (x86)/ES3_Book
EGL_LIBRARY	EGL_LIBRARY-NOTFOUND
OPENGLES3_LIBRARY	OPENGLES3_LIBRARY-NOTFOUND

Press Configure to update and display new values in red, then press Generate to generate selected build files.

Current Generator: Visual Studio 10

```
Check for working C compiler using: Visual Studio 10
Check for working C compiler using: Visual Studio 10 -- works
Detecting C compiler ABI info
Detecting C compiler ABI info - done
Check for working CXX compiler using: Visual Studio 10
Check for working CXX compiler using: Visual Studio 10 -- works
Detecting CXX compiler ABI info
Detecting CXX compiler ABI info - done
CMake Error: The following variables are used in this project, but they are set to NOTFOUND.
Please set them or make sure they are set and tested correctly in the CMake files:
EGL_LIBRARY
    linked by target "Common" in directory C:/Users/Dan/src/opengles-book/ES30/Code/Common
OPENGLES3_LIBRARY
    linked by target "Common" in directory C:/Users/Dan/src/opengles-book/ES30/Code/Common

Configuring incomplete, errors occurred!
```

Figure 16-1 Building Samples with CMake GUI on Windows

If you are using a different emulator, locate the EGL and OpenGL ES 3.0 libraries for that library and set them to the CMake variables. After setting the EGL and OpenGL ES 3.0 libraries, click Configure again in the cmake-gui and then click Generate. You can now navigate to the folder you chose to build the binaries in CMake and open `ES3_Book.sln` in Microsoft Visual Studio. From this solution, you can build and run all of the sample code for the book.

If you do not have `libEGL.dll` and `libGLESv2.dll` in your path, you will need to copy those files to the directory to which each sample executable is built to be able to run the sample. Also, note that libGLESv2 is the recommended Khronos naming convention for the OpenGL ES 3.0 library. This is the same name as the OpenGL ES 2.0 library. The names match because OpenGL ES 3.0 is backward compatible with OpenGL ES 2.0; thus the same library can be used for both APIs.

Building for Ubuntu Linux

This section describes how to build the sample code using the PowerVR OpenGL ES 3.0 Emulator on Ubuntu Linux (tested on Ubuntu 12.04.1 LTS 64-bit). In addition to installing the PowerVR OpenGL ES 3.0 Emulator (by default, this installs to `/opt/Imagination/PowerVR/GraphicsSDK`), you will need to make sure you have installed the appropriate packages, including cmake and gcc. A good starting point is to install the following packages:

```
$ sudo apt-get install build-essential cmake cmake-curses-gui
```

To build the sample code, first create a build folder at the root of the source project (where CMakeLists.txt is found):

```
~/src/opengles-book$ mkdir build
~/src/opengles-book/build$ cd build
~/src/opengles-book/build$ cmake ../
```

If all has gone correctly, you will likely see an error message that the `EGL_LIBRARY` and `OPENGLES3_LIBRARY` are not found. To set the libraries, run the following (note that it is “ccmake” and not “cmake”):

```
~/src/opengles-book/build$ ccmake ../
```

You will see that the value of `EGL_LIBRARY` is `EGL_LIBRARY-NOTFOUND`; similarly, `OPENGLES3_LIBRARY` is set to `OPENGLES3_LIBRARY-NOTFOUND`.

Assuming you installed the PowerVR SDK to the default location, you can set these variables to the `libEGL.so` and `libGLESv2.so` files, as follows:

- `EGL_LIBRARY:`
  `/opt/Imagination/PowerVR/GraphicsSDK/PVRVFrame/`
  `EmulationLibs/Linux_x86_64/libEGL.so`
- `OPENGLES3_LIBRARY:`
  `/opt/Imagination/PowerVR/GraphicsSDK/PVRVFrame/`
  `EmulationLibs/Linux_x86_64/libGLESv2.so`

Now you can press "c" to configure and "g" to generate and exit ccmake. The code is now ready to build; simply type the following:

```
~/src/opengles-book/build$ make
```

This should build `libCommon.a` along with all of the sample code. You are now ready to run the `Hello_Triangle` sample:

```
build$ cd Chapter_2/Hello_Triangle
build$ ./Hello_Triangle
```

If you find that you are unable to run the program because the `libEGL.so` and `libGLESv2.so` are not found, set `LD_LIBRARY_PATH` to point to the directory location as follows:

```
$ export
LD_LIBRARY_PATH=/opt/Imagination/PowerVR/GraphicsSDK/PVRVFrame/
EmulationLibs/Linux_x86_64/
```

Building for Android 4.3+ NDK (C++)

Support for OpenGL ES 3.0 in Android 4.3 was announced in July 2013. There are two ways of accessing OpenGL ES 3.0 on Android: either through the Native Development Kit (NDK) using C/C++ or through the Software Development Kit (SDK) using Java. We have provided the sample code in both C and Java to support development with either language. This section covers how to build and run the C Android 4.3 samples using the NDK. The next section covers how to build and run the Java Android 4.3 samples using the SDK. OpenGL ES 3.0 has been supported in the Android NDK starting with Android NDK r9. OpenGL ES 3.0 is supported on Android devices supporting Android 4.3 (API level 18) or greater.

Prerequisites

Before building the book sample code for Android NDK r9+, you need to install several prerequisites. The Android Developer Tools are cross-platform tools, so you can pick either Windows (Cygwin), Linux, or Mac OS X as a build platform. In this section, we cover building under Windows, but the instructions will be nearly equivalent on the other platforms. The following software is required:

- Java SE Development Kit (JDK) 7 (http://oracle.com/technetwork/java/javase/downloads/index.html)—For Windows x64, you would install `jdk-7u45-windows-x64.exe`.
- Android SDK (http://developer.android.com/sdk/index.html)—The easiest way is to download and decompress the SDK Android Developer Tools (ADT) bundle. For the purposes of these instructions, the ADT will be installed to `C:\Android\adt-bundle-windows-x86_64-20130911`.
- Android 4.3 (API 18)—After downloading ADT, run the SDK Manager and install Android 4.3 (API 18).
- Android NDK (http://developer.android.com/tools/sdk/ndk/index.html)—Download and decompress to a directory (e.g., `C:\Android\android-ndk-r9-windows-x86_64`) the latest Android NDK.
- Cygwin (http://cygwin.com/)—The Android NDK uses Cygwin as an environment for running the build tools on Windows. If you are developing on Mac OS X or Linux, you will not need Cygwin.
- Apache Ant 1.9.2+ (http://ant.apache.org/bindownload.cgi)—Ant is used for building the samples with the NDK. Download and decompress to a folder (e.g., `C:\Android\apache-ant-1.9.2`).

After installing all of the prerequisites, you need to set up your `PATH` to include the Android SDK `tools/` and `platform-tools/` folders, Android NDK root folder, and Ant `bin/` folder. You will also need to set your `JAVA_HOME` variable to point to the folder in which you installed the JDK. For example, the following was added to the end of `~/.bashrc` in Cygwin to set up the environment for the installation directories previously used:

```
export JAVA_HOME="/cygdrive/c/Program Files/Java/jdk1.7.0_40"
export ANDROID_SDK=/cygdrive/c/Android/adt-bundle-windows-
x86_64-20130911/sdk
export ANDROID_NDK=/cygdrive/c/Android/android-ndk-r9-windows
-x86_64/android-ndk-r9
```

```
export ANT=/cygdrive/c/Android/apache-ant-1.9.2/bin
export PATH=$PATH:${ANDROID_NDK}
export PATH=$PATH:${ANT}
export PATH=$PATH:${ANDROID_SDK}/tools
export PATH=$PATH:${ANDROID_SDK}/platform-tools
```

Building the Example Code with Android NDK

Once the prerequisites have been installed, building the samples with the Android NDK is straightforward. From a terminal (Cygwin on Windows), navigate to the `Android/` folder for the sample you want to build and enter the following commands:

```
Hello_Triangle/Android $ android.bat update project -p . -t
android-18
Hello_Triangle/Android/jni $ cd jni
Hello_Triangle/Android/jni $ ndk-build
Hello_Triangle/Android/jni $ cd ..
Hello_Triangle/Android $ ant debug
Hello_Triangle/Android $ adb install -r bin/NativeActivity-debug.apk
```

Note that on Mac OS X or Linux, you would use the command `android` instead of `android.bat` (the build steps are otherwise the same). The `android.bat` command will generate the project build files for the example. Navigating to the `jni/` folder and entering `ndk-build` will compile the C source code for the project and generate the library file for the sample. Finally, running `ant debug` will build the final `apk` file that is installed to the device (done with the final step using the `adb` tool).

Once the sample is installed on the device, an icon for it will appear in the Apps list on the device. Any log message output from the sample can be viewed using `adb logcat`.

Building for Android 4.3+ SDK (Java)

The sample code in the book is written in native C, which is why we chose to port it to the Android NDK. While working with the NDK may be useful to Android developers who plan to write cross-platform native code, many Android applications are written in Java using the SDK instead of the NDK. To help developers who wish to work in Java with the SDK instead of the NDK, we also provide the book sample code in Java.

If you have installed the Android ADT bundle (as described in the *Prerequisites* section of *Building for the Android 4.3 NDK [C++]*), then you have everything you need to run the Java versions of the applications. The Java samples are located in the `Android_Java/` folder at the root of the sample code directory. To build and run the Java examples, simply open Eclipse and in your Workspace choose Import > General > Existing Projects Into Workspace. Point the import dialog to the `Android_Java/` folder and you will be able to import all of the sample code from the book. Once you have imported the samples, you will be able to build and run them from Eclipse just as you would any Android application.

In general, the Java samples are equivalent to their native counterparts. The main difference is observed with asset loading, where in some cases the shaders are stored in external assets rather than placed inline with the code. This is generally a better practice and makes editing the shaders more straightforward. The reason this was not done in the C versions of the samples was to reduce platform variability in how files and other assets are loaded and to make the samples self-contained in a single file.

Building for iOS 7

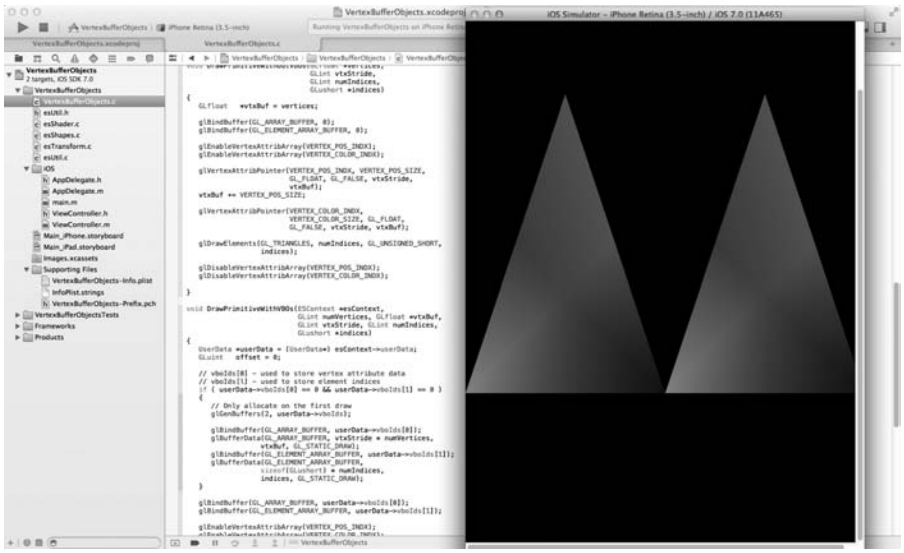
Support for OpenGL ES 3.0 was added to iOS starting with version 7. The iPhone 5s (released in September 2013) is the first iOS device that supports OpenGL ES 3.0. The iOS Simulator that runs on Mac OS X also supports OpenGL ES 3.0, so it is possible to run and debug the book code samples without having an OpenGL ES 3.0–capable iOS device. This section details the steps to get up and running with the code samples on iOS7 using Xcode 5 on Mac OS X 10.8.5.

Prerequisites

The only prerequisite aside from Mac OS X 10.8.5 is to download and install Xcode 5. This version of Xcode contains the SDK for iOS 7 and is capable of building and running the sample code for the book.

Building the Example Code with Xcode 5

Each sample in the book has an `iOS/` folder that contains the xcodeproj and related files needed for building on iOS. A screenshot of an example project open in Xcode and running on the iOS 7 Simulator is shown in Figure 16-2.



```
                              GLint vtxStride,
                              GLint numIndices,
                              GLushort *indices)
{
   GLfloat   *vtxBuf = vertices;

   glBindBuffer(GL_ARRAY_BUFFER, 0);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, 0);

   glEnableVertexAttribArray(VERTEX_POS_INDX);
   glEnableVertexAttribArray(VERTEX_COLOR_INDX);

   glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                         GL_FLOAT, GL_FALSE, vtxStride,
                         vtxBuf);
   vtxBuf += VERTEX_POS_SIZE;

   glVertexAttribPointer(VERTEX_COLOR_INDX,
                         VERTEX_COLOR_SIZE, GL_FLOAT,
                         GL_FALSE, vtxStride, vtxBuf);

   glDrawElements(GL_TRIANGLES, numIndices, GL_UNSIGNED_SHORT,
                  indices);

   glDisableVertexAttribArray(VERTEX_POS_INDX);
   glDisableVertexAttribArray(VERTEX_COLOR_INDX);

}

void DrawPrimitiveWithVBOs(ESContext *esContext,
                           GLint numVertices, GLfloat *vtxBuf,
                           GLint vtxStride, GLint numIndices,
                           GLushort *indices)
{
   UserData *userData = (UserData*) esContext->userData;
   GLuint   offset = 0;

   // vboIds[0] - used to store vertex attribute data
   // vboIds[1] - used to store element indices
   if ( userData->vboIds[0] == 0 && userData->vboIds[1] == 0 )
   {
      // Only allocate on the first draw
      glGenBuffers(2, userData->vboIds);

      glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
      glBufferData(GL_ARRAY_BUFFER, vtxStride * numVertices,
                   vtxBuf, GL_STATIC_DRAW);
      glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, userData->vboIds[1]);
      glBufferData(GL_ELEMENT_ARRAY_BUFFER,
                   sizeof(GLushort) * numIndices,
                   indices, GL_STATIC_DRAW);
   }

   glBindBuffer(GL_ARRAY_BUFFER, userData->vboIds[0]);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, userData->vboIds[1]);

   glEnableVertexAttribArray(VERTEX_POS_INDX);
```

Figure 16-2 VertexArrayObjects Sample in Xcode Running on iOS 7 Simulator

Notice that each sample project builds the framework files (`esUtil.c`, `esTransform.c`, `esShapes.c`, and `esShader.c`). Additionally, each sample contains Objective-C files from the `Common/iOS` folder that wrap the interface to the ES framework. The primary file is `ViewController.m`, which implements an iOS `GLKViewController` and calls back into registered update, draw, and shutdown callback functions of each sample. This abstraction mechanism allows each sample in the book to run unmodified on iOS.

To create your own iOS 7 application using the code framework from the book, in Xcode 5 you can navigate from File > New > Project, and choose an OpenGL Game. Once it creates the new project, remove the generated `AppDelegate.h`, `AppDelegate.m`, `Shader.vsh`, `Shader.fsh`, `ViewController.h`, `ViewController.m`, and `main.m` files. Next, select "Add files to <project>..." and choose all of the `.c` files in the `Common/Source` path along with all of the files in `Common/Source/iOS`. Finally, in the Build Settings for your project, add the `Common/Include` path to the Search Paths > User Header Search Paths. You can then create a sample using one of the examples from the book as a template.

You will probably find it much easier to use the iOS GLKit framework than to use the framework in our book if you are developing an iOS-only application. The GLKit provides functionality similar to the book

ES code framework, but is much more extensive. The one advantage to our framework is that it is not iOS-specific, so you may find this a useful approach if you are developing cross-platform applications designed to run on many different operating systems.

Summary

In this chapter, we covered how to build the sample code using OpenGL ES 3.0 emulators on Windows and Linux. We also covered how to build the sample code for OpenGL ES 3.0 on Android 4.3+ NDK using C, Android 4.3+ SDK with Java, and iOS7. The platforms supporting OpenGL ES are rapidly evolving. Please check the book website (opengles-book .com) for updated information on building for new platforms and new versions of existing platforms.

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Appendix A

GL_HALF_FLOAT

GL_HALF_FLOAT is a vertex and texture data type supported by OpenGL ES 3.0. The GL_HALF_FLOAT data type is used to specify 16-bit floating-point values. This can be useful, for example, in specifying vertex attributes such as texture coordinates, normals, binormals, and tangent vectors. Using GL_HALF_FLOAT rather than GL_FLOAT provides a two times reduction in memory bandwidth required to read vertex or texture data by the GPU.

One might argue that we can use GL_SHORT or GL_UNSIGNED_SHORT instead of a 16-bit floating-point data type and get the same memory footprint and bandwidth savings. However, with that approach, you will need to scale the data or matrices appropriately and apply a transform in the vertex shader. For example, consider the case where a texture pattern is to be repeated four times horizontally and vertically over a quad. GL_SHORT can be used to store the texture coordinates. The texture coordinates could be stored as a value of 4.12 or 8.8. The texture coordinate values stored as GL_SHORT are scaled by (1 << 12) or (1 << 8) to give us a fixed-point representation that uses 4 bits or 8 bits of integer and 12 bits or 8 bits of fraction. Because OpenGL ES does not understand such a format, the vertex shader will then need to apply a matrix to unscale these values, which affects the vertex shading performance. These additional transforms are not required if a 16-bit floating-point format is used. Further, values represented as floating-point numbers have a larger dynamic range than fixed-point values because of the use of an exponent in the representation.

Note: Fixed-point values have a different error metric than floating-point values. The absolute error in a floating-point number is proportional to the magnitude of the value, whereas the absolute error in a fixed-point format is constant. Developers need to be aware of these precision issues when choosing which data type to use when generating coordinates for a particular format.

16-Bit Floating-Point Number

Figure A-1 describes the representation of a half-float number. A half-float is a 16-bit floating-point number with 10 bits of mantissa **m**, 5 bits of exponent **e**, and a sign bit **s**.

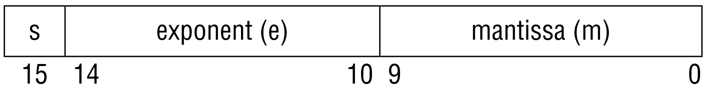

Figure A-1 A 16-Bit Floating-Point Number

The following rules should be used when interpreting a 16-bit floating-point number:

- If exponent e is between 1 and 30, the half-float value is computed as $(-1)^s * 2^{e-15} * (1 + m/1024)$.
- If exponent e and mantissa m are both 0, the half-float value is 0.0. The sign bit is used to represent –ve 0.0 or +ve 0.0.
- If exponent e is 0 and mantissa m is not 0, the half-float value is a denormalized number.
- If exponent e is 31, the half-float value is either infinity (+ve or –ve) or a NaN (“not a number”) depending on whether the mantissa m is zero.

A few examples follow:

```
0      00000      0000000000    = 0.0
0      00000      0000001111    = a denorm value
0      11111      0000000000    = positive infinity
1      11111      0000000000    = negative infinity
0      11111      0000011000    = NaN
1      11111      1111111111    = NaN
0      01111      0000000000    = 1.0
1      01110      0000000000    = -0.5
0      10100      1010101010    = 54.375
```

OpenGL ES 3.0 implementations must be able to accept input half-float data values that are infinity, NaN, or denormalized numbers. They do not have to support 16-bit floating-point arithmetic operations with these values. Most implementations will convert denormalized numbers and NaN values to zero.

Converting a Float to a Half-Float

The following routines describe how to convert a single-precision floating-point number to a half-float value, and vice versa. The conversion routines are useful when vertex attributes are generated using single-precision floating-point calculations but then converted to half-floats before they are used as vertex attributes:

```
// −15 stored using a single-precision bias of 127
const unsigned int  HALF_FLOAT_MIN_BIASED_EXP_AS_SINGLE_FP_EXP =
0x38000000;
// max exponent value in single precision that will be converted
// to Inf or NaN when stored as a half-float
const unsigned int  HALF_FLOAT_MAX_BIASED_EXP_AS_SINGLE_FP_EXP =
0x47800000;

// 255 is the max exponent biased value
const unsigned int  FLOAT_MAX_BIASED_EXP = (0x1F << 23);

const unsigned int  HALF_FLOAT_MAX_BIASED_EXP = (0x1F << 10);

typedef unsigned short    hfloat;

hfloat
convertFloatToHFloat(float *f)
{
   unsigned int   x = *(unsigned int *)f;
   unsigned int   sign = (unsigned short)(x >> 31);
   unsigned int   mantissa;
   unsigned int   exp;
   hfloat         hf;

   // get mantissa
   mantissa = x & ((1 << 23) - 1);
   // get exponent bits
   exp = X & FLOAT_MAX_BIASED_EXP;
   if (exp >= HALF_FLOAT_MAX_BIASED_EXP_AS_SINGLE_FP_EXP)
   {
      // check if the original single-precision float number
      // is a NaN
```

```
        if (mantissa && (exp == FLOAT_MAX_BIASED_EXP))
        {
           // we have a single-precision NaN
           mantissa = (1 << 23) - 1;
        }
        else
        {
           // 16-bit half-float representation stores number
           // as Inf mantissa = 0;
        }
        hf = (((hfloat)sign) << 15) |
              (hfloat)(HALF_FLOAT_MAX_BIASED_EXP) |
              (hfloat)(mantissa >> 13);
     }
     // check if exponent is <= -15
     else if (exp <= HALF_FLOAT_MIN_BIASED_EXP_AS_SINGLE_FP_EXP)
     {
        // store a denorm half-float value or zero
        exp = (HALF_FLOAT_MIN_BIASED_EXP_AS_SINGLE_FP_EXP - exp)
               >> 23;
        mantissa >>= (14 + exp);

        hf = (((hfloat)sign) << 15) | (hfloat)(mantissa);
     }
     else
     {
        hf = (((hfloat)sign) << 15) |
              (hfloat)
              ((exp - HALF_FLOAT_MIN_BIASED_EXP_AS_SINGLE_FP_EXP)
              >> 13)|
               (hfloat)(mantissa >> 13);
     }
     return hf;
  }
  float
  convertHFloatToFloat(hfloat hf)
  {
     unsigned int   sign = (unsigned int)(hf >> 15);
     unsigned int   mantissa = (unsigned int)(hf &
                    ((1 << 10) - 1));
     unsigned int   exp = (unsigned int)(hf &
                    HALF_FLOAT_MAX_BIASED_EXP);
     unsigned int   f;

     if (exp == HALF_FLOAT_MAX_BIASED_EXP)
     {
        // we have a half-float NaN or Inf
        // half-float NaNs will be converted to a single-
        // precision NaN
```

```
      // half-float Infs will be converted to a single-
      // precision Inf
      exp = FLOAT_MAX_BIASED_EXP;
      if (mantissa)
          mantissa = (1 << 23) - 1;   // set all bits to
                                      // indicate a NaN
   }
   else if (exp == 0x0)
   {
      // convert half-float zero/denorm to single-precision
      // value
      if (mantissa)
      {
         mantissa <<= 1;
         exp = HALF_FLOAT_MIN_BIASED_EXP_AS_SINGLE_FP_EXP;
         // check for leading 1 in denorm mantissa
         while ((mantissa & (1 << 10)) == 0)
         {
            // for every leading 0, decrement single-
            // precision exponent by 1
            // and shift half-float mantissa value to the
            // left mantissa <<= 1;
            exp -= (1 << 23);
         }
         // clamp the mantissa to 10 bits
         mantissa &= ((I << 10) - 1);
         // shift left to generate single-precision mantissa
         // of 23-bits mantissa <<= 13;
      }
   }
   else
   {
      // shift left to generate single-precision mantissa of
      // 23-bits mantissa <<= 13;
      // generate single-precision biased exponent value
      exp = (exp << 13) +
      HALF_FLOAT_MIN_BIASED_EXP_AS_SINGLE_FP_EXP;
   }
   f = (sign << 31) | exp | mantissa;
   return *((float *)&f);
}
```

Appendix B

Built-In Functions

The OpenGL ES shading language built-in functions described in this appendix are copyrighted by Khronos and are reprinted with permission from the ***OpenGL ES 3.00.4 Shading Language Specification***. The latest OpenGL ES 3.0 Shading Language specification can be downloaded from http://khronos.org/registry/gles/.

The OpenGL ES Shading Language defines an assortment of built-in convenience functions for scalar and vector operations. Many of these built-in functions can be used in more than one type of shader, but some are intended to provide a direct mapping to hardware and so are available only for a specific type of shader.

The built-in functions basically fall into three categories:

- They expose some necessary hardware functionality in a convenient way such as accessing a texture map. There is no way in the language for these functions to be emulated by a shader.
- They represent a trivial operation (clamp, mix, etc.) that is simple for the user to write, but they are very common and might have direct hardware support. It is a very hard problem for the compiler to map expressions to complex assembler instructions.
- They represent an operation graphics hardware that is likely to accelerate at some point. The trigonometry functions fall into this category.

Many of the functions are similar to the same named ones in common C libraries, but they support vector input as well as the more traditional scalar input.

Applications should be encouraged to use the built-in functions rather than do the equivalent computations in their own shader code because the built-in functions are assumed to be optimal (e.g., perhaps supported directly in hardware).

When the built-in functions are specified below, where the input arguments (and corresponding output) can be **float**, **vec2**, **vec3**, or **vec4**, *genType* is used as the argument. Where the input arguments (and corresponding output) can be **int**, **ivec2**, **ivec3**, or **ivec4**, *genIType* is used as the argument. Where the input arguments (and corresponding output) can be **uint**, **uvec2**, **uvec3**, or **uvec4**, *genUType* is used as the argument. Where the input arguments (or corresponding output) can be **bool**, **bvec2**, **bvec3**, or **bvec4**, *genBType* is used as the argument. For any specific use of a function, the actual types substituted for *genType*, *genIType*, *genUType*, or *genBType* have to have the same number of components for all arguments and for the return type. Similarly for **mat**, which can be any matrix basic type.

The precision of built-in functions is dependent on the function and arguments. There are three categories:

- Some functions have predefined precisions. The precision is specified; for example,

  highp ivec2 **textureSize** (gsampler2D *sampler*, int *lod*)

- For the texture sampling functions, the precision of the return type matches the precision of the sampler type:

  ```
  uniform lowp sampler2D sampler;

  highp vec2 coord;

  . . .

  // texture() returns lowp

  lowp vec4 col = texture(sampler, coord);
  ```

- For other built-in functions, a call will return a precision qualification matching the highest precision qualification of the call's input arguments.

The built-in functions are assumed to be implemented according to the equations specified in the following sections.

Angle and Trigonometry Functions

Function parameters specified as *angle* are assumed to be in units of radians. In no case will any of these functions result in a divide by zero error. If the divisor of a ratio is 0, then results will be undefined.

These functions all operate component-wise. The description shown in Table B-1 is per component.

Table B-1 Angle and Trigonometry Functions

Syntax	**Description**
genType **radians** (genType *degrees*)	Converts *degrees* to radians, i.e., π/180 * *degrees*.
genType **degrees** (genType *radians*)	Converts *radians* to degrees, i.e., 180/π * *radians*.
genType **sin** (genType *angle*)	The standard trigonometric sine function. Return values are in the range [–1, 1].
genType **cos** (genType *angle*)	The standard trigonometric cosine function. Return values are in the range [–1, 1].
genType **tan** (genType *angle*)	The standard trigonometric tangent function.
genType **asin** (genType *x*)	Arc sine. Returns an angle whose sine is *x*. The range of values returned by this function is [–π/2, π/2]. Results are undefined if |*x*| > 1.
genType **acos** (genType *x*)	Arc cosine. Returns an angle with cosine *x*. The range of values returned by this function is [0, π]. Results are undefined if |*x*| > 1.
genType **atan** (genType *y*, genType *x*)	Arc tangent. Returns an angle with tangent *y/x*. The signs of *x* and *y* are used to determine what quadrant the angle is in. The range of values returned by this function is [–π, π]. Results are undefined if *x* and *y* are both 0.
genType **atan** (genType *y_over_x*)	Arc tangent. Returns an angle with tangent *y_over_x*. The range of values returned by this function is [–π/2, π/2].

(continues)

Table B-1 Angle and Trigonometry Functions *(continued)*

Syntax	**Description**
genType **sinh** (genType *x*)	Returns the hyperbolic sine function $(e^x - e^{-x})/2$
genType **cosh** (genType *x*)	Returns the hyperbolic cosine function $(e^x + e^{-x})/2$
genType **tanh** (genType *x*)	Returns the hyperbolic tangent function $\sinh(x)/\cosh(x)$
genType **asinh** (genType *x*)	Arc hyperbolic sine; returns the inverse of **sinh**.
genType **acosh** (genType *x*)	Arc hyperbolic cosine; returns the non-negative inverse of **cosh**. Results are undefined if $x < 1$.
genType **atanh** (genType *x*)	Arc hyperbolic tangent; returns the inverse of **tanh**. Results are undefined if $\|x\| >= 1$.

Exponential Functions

Exponential functions all operate component-wise. The description shown in Table B-2 is per component.

Table B-2 Exponential Functions

Syntax	**Description**
genType **pow** (genType *x*, genType *y*)	Returns *x* raised to the *y* power, i.e., x^y. Results are undefined if $x < 0$. Results are undefined if $x = 0$ and $y <= 0$.
genType **exp** (genType *x*)	Returns the natural exponentiation of *x*, i.e., e^x.
genType **log** (genType *angle*)	Returns the natural logarithm of *x*, i.e., returns the value *y*, which satisfies the equation $x = e^y$. Results are undefined if $x <= 0$.
genType **exp2** (genType *angle*)	Returns 2 raised to the *x* power, i.e., 2^x.

Table B-2 Exponential Functions *(continued)*

Syntax	**Description**
genType **log2** (genType *angle*)	Returns the base 2 logarithm of x, i.e., returns the value y, which satisfies the equation $x = 2^y$. Results are undefined if $x <= 0$.
genType **sqrt** (genType *x*)	Returns the positive square root of x. Results are undefined if $x < 0$.
genType **inversesqrt** (genType *x*)	Returns the reciprocal of the positive square root of x. Results are undefined if $x <= 0$.

Common Functions

Common functions all operate component-wise. The description shown in Table B-3 is per component.

Table B-3 Common Functions

Syntax	**Description**
genType **abs** (genType *x*) genIType **abs** (genIType *x*)	Returns x if $x >= 0$; otherwise, it returns $-x$.
genType **sign** (genType *x*) genIType **sign** (genIType *x*)	Returns 1.0 if $x > 0$, 0.0 if $x = 0$, or –1.0 if $x < 0$.
genType **floor** (genType *x*)	Returns a value equal to the nearest integer that is less than or equal to x.
genType **trunc** (genType *x*)	Returns a value equal to the nearest integer to x whose absolute value is not larger than the absolute value of x.

(continues)

Table B-3 Common Functions *(continued)*

Syntax	**Description**
genType **round** (genType *x*)	Returns a value equal to the nearest integer to *x*. The fraction 0.5 will round in a direction chosen by the implementation, presumably the direction that is fastest. This includes the possibility that **round**(*x*) returns the same value as **roundEven**(*x*) for all values of *x*.
genType **roundEven** (genType *x*)	Returns a value equal to the nearest integer to *x*. A fractional part of 0.5 will round toward the nearest even integer. (Both 3.5 and 4.5 for *x* will return 4.0.)
genType **ceil** (genType *x*)	Returns a value equal to the nearest integer that is greater than or equal to *x*.
genType **fract** (genType *x*)	Returns *x* – **floor**(*x*).
genType **mod** (genType *x*, float *y*) genType **mod** (genType *x*, genType *y*)	Modulus (modulo). Returns *x* – *y* * **floor**(*x*/*y*).
genType **min** (genType *x*, genType *y*) genType **min** (genType *x*, float *y*) genIType **min** (genIType *x*, genIType *y*) genIType **min** (genIType *x*, int *y*) genUType **min** (genUType *x*, genUType *y*) genUType **min** (genUType *x*, uint *y*)	Returns *y* if *y* < *x*; otherwise, it returns *x*.
genType **max** (genType *x*, genType *y*) genType **max** (genType *x*, float *y*) genIType **max** (genIType *x*, genIType *y*) genIType **max** (genIType *x*, int *y*) genUType **max** (genUType *x*, genUType *y*) genUType **max** (genUType *x*, uint *y*)	Returns *y* if *x* < *y*; otherwise, it returns *x*.

Table B-3 Common Functions *(continued)*

Syntax	**Description**
genType **clamp** (genType *x*, genType *minVal*, genType *maxVal*) genType **clamp** (genType *x*, float *minVal*, float *maxVal*) genIType **clamp** (genIType *x*, genIType *minVal*, genIType *maxVal*) genIType **clamp** (genIType *x*, int *minVal*, int *maxVal*) genUType **clamp** (genUType *x*, genUType *minVal*, genUType *maxVal*) genUType **clamp** (genUType *x*, uint *minVal*, uint *maxVal*)	Returns **min (max** (*x*, *minVal*), *maxVal*) Results are undefined if *minVal* > *maxVal*.
genType **mix** (genType *x*, genType *y*, genType *a*) genType **mix** (genType *x*, genType *y*, float *a*)	Returns the linear blend of *x* and *y*, i.e., *x* * (1 – *a*) + *y* * *a*.
genType **mix** (genType *x*, genType *y*, genBType *a*)	Selects which vector each returned component comes from. For a component of *a* that is false, the corresponding component of *x* is returned. For a component of *a* that is true, the corresponding component of *y* is returned. Components of *x* and *y* that are not selected are allowed to be invalid floating-point values and will have no effect on the results. Thus, this provides different functionality than genType **mix**(genType *x*, genType *y*, genType(*a*)) where *a* is a boolean vector.

(continues)

Table B-3 Common Functions *(continued)*

Syntax	**Description**
genType **step** (genType *edge*, genType *x*) genType **step** (float *edge*, genType *x*)	Returns 0.0 if *x* < *edge*; otherwise, it returns 1.0.

genType **smoothstep** (genType *edge0*, genType *edgel*, genType *x*)
genType **smoothstep** (float *edge0*, float *edgel*, gemType *x*)
	Returns 0.0 if *x* <= *edge0* and 1.0 if *x* >= *edgel* and performs smooth Hermite interpolation between 0 and 1 when *edge0* < *x* < *edgel*. This is useful in cases where you would want a threshold function with a smooth transition. This is equivalent to:
	`// genType is float, vec2, vec3,`
	`// or vec4`
	`genType t;`
	`t = clamp((x - edge0)/`
	`    (edgel - edge0), 0, 1);`
	`return t * t * (3 - 2 * t);`
	Results are undefined if *edge0* >= *edgel*.

genBType **isnan** (genType *x*)	Returns **true** if *x* holds a NaN. Returns **false** otherwise.
genBType **isinf** (genType *x*)	Returns **true** if *x* holds a positive infinity or negative infinity. Returns **false** otherwise.
genIType **floatBitsToInt** (genType *value*) genUType **floatBitsToUint** (genType *value*)	Returns a signed or unsigned highp integer value representing the encoding of a floating-point value. For highp floating point, the value's bit-level representation is preserved. For mediump and lowp, the value is first converted to highp floating point and the encoding of that value is returned.
genType **intBitsToFloat** (genIType *value*) genType **uintBitsToFloat** (genUType *value*)	Returns a highp floating-point value corresponding to a signed or unsigned integer encoding of a floating-point value. If an inf or NaN is passed in, it will not signal, and the resulting floating-point value is unspecified. Otherwise, the bit-level representation is preserved. For lowp and mediump, the value is first converted to the corresponding signed or unsigned highp integer and then reinterpreted as a highp floating-point value as before.

Floating-Point Pack and Unpack Functions

Floating-point pack and unpack functions do not operate component-wise, rather as described in each case (Table B-4).

Table B-4 Floating-Point Pack and Unpack Functions

Syntax	Description
highp uint **packSnorm2x16** (vec2 *v*)	First, converts each component of the normalized floating-point value *v* into 16-bit integer values. Then, the results are packed into the returned 32-bit unsigned integer. The conversion for component *c* of *v* to fixed point is done as follows: **packSnorm2x16:** round(clamp(*c*, –1, +1) * 32767.0) The first component of the vector will be written to the least significant bits of the output; the last component will be written to the most significant bits.
highp vec2 **unpackSnorm 2x16** (highp uint *p*)	First, unpacks a single 32-bit unsigned integer *p* into a pair of 16-bit unsigned integers. Then, each component is converted to a normalized floating-point value to generate the returned two-component vector. The conversion for unpacked fixed-point value *f* to floating point is done as follows: **unpackSnorm2x16:** clamp(*f*/32767.0, –1, +1) The first component of the returned vector will be extracted from the least significant bits of the input; the last component will be extracted from the most significant bits.
highp vec2 **unpackUnorm2x16** (highp uint *p*)	First, unpacks a single 32-bit unsigned integer *p* into a pair of 16-bit unsigned integers. Then, each component is converted to a normalized floating-point value to generate the returned two-component vector.

(continues)

Table B-4 Floating-Point Pack and Unpack Functions *(continued)*

Syntax	**Description**
	The conversion for unpacked fixed-point value *f* to floating point is done as follows: **unpackUnorm2x16:** *f*/65535.0 The first component of the returned vector will be extracted from the least significant bits of the input; the last component will be extracted from the most significant bits.
highp uint **packHalf2x16** (mediumpvec2 *v*)	Returns an unsigned integer obtained by converting the components of a two-component floating-point vector to the 16-bit floating-point representation found in the OpenGL ES Specification, and then packing these two 16-bit integers into a 32-bit unsigned integer. The first vector component specifies the 16 least significant bits of the result; the second component specifies the 16 most significant bits.
mediump vec2 **unpackHalf2x16** (highp uint *v*)	Returns a two-component floating-point vector with components obtained by unpacking a 32-bit unsigned integer into a pair of 16-bit values, interpreting those values as 16-bit floating-point numbers according to the OpenGL ES Specification, and converting them to 32-bit floating-point values. The first component of the vector is obtained from the 16 least significant bits of *v*; the second component is obtained from the 16 most significant bits of *v*.

Geometric Functions

Geometric functions operate on vectors as vectors, not component-wise. Table B-5 describes these functions.

Table B-5 Geometric Functions

Syntax	Description
float **length** (genType *x*)	Returns the length of vector *x*, $\sqrt{X[0]^2 + X[1]^2 + \ldots}$
float **distance** (genType *p0*, genType *p1*)	Returns the distance between *p0* and *p1*, i.e., **length** (*p0* – *p1*).
float **dot** (genType *x*, genType *y*)	Returns the dot product of *x* and *y*, i.e., *x*[0] * *y*[0] + *x*[l] * *y*[l] + ...
vec3 **cross** (vec3 *x*, vec3 *y*)	Returns the cross product of *x* and *y*, i.e., *result*[0] = *x*[1] * *y*[2] – *y*[1] * *x*[2] *result*[1] = *x*[2] * *y*[0] – *y*[2] * *x*[0] *result*[2] = *x*[0] * *y*[1] – *y*[0] * *x*[1]
genType **normalize** (genType *x*)	Returns a vector in the same direction as *x* but with a length of 1. Returns *x*/**length**(*x*).
genType **faceforward** (genType *N*, genType *I*, genType N_{ref})	If **dot**(N_{ref}, *I*) < 0, return *N*; otherwise, return –*N*.
genType **reflect** (genType *I*, genType *N*)	For the incident vector *I* and surface orientation *N*, returns the reflection direction: *I* – 2 * **dot**(*N*, *I*) * *N* *N* must already be normalized to achieve the desired result.

genType **refract** (genType *I*, genType *N*, float *eta*)	For the incident vector *I*, surface normal *N*, and ratio of indices of refraction *eta,* return the refraction vector. The result is computed by
	`k = 1.0 - eta * eta *`
	`   (1.0 - dot(N, I)`
	`   * dot(N, I))`
	`if (k < 0.0)`
	`   // genType is float, vec2,`
	`   // vec3, or vec4`
	`   return genType(0.0)`
	`else`
	`   return eta * I - (eta *`
	`      dot(N, I) + sqrt(k)) * N`
	Input parameters for the incident vector *I* and the surface normal *N* must already be normalized to get the desired results.

Matrix Functions

The built-in functions that operate on matrices are described in Table B-6.

Table B-6 Matrix Functions

Syntax	Description
mat2 **matrixCompMult** (mat2 *x*, mat2 *y*) mat3 **matrixCompMult** (mat3 *x*, mat3 *y*) mat4 **matrixCompMult** (mat4 *x*, mat4 *y*)	Multiply matrix *x* by matrix *y* component-wise, i.e., *result*[*i*][*j*] is the scalar product of *x*[*i*][*j*] and *y*[*i*][*j*]. Note: To get linear algebraic matrix multiplication, use the multiply operator (*).
mat2 **outerProduct**(vec2 *c*, vec2 *r*) mat3 **outerProduct**(vec3 *c*, vec3 *r*) mat4 **outerProduct**(vec4 *c*, vec4 *r*) mat2x3 **outerProduct**(vec3 *c*, vec2 *r*) mat3x2 **outerProduct**(vec2 *c*, vec3 *r*) mat2x4 **outerProduct**(vec4 *c*, vec2 *r*) mat4x2 **outerProduct**(vec2 *c*, vec4 *r*) mat3x4 **outerProduct**(vec4 *c*, vec3 *r*) mat4x3 **outerProduct**(vec3 *c*, vec4 *r*)	Treats the first parameter *c* as a column vector (matrix with one column) and the second parameter *r* as a row vector (matrix with one row) and does a linear algebraic matrix multiply *c* * *r*, yielding a matrix whose number of rows is the number of components in *c* and whose number of columns is the number of components in *r*.
mat2 **transpose**(mat2 *m*) mat3 **transpose**(mat3 *m*) mat4 **transpose**(mat4 *m*) mat2x3 **transpose**(mat3x2 *m*) mat3x2 **transpose**(mat2x3 *m*) mat2x4 **transpose**(mat4x2 *m*) mat4x2 **transpose**(mat2x4 *m*) mat3x4 **transpose**(mat4x3 *m*) mat4x3 **transpose**(mat3x4 *m*)	Returns a matrix that is the transpose of *m*. The input matrix *m* is not modified.
float **determinant**(mat2 *m*) float **determinant**(mat3 *m*) float **determinant**(mat4 *m*)	Returns the determinant of *m*.
mat2 **inverse**(mat2 *m*) mat3 **inverse**(mat3 *m*) mat4 **inverse**(mat4 *m*)	Returns a matrix that is the inverse of *m*. The input matrix *m* is not modified. The values in the returned matrix are undefined if *m* is singular or poorly conditioned (nearly singular).

Vector Relational Functions

Relational and equality operators (<, <=, >, >=, ==, !=) are defined to produce scalar boolean results. For vector results, use the following built-in functions. In Table B-7, "bvec" is a placeholder for one of **bvec2**, **bvec3**, or **bvec4**; "ivec" is a placeholder for one of **ivec2**, **ivec3**, or **ivec4**; "uvec" is a placeholder for **uvec2**, **uvec3**, or **uvec4**; and "vec" is a placeholder for **vec2**, **vec3**, or **vec4**. In all cases, the sizes of the input and return vectors for any particular call must match.

Table B-7 Vector Relational Functions

Syntax	**Description**
bvec **lessThan** (vec *x*, vec *y*) bvec **lessThan** (ivec *x*, ivec *y*) bvec **lessThan** (uvec *x*, uvec *y*)	Returns the component-wise compare of *x* < *y*.
bvec **lessThanEqual** (vec *x*, vec *y*) bvec **lessThanEqual** (ivec *x*, ivec *y*) bvec **lessThanEqual** (uvec *x*, uvec *y*)	Returns the component-wise compare of x <= *y*.
bvec **greaterThan** (vec *x*, vec *y*) bvec **greaterThan** (ivec *x*, ivec *y*) bvec **greaterThan** (uvec *x*, uvec *y*)	Returns the component-wise compare of *x* > *y*.
bvec **greaterThanEqual** (vec *x*, vec *y*) bvec **greaterThanEqual** (ivec *x*, ivec *y*) bvec **greaterThanEqual** (uvec *x*, uvec *y*)	Returns the component-wise compare of *x* >= *y*.
bvec **equal** (vec *x*, vec *y*) bvec **equal** (ivec *x*, ivec *y*) bvec **equal** (uvec *x*, uvec *y*)	Returns the component-wise compare of *x* == *y*.
bvec **notEqual** (vec *x*, vec *y*) bvec **notEqual** (ivec *x*, ivec *y*) bvec **notEqual** (uvec *x*, uvec *y*)	Returns the component-wise compare of *x* != *y*.
bool **any** (bvec2 *x*) bool **any** (bvec3 *x*) bool **any** (bvec4 *x*)	Returns true if any component of *x* is **true**.
bool **all** (bvec2 *x*) bool **all** (bvec3 *x*) bool **all** (bvec4 *x*)	Returns true only if all components of *x* are **true**.
bvec2 **not** (bvec2 *x*) bvec3 **not** (bvec3 *x*) bvec4 **not** (bvec4 *x*)	Returns the component-wise logical complement of *x*.

Texture Lookup Functions

Texture lookup functions are available to vertex and fragment shaders. However, level of detail is not implicitly computed for vertex shaders. The functions in Table B-8 provide access to textures through samplers, as set up through the OpenGL ES API. Texture properties such as size, pixel format, number of dimensions, filtering method, number of mipmap levels, depth comparison, and so on are also defined by OpenGL ES API calls. Such properties are taken into account as the texture is accessed via the built-in functions defined below.

Texture data can be stored by the GL as floating-point, unsigned normalized integer, unsigned integer, or signed integer data. This is determined by the type of the internal format of the texture. Texture lookups on unsigned normalized integer and floating-point data return floating-point values in the range [0, 1].

Texture lookup functions are provided that can return their result as floating-point, unsigned integer, or signed integer values, depending on the sampler type passed to the lookup function. Care must be taken to use the right sampler type for texture access. Table B-8 lists the supported combinations of sampler types and texture internal formats. Blank entries are unsupported. Doing a texture lookup will return undefined values for unsupported combinations.

Table B-8 Supported Combinations of Sampler and Internal Texture Formats

Internal Texture Format	**Floating-Point Sampler Types**	**Signed Integer Sampler Types**	**Unsigned Integer Sampler Types**
Floating point	Supported		
Normalized integer	Supported		
Signed integer		Supported	
Unsigned integer			Supported

If an integer sampler type is used, the result of a texture lookup is an ivec4. If an unsigned integer sampler type is used, the result of a texture lookup is a uvec4. If a floating-point sampler type is used, the result of a texture lookup is a vec4, where each component is in the range [0, 1].

In the prototypes below, the "g" in the return type "gvec4" is used as a placeholder for nothing; "i" or "u" making a return type of vec4, ivec4, or uvec4. In these cases, the sampler argument type also starts with "g", indicating the same substitution done on the return type; it is either a floating-point, signed integer, or unsigned integer sampler, matching the basic type of the return type, as described above.

For shadow forms (the sampler parameter is a shadow type), a depth comparison lookup on the depth texture bound to *sampler* is done as described in section 3.8.16, "Texture Comparison Modes," of the OpenGL ES Graphics System Specification. See the table below for which component specifies *Dref*. The texture bound to *sampler* must be a depth texture, or results are undefined. If a non-shadow texture call is made to a sampler that represents a depth texture with depth comparisons turned on, then results are undefined. If a shadow texture call is made to a sampler that represents a depth texture with depth comparisons turned off, then results are undefined. If a shadow texture call is made to a sampler that does not represent a depth texture, then results are undefined.

In all functions below, the *bias* parameter is optional for fragment shaders. The *bias* parameter is not accepted in a vertex shader. For a fragment shader, if *bias* is present, it is added to the implicit level of detail prior to performing the texture access operation.

The implicit level of detail is selected as follows: For a texture that is not mipmapped, the texture is used directly. If it is mipmapped and running in a fragment shader, the LOD computed by the implementation is used to do the texture lookup. If it is mipmapped and running on the vertex shader, then the base texture is used.

Some texture functions (non-"**Lod**" and non-"**Grad**" versions) may require implicit derivatives. Implicit derivatives are undefined within non-uniform control flow and for vertex texture fetches.

For **Cube** forms, the direction of *P* is used to select which face to do a two-dimensional texture lookup in, as described in section 3.8.10, "Cube Map Texture Selection," in the OpenGL ES Graphics System Specification.

For **Array** forms, the array layer used will be

$$max(0, min(d - 1, floor(layer + 0.5)))$$

where *d* is the depth of the texture array and *layer* comes from the component indicated in Table B-9.

Table B-9 Texture Lookup Functions

Syntax	**Description**
highp ivec2 **textureSize** (gsampler2D *sampler*, int *lod*) highp ivec3 **textureSize** (gsampler3D *sampler*, int *lod*) highp ivec2 **textureSize** (gsamplerCube *sampler*, int *lod*) highp ivec2 **textureSize** (sampler2DShadow *sampler*, int *lod*) highp ivec2 **textureSize** (samplerCubeShadow *sampler*, int *lod*) highp ivec3 **textureSize** (gsampler2DArray *sampler*, int *lod*) highp ivec3 **textureSize** (sampler2DArrayShadow *sampler*, int *lod*)	Returns the dimensions of level *lod* for the texture bound to sampler, as described in section 2.11.9, "Shader Execution," of the OpenGL ES 3.0 Graphics System Specification, under "Texture Size Query." The components in the return value are filled in, in order, with the width, height, and depth of the texture. For the array forms, the last component of the return value is the number of layers in the texture array.
gvec4 **texture** (gsampler2D *sampler*, vec2 *P* [, float *bias*]) gvec4 **texture** (gsampler3D *sampler*, vec3 *P* [, float *bias*]) gvec4 **texture** (gsamplerCube *sampler*, vec3 *P* [, float *bias*]) float **texture** (sampler2DShadow *sampler*, vec3 *P* [, float *bias*]) float **texture** (samplerCubeShadow *sampler*, vec4 *P* [, float *bias*]) gvec4 **texture** (gsampler2DArray *sampler*, vec3 *P* [, float *bias*]) float **texture** (sampler2DArrayShadow *sampler*, vec4 *P*)	Use the texture coordinate *P* to do a texture lookup in the texture currently bound to *sampler*. The last component of *P* is used as *Dref* for the shadow forms. For array forms, the array layer comes from the last component of *P* in the non-shadow forms, and the second-to-last component of *P* in the shadow forms.

Table B-9 Texture Lookup Functions *(continued)*

Syntax	**Description**
gvec4 **textureProj** (gsampler2D *sampler*, vec3 *P* [, float *bias*]) gvec4 **textureProj** (gsampler2D *sampler*, vec4 *P* [, float *bias*]) gvec4 **textureProj** (gsampler3D *sampler*, vec4 *P* [, float *bias*]) float **textureProj** (sampler2DShadow *sampler*, vec4 *P* [, float *bias*])	Do a texture lookup with projection. The texture coordinates consumed from *P*, not including the last component of *P*, are divided by the last component of *P* to form projected coordinates *P'*. The resulting third component of *P'* in the shadow forms is used as *Dref*. The third component of *P* is ignored when *sampler* has type gsampler2D and *P* has type vec4. After these values are computed, texture lookup proceeds as in **texture**.
gvec4 **textureLod** (gsampler2D *sampler*, vec2 *P*, float *lod*) gvec4 **textureLod** (gsampler3D *sampler*, vec3 *P*, float *lod*) gvec4 **textureLod** (gsamplerCube *sampler*, vec3 *P*, float *lod*) float **textureLod** (sampler2DShadow *sampler*, vec3 *P*, float *lod*) gvec4 **textureLod** (gsampler2DArray *sampler*, vec3 *P*, float *lod*)	Do a texture lookup as in texture but with explicit LOD; *lod* specifies λ base and sets the partial derivatives used for the texture minification equations to 0.

(continues)

Table B-9 Texture Lookup Functions *(continued)*

Syntax	**Description**
gvec4 **textureOffset** (gsampler2D *sampler*, vec2 *P*, ivec2 *offset* [, float *bias*]) gvec4 **textureOffset** (gsampler3D *sampler*, vec3 *P*, ivec3 *offset* [, float *bias*]) float **textureOffset** (sampler2DShadow *sampler*, vec3 *P*, ivec2 *offset* [, float *bias*]) gvec4 **textureOffset** (gsampler2DArray *sampler*, vec3 *P*, ivec2 *offset* [, float *bias*])	Do a texture lookup as in texture but with *offset* added to the (u, v, w) texel coordinates before looking up each texel. The offset value must be a constant expression. A limited range of offset values are supported; the minimum and maximum offset values are implementation-dependent and given by `MIN_PROGRAM_TEXEL_OFFSET` and `MAX_PROGRAM_TEXEL_OFFSET`, respectively. Note that offset does not apply to the layer coordinate for texture arrays. Note that texel offsets are also not supported for cubemaps.
gvec4 **textureProjLod** (gsampler2D *sampler*, vec3 *P*, float *lod*) gvec4 **textureProjLod** (gsampler2D *sampler*, vec4 *P*, float *lod*) gvec4 **textureProjLod** (gsampler3D *sampler*, vec4 *P*, float *lod*) float **textureProjLod** (sampler2DShadow *sampler*, vec4 *P*, float *lod*)	Do a projective texture lookup with explicit LOD. See **textureProj** and **textureLod**.
gvec4 **textureProjLodOffset** (gsampler2D *sampler*, vec3 *P*, float *lod*, ivec2 *offset*) gvec4 **textureProjLodOffset** (gsampler2D *sampler*, vec4 *P*, float *lod*, ivec2 *offset*) gvec4 **textureProjLodOffset** (gsampler3D *sampler*, vec4 *P*, float *lod*, ivec3 *offset*) float **textureProjLodOffset** (sampler2DShadow *sampler*, vec4 *P*, float *lod*, ivec2 *offset*)	Do an offset projective texture lookup with explicit LOD. See **textureProj**, **textureLod**, and **textureOffset**.

Table B-9 Texture Lookup Functions *(continued)*

Syntax	**Description**
gvec4 **textureGrad** (gsampler2D *sampler*, vec2 *P*, vec2 *dPdx*, vec2 *dPdy*) gvec4 **textureGrad** (gsampler3D *sampler*, vec3 *P*, vec3 *dPdx*, vec3 *dPdy*) gvec4 **textureGrad** (gsamplerCube *sampler*, vec3 *P*, vec3 *dPdx*, vec3 *dPdy*) float **textureGrad** (sampler2DShadow *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*) float **textureGrad** (samplerCubeShadow *sampler*, vec4 *P*, vec3 *dPdx*, vec3 *dPdy*) gvec4 **textureGrad** (gsampler2DArray *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*) float **textureGrad** (sampler2DArrayShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*)	Do a texture lookup as in **texture** but with explicit gradients. The partial derivatives of **P** are with respect to window *x* and window *y*.
gvec4 **textureGradOffset** (gsampler2D *sampler*, vec2 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*) gvec4 **textureGradOffset** (gsampler3D *sampler*, vec3 *P*, vec3 *dPdx*, vec3 *dPdy*, ivec3 *offset*) float **textureGradOffset** (sampler2DShadow *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*) gvec4 **textureGradOffset** (gsampler2DArray *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*) float **textureGradOffset** (sampler2DArrayShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*)	Do a texture lookup with both explicit gradient and offset, as described in **textureGrad** and **textureOffset**.

(continues)

Table B-9 Texture Lookup Functions *(continued)*

Syntax	**Description**
gvec4 **textureProjGrad** (gsampler2D *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*) gvec4 **textureProjGrad** (gsampler2D *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*) gvec4 **textureProjGrad** (gsampler3D *sampler*, vec4 *P*, vec3 *dPdx*, vec3 *dPdy*) float **textureProjGrad** (sampler2DShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*)	Do a texture lookup both projectively, as described in **textureProj**, and with explicit gradient, as described in **textureGrad**. The partial derivatives *dPdx* and dPdy are assumed to be already projected.
gvec4 **textureProjGradOffset** (gsampler2D *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 offset) gvec4 **textureProjGradOffset** (gsampler2D *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 offset) gvec4 **textureProjGradOffset** (gsampler3D *sampler*, vec4 *P*, vec3 *dPdx*, vec3 *dPdy*, ivec3 offset) float **textureProjGradOffset** (sampler2DShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 offset)	Do a texture lookup projectively and with explicit gradient as described in **textureProjGrad**, as well as with offset, as described in **textureOffset**.

Fragment Processing Functions

Fragment processing functions are only available in fragment shaders.

Derivatives may be computationally expensive and/or numerically unstable. Therefore, an OpenGL ES implementation may approximate the true derivatives by using a fast but not entirely accurate derivative computation. Derivatives are undefined within non-uniform control flow.

The expected behavior of a derivative is specified using forward–backward differencing.

Forward differencing:

$$F(x + dx) - F(x) \sim dFdx(x) * dx$$

$$dFdx \sim (F(x + dx) - F(x))/dx$$

Backward differencing:

$$F(x - dx) - F(x) \sim -dFdx(x) * dx$$

$$dFdx \sim (F(x) - F(x - dx))/dx$$

With single-sample rasterization, $dx <= 1.0$ in the preceding equations. For multisample rasterization, $dx < 2.0$ in the preceding equations.

dFdy is approximated similarly, with *y* replacing *x*.

An OpenGL ES implementation can use the preceding or other methods to perform the calculation, subject to the following conditions:

- The method can use piecewise linear approximations. Such linear approximations imply that higher-order derivatives, **dFdx**(**dFdx**(*x*)) and above, are undefined.
- The method can assume that the function evaluated is continuous. Therefore derivatives within the body of a non-uniform conditional are undefined.
- The method can differ per fragment, subject to the constraint that the method can vary by window coordinates, not screen coordinates. The invariance requirement is relaxed for derivative calculations, because the method can be a function of fragment location.

Other properties that are desirable, but not required, are

- Functions should be evaluated within the interior of a primitive (interpolated, not extrapolated).
- Functions for **dFdx** should be evaluated while holding *y* constant. Functions for **dFdy** should be evaluated while holding *x* constant. However, mixed higher-order derivatives, like **dFdx**(**dFdy**(*y*)) and **dFdy**(**dFdx**(*x*)), are undefined.
- Derivatives of constant arguments should be 0.

In some implementations, varying degrees of derivative accuracy can be obtained by providing hints using `glHint (GL_FRAGMENT_SHADER_DERIVATIVE_HINT)`, allowing a user to make an image quality versus speed trade-off.

Table B-10 describes the fragment processing functions.

Table B-10 Fragment Processing Functions

Syntax	**Description**
genType **dFdx** (genType *p*)	Returns the derivative in *x* using local differencing for the input argument *p*.
genType **dFdy** (genType *p*)	Returns the derivative in *y* using local differencing for the input argument *p*.
genType **fwidth** (genType *p*)	Returns the sum of the absolute derivative in *x* and *y* using local differencing for the input argument *p*; i.e., *result* = **abs** (**dFdx** (*p*)) + **abs** (**dFdy** (*p*)).

ES Framework API

The example programs throughout the book use a framework of utility functions for performing common OpenGL ES 3.0 functions. These utility functions are not part of OpenGL ES 3.0, but rather are custom functions that we wrote to support the sample code in the book. The ES Framework API is included with the source code for the book available from the book website at opengles-book.com. The ES Framework API provides routines for tasks such as creating a window, setting up callback functions, loading a shader, loading a program, and creating geometry. The purpose of this appendix is to provide documentation for the ES Framework API functions used throughout the book.

Framework Core Functions

This section provides documentation on the core functions in the ES Framework API.

```
GLboolean ESUTIL_API esCreateWindow(ESContext * esContext,
                                    const char * title,
                                    GLint width,
                                    GLint height,
                                    GLuint flags)
```

Create a window with the specified parameters.

Parameters:

`esContext`	application context
`title`	name for title bar of window

(continues)

(continued)

width	width in pixels of window to create
height	height in pixels of window to create
flags	bitfield for the window creation flags
	`ES_WINDOW_RGB`—specifies that the color buffer should have R, G, B channels
	`ES_WINDOW_ALPHA`—specifies that the color buffer should have alpha
	`ES_WINDOW_DEPTH`—specifies that a depth buffer should be created
	`ES_WINDOW_STENCIL`—specifies that a stencil buffer should be created
	`ES_WINDOW_MULTISAMPLE`—specifies that a multisample buffer should be created

Returns:

`GL_TRUE` if window creation is successful; `GL_FALSE` otherwise

```
void ESUTIL_API esRegisterDrawFunc(ESContext * esContext,
                    void(ESCALLBACK *drawFunc) (ESContext *))
```

Register a draw callback function to be used to render each frame.

Parameters:

esContext	application context
drawFunc	draw callback function that will be used to render the scene

```
void ESUTIL_API esRegisterUpdateFunc(ESContext * esContext,
                   void(ESCALLBACK *updateFunc)
                   (ESContext *, float))
```

Register an update callback function to be used to update on each time step.

Parameters:

esContext	application context
updateFunc	update callback function that will be used to render the scene

```
void ESUTIL_API esRegisterKeyFunc(ESContext * esContext,
                  void(ESCALLBACK * keyFunc)
                  (ESContext *, unsigned char, int, int))
```

Register a keyboard input processing callback function.

Parameters:

esContext	application context
keyFunc	key callback function for application processing of keyboard input

```
void  ESUTIL_API esRegisterShutdownFunc(ESContext * esContext,
                  void(ESCALLBACK * shutdownFunc)
                  (ESContext *))
```

Register a callback function to be called at shutdown.

Parameters:

esContext	application context
shutdownFunc	shutdown function called at application shutdown

```
GLuint ESUTIL_API esLoadShader(GLenum type,
                               const char * shaderSrc)
```

Load a shader, check for compile errors, print error messages to output log.

Parameters:

type	type of shader (GL_VERTEX_SHADER or GL_FRAGMENT_SHADER)
shaderSrc	shader source string

Returns:

A new shader object on success, 0 on failure

```
GLuint ESUTIL_API esLoadProgram(const char * vertShaderSrc,
                                const char * fragShaderSrc)
```

Load a vertex and fragment shader, create a program object, link program. Errors are output to the log.

(continues)

(continued)

Parameters:

vertShaderSrc	vertex shader source code
fragShaderSrc	fragment shader source code

Returns:

A new program object linked with the vertex/fragment shader pair; 0 on failure

```
char* ESUTIL_API esLoadTGA(char * fileName, int * width,
                           int * height)
```

Loads an 8-bit, 24-bit, or 32-bit TGA image from a file.

Parameters:

filename	name of the file on disk
width	width of loaded image in pixels
height	height of loaded image in pixels

Returns:

Pointer to loaded image; `NULL` on failure.

```
int ESUTIL_API esGenSphere(int numSlices, float radius,
                   GLfloat ** vertices, GLfloat ** normals,
                   GLfloat ** texCoords, GLuint ** indices)
```

Generates geometry for a sphere. Allocates memory for the vertex data and stores the results in the arrays. Generates index list for a `GL_TRIANGLE_STRIP`.

Parameters:

numSlices	the number of vertical and horizontal slices in the sphere
vertices	if not `NULL`, will contain array of float3 positions
normals	if not `NULL`, will contain array of float3 normals
texCoords	if not `NULL`, will contain array of float2 texCoords
indices	if not `NULL`, will contain the array of indices for the triangle strip

Returns:

The number of indices required for rendering the buffers (the number of indices stored in the indices array if it is not `NULL`) as a `GL_TRIANGLE_STRIP`

```
int ESUTIL_API  esGenCube(float scale, GLfloat ** vertices,
                     GLfloat ** normals, GLfloat ** texCoords,
                     GLuint ** indices)
```

Generates geometry for a cube. Allocates memory for the vertex data and stores the results in the arrays. Generates index list for `GL_TRIANGLES`.

Parameters:

`Scale`	the size of the cube, use 1.0 for a unit cube
`vertices`	if not `NULL`, will contain array of float3 positions
`normals`	if not `NULL`, will contain array of float3 normals
`texCoords`	if not `NULL`, will contain array of float2 texCoords
`indices`	if not `NULL`, will contain the array of indices for the triangle list

Returns:

The number of indices required for rendering the buffers (the number of indices stored in the indices array if it is not `NULL`) as `GL_TRIANGLES`

```
int ESUTIL_API esGenSquareGrid(int size, GLfloat ** vertices,
                     GLuint ** indices)
```

Generates a square grid consisting of triangles. Allocates memory for the vertex data and stores the results in the arrays. Generates index list for `GL_TRIANGLES`.

Parameters:

`Scale`	the size of the cube, use 1.0 for a unit cube
`vertices`	if not `NULL`, will contain array of float3 positions
`indices`	if not `NULL`, will contain the array of indices for the triangle list

Returns:

The number of indices required for rendering the buffers (the number of indices stored in the indices array if it is not `NULL`) as `GL_TRIANGLES`

```
void ESUTIL_API esLogMessage (const char * formatStr, ...)
```

Log a message to the debug output for the platform.

Parameters:

`formatStr`	format string for error log

Transformation Functions

We now describe utility functions that perform commonly used transformations such as scale, rotate, translate, and matrix multiplication. Most vertex shaders will use one or more matrices to transform the vertex position from local coordinate space to clip coordinate space (refer to Chapter 7, “Primitive Assembly and Rasterization,” for a description of the various coordinate systems). Matrices are also used to transform other vertex attributes such as normals and texture coordinates. The transformed matrices can then be used as values for appropriate matrix uniforms used in a vertex or fragment shader. You will notice similarities between these functions and appropriate functions defined in OpenGL and OpenGL ES 1.x. For example, `esScale` should be quite similar to `glScale`, `esFrustum` should be similar to `glFrustum`, and so on.

A new type, `ESMatrix`, is defined in the framework. This is used to represent a 4 × 4 floating-point matrix and is declared as follows:

```
typdedef  struct  {
   GLfloat   m[4][4];
}ESMatrix;
```

```
void ESUTIL_API esFrustum(ESMatrix *result,
                          GLfloat left, GLfloat right,
                          GLfloat bottom, GLfloat top,
                          GLfloat nearZ, GLfloat farZ)
```

Multiply matrix specified by *`result`* with a perspective projection matrix and return new matrix in *`result`*.

Parameters:

`result`	the input matrix
`left, right`	specify the coordinates for the left and right clipping planes
`bottom, top`	specify the coordinates for the bottom and top clipping planes
`nearZ, farZ`	specify the distances to the near and far depth clipping planes; both distances must be positive

Returns:

The new matrix after the perspective projection matrix has been multiplied is returned in *`result`*

```
void ESUTIL_API esPerspective(ESMatrix *result,
                              GLfloat fovy, GLfloat aspect
                              GLfloat nearZ, GLfloat farZ)
```

Multiply matrix specified by `result` with a perspective projection matrix and return new matrix in `result`. This function is provided as a convenience to more easily create a perspective matrix than by directly using `esFrustum`.

Parameters:

result	the input matrix
fovy	specifies the field of view in degrees, should be between (0, 180)
aspect	the aspect ratio of the rendering window (e.g., width/height)
nearZ, *farZ*	specify the distances to the near and far depth clipping planes; both distances must be positive

Returns:

The new matrix after the perspective projection matrix has been multiplied is returned in `result`

```
void ESUTIL_API esOrtho(ESMatrix *result,
                        GLfloat left, GLfloat right,
                        GLfloat bottom, GLfloat top,
                        GLfloat nearZ, GLfloat farZ)
```

Multiply matrix specified by `result` with an orthographic projection matrix and return new matrix in `result`.

Parameters:

result	the input matrix
left, *right*	specify the coordinates for the left and right clipping planes
bottom, *top*	specify the coordinates for the bottom and top clipping planes
nearZ, *farZ*	specify the distances to the near and far depth clipping planes; both `nearZ` and `farZ` can be positive or negative

Returns:

The new matrix after the orthographic projection matrix has been multiplied is returned in `result`

```
void ESUTIL_API esScale(ESMatrix *result, GLfloat sx,
                        GLfloat sy, GLfloat sz)
```

Multiply matrix specified by `result` with a scaling matrix and return new matrix in `result`.

Parameters:

result	the input matrix
sx, *sy*, *sz*	specify the scale factors along the *x*-, *y*-, and *z*-axes, respectively

Returns:

The new matrix after the scaling operation has been performed is returned in `result`

```
void ESUTIL_API esTranslate(ESMatrix *result, GLfloat tx,
GLfloat ty, GLfloat tz)
```

Multiply matrix specified by `result` with a translation matrix and return new matrix in `result`.

Parameters:

result	the input matrix
tx, *ty*, *tz*	specify the translate factors along the *x*-, *y*-, and *z*-axes, respectively

Returns:

The new matrix after the translation operation has been performed is returned in `result`

```
void ESUTIL_API esRotate(ESMatrix *result, GLfloat angle,
                         GLfloat x, GLfloat y, GLfloat z)
```

Multiply matrix specified by `result` with a rotation matrix and return new matrix in `result`.

Parameters:

result	the input matrix
angle	specifies the angle of rotation, in degrees

`x, y, z` specify the *x*-, *y*-, and *z*-coordinates of a vector

Returns:

The new matrix after the rotation operation has been performed is returned in *`result`*

```
void ESUTIL_API esMatrixMultiply(ESMatrix *result,
                                 ESMatrix *srcA,
                                 ESMatrix *srcB)
```

This function multiplies the matrices *`srcA`* and *`srcB`* and returns the multiplied matrix in *`result`*.

`result = srcA × srcB`

Parameters:

`result`	pointer to memory where the multiplied matrix will be returned
`srcA, srcB`	input matrices to be multiplied

Returns:

A multiplied matrix

```
void ESUTIL_API esMatrixLoadIdentity(ESMatrix *result)
```

Parameters:

`result`	pointer to memory where the identity matrix will be returned

Returns:

An identity matrix

```
void ESUTIL_API esMatrixLookAt(ESMatrix *result,
             GLfloat posX, GLfloat posY, GLfloat posZ,
             GLfloat lookAtX, GLfloat lookAtY, GLfloat lookAtZ,
             GLfloat upX, GLfloat upY, GLfloat upZ)
```

Generate a view transformation matrix using eye position, look at vector, and up vector.

(continues)

(continued)

Parameters:

`result`	the output matrix
`posX`, *`posY`*, *`posZ`*	specify the coordinates of the eye position
`lookAtX`, *`lookAtY`*, *`lookAtZ`*	specify the look at vector
`upX`, *`upY`*, *`upZ`*	specify the up vector

Returns:

The view transformation matrix result

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OpenGL® ES is a software interface to graphics hardware. The interface consists of a set of 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. Specifications available at www.khronos.org/registry/gles/

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OpenGL ES Command Syntax [2.3]

Open GL ES commands are formed from a return type, a name, and optionally a type letter: i for 32-bit int, i64 for int64, f for 32-bit float, or ui for 32-bit uint, as shown by the prototype below:

return-type **Name**{1234}{i i64 f ui}{v} (*[args ,] T arg1 , . . . , T argN [, args]*);

The arguments enclosed in brackets (*[args ,]* and *[, args]*) may or may not be present. The argument type T and the number *N* of arguments may be indicated by the command name suffixes. *N* is 1, 2, 3, or 4 if present. If "v" is present, an array of *N* items is passed by a pointer. For brevity, the OpenGL documentation and this reference may omit the standard prefixes. The actual names are of the forms: glFunctionName(), GL_CONSTANT, GLtype

GL Data Types [2.3]

GL types are not C types.

GL Type	Min Bit Width	Description
boolean	1	Boolean
byte	8	Signed 2's complement binary integer
ubyte	8	Unsigned binary integer
char	8	Characters making up strings
short	16	Signed 2's complement binary integer
ushort	16	Unsigned binary integer
int	32	Signed 2's complement binary integer
uint	32	Unsigned binary integer
int64	64	Signed 2's complement binary integer
uint64	64	Unsigned binary integer
fixed	32	Signed 2's complement 16.16 scaled integer
sizei	32	Non-negative binary integer size
enum	32	Enumerated binary integer value
intptr	*ptrbits*	Signed 2's complement binary integer
sizeiptr	*ptrbits*	Non-negative binary integer size
sync	*ptrbits*	Sync object handle
bitfield	32	Bit field
half	16	Half-precision float encoded in unsigned scalar
float	32	Floating-point value
clampf	32	Floating-point value clamped to [0, 1]

Errors [2.5]

enum **GetError**(void); //Returns one of the following:

NO_ERROR	No error encountered
INVALID_ENUM	Enum argument out of range
INVALID_VALUE	Numeric argument out of range
INVALID_OPERATION	Operation illegal in current state
INVALID_FRAMEBUFFER_OPERATION	Framebuffer is incomplete
OUT_OF_MEMORY	Not enough memory left to execute command

Viewport , Clipping [2.12.1]

void **DepthRangef**(float *n*, float *f*);

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

Buffer Objects [2.9]

Buffer objects hold vertex array data or indices in high-performance server memory.

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

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

Creating and Binding Buffer Objects

void **BindBuffer**(enum *target*, uint *buffer*);
target: {ELEMENT_}ARRAY_BUFFER, UNIFORM_BUFFER, PIXEL_{UN}PACK_BUFFER, COPY_{READ, WRITE}_BUFFER, TRANSFORM_FEEDBACK_BUFFER

void **BindBufferRange**(enum *target*, uint *index*, uint *buffer*, intptr *offset*, sizeiptr *size*);
target: {TRANSFORM_FEEDBACK, UNIFORM}_BUFFER

void **BindBufferBase**(enum *target*, uint *index*, uint *buffer*);
target: {TRANSFORM_FEEDBACK, UNIFORM}_BUFFER

Creating Buffer Object Data Stores

void **BufferData**(enum *target*, sizeiptr *size*, const void **data*, enum *usage*);
target: See ***BindBuffer***
usage: {STATIC, STREAM, DYNAMIC}_{DRAW, READ, COPY}

void **BufferSubData**(enum *target*, intptr *offset*, sizeiptr *size*, const void **data*);
target: See ***BindBuffer***

Mapping and Unmapping Buffer Data

void ***MapBufferRange**(enum *target*, intptr *offset*, sizeiptr *length*, bitfield *access*);
target: See ***BindBuffer***
access: Bitwise OR of MAP_{READ, WRITE}_BIT, MAP_INVALIDATE_{RANGE, BUFFER_BIT}, MAP_FLUSH_EXPLICIT_BIT, MAP_UNSYNCHRONIZED_BIT

void **FlushMappedBufferRange**(enum *target*, intptr *offset*, sizeiptr *length*);
target: See ***BindBuffer***

boolean **UnmapBuffer**(enum *target*);
target: See ***BindBuffer***

Copying Between Buffers

void **CopyBufferSubData**(enum *readtarget*, enum *writetarget*, intptr *readoffset*, intptr *writeoffset*, sizeiptr *size*);
readtarget, writetarget: See target for ***BindBuffer***

Buffer Object Queries [6.1.9]

boolean **IsBuffer**(uint *buffer*);

void **GetBufferParameteriv**(enum *target*, enum *pname*, int * *data*);
target: See ***BindBuffer***
pname: BUFFER_{SIZE, USAGE, ACCESS_FLAGS, MAPPED}, BUFFER_ MAP_{POINTER, OFFSET, LENGTH}

void **GetBufferParameteri64v**(enum *target*, enum *pname*, int64 **data*);
target, pname: See ***GetBufferParameteriv***

void **GetBufferPointerv**(enum *target*, enum *pname*, void ***params*);
target: See ***BindBuffer***
pname: BUFFER_ MAP_POINTER

Transform Feedback [2.14, 6.1.11]

void **GenTransformFeedbacks**(sizei *n*, uint **ids*);

void **DeleteTransformFeedbacks**(sizei *n*, const uint **ids*);

void **BindTransformFeedback**(enum *target*, uint *id*);
target: TRANSFORM_FEEDBACK

void **BeginTransformFeedback**(enum *primitiveMode*);
primitiveMode: TRIANGLES, LINES, POINTS

void **EndTransformFeedback**(void);

void **PauseTransformFeedback**(void);

void **ResumeTransformFeedback**(void);

boolean **IsTransformFeedback**(uint *id*);

Vertex Array Objects [2.10, 6.1.10]

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

boolean **IsVertexArray**(uint *array*);

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

void **BindVertexArray**(uint *array*);

Reading, Copying Pixels [4.3.1-2]

void **ReadPixels**(int *x*, int *y*, sizei *width*, sizei *height*, enum *format*, enum *type*, void **data*);
format: RGBA, RGBA_INTEGER
type: INT, UNSIGNED_INT_2_10_10_10_REV, UNSIGNED_{BYTE, INT}
Note: [4.3.1] **ReadPixels()** also accepts a queriable implementation-chosen *format/type* combination.

void **ReadBuffer**(enum *src*);
src: BACK, NONE, or COLOR_ATTACHMENT*i* where *i* may range from zero to the value of MAX_COLOR_ATTACHMENTS - 1

void **BlitFramebuffer**(int *srcX0*, int *srcY0*, int *srcX1*, int *srcY1*, int *dstX0*, int *dstY0*, int *dstX1*, int *dstY1*, bitfield *mask*, enum *filter*);
mask: Bitwise OR of {COLOR, DEPTH, STENCIL}_BUFFER_BIT
filter: LINEAR or NEAREST

Rasterization [3]

Points [3.4]

Point size is taken from the shader built-in **gl_PointSize** and clamped to the implementation-dependent point size range.

Line Segments [3.5]

void **LineWidth**(float *width*);

Polygons [3.6]

void **FrontFace**(enum *dir*);
dir: CCW, CW

void **CullFace**(enum *mode*);
mode: FRONT, BACK, FRONT_AND_BACK

Enable/**Disable**(CULL_FACE);

void **PolygonOffset**(float *factor*, float *units*);

Enable/**Disable**(POLYGON_OFFSET_FILL);

Asynchronous Queries [2.13, 6.1.7]

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

void **BeginQuery**(enum *target*, uint *id*);
target: ANY_SAMPLES_PASSED{_CONSERVATIVE}

void **EndQuery**(enum *target*);
target: ANY_SAMPLES_PASSED{_CONSERVATIVE}

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

boolean **IsQuery**(uint *id*);

void **GetQueryiv**(enum *target*, enum *pname*, int **params*);

void **GetQueryObjectuiv**(uint *id*, enum *pname*, uint **params*);

Vertices

Current Vertex State [2.7]

void **VertexAttrib{1234}f**(uint *index*, float *values*);

void **VertexAttrib{1234}fv**(uint *index*, const float **values*);

void **VertexAttribI4{i ui}**(uint *index*, T *values*);

void **VertexAttribI4{i ui}v**(uint *index*, const T *values*);

Vertex Arrays [2.8]

Vertex data may be sourced from arrays stored in client's address space (via a pointer) or in server's address space (in a buffer object).

void **VertexAttribPointer**(uint *index*, int *size*, enum *type*, boolean *normalized*, sizei *stride*, const void **pointer*);
type: {UNSIGNED_}BYTE, {UNSIGNED_}SHORT, {UNSIGNED_}INT, FIXED, {HALF_}FLOAT, {UNSIGNED_}INT_2_10_10_10_REV
index: [0, MAX_VERTEX_ATTRIBS - 1]

void **VertexAttribIPointer**(uint *index*, int *size*, enum *type*, sizei *stride*, const void **pointer*);
type: {UNSIGNED_}BYTE, {UNSIGNED_}SHORT, {UNSIGNED_}INT
index: [0, MAX_VERTEX_ATTRIBS - 1]

void **EnableVertexAttribArray**(uint *index*);

void **DisableVertexAttribArray**(uint *index*);

void **VertexAttribDivisor**(uint *index*, uint *divisor*);
index: [0, MAX_VERTEX_ATTRIBS - 1]

void **Enable**(enum *target*);

void **Disable**(enum *target*);
target: PRIMITIVE_RESTART_FIXED_INDEX

Drawing [2.8.3]

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

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

void **DrawElements**(enum *mode*, sizei *count*, enum *type*, const void **indices*);
type: UNSIGNED_BYTE, UNSIGNED_SHORT, UNSIGNED_INT

void **DrawElementsInstanced**(enum *mode*, sizei *count*, enum *type*, const void **indices*, sizei *primcount*);
type: UNSIGNED_BYTE, UNSIGNED_SHORT, UNSIGNED_INT

void **DrawRangeElements**(enum *mode*, uint *start*, uint *end*, sizei *count*, enum *type*, const void **indices*);
mode: POINTS, TRIANGLES, LINES, LINE_{STRIP, LOOP}, TRIANGLE_STRIP, TRIANGLE_FAN
type: UNSIGNED_BYTE, UNSIGNED_SHORT, UNSIGNED_INT

Shaders and Programs

Shader Objects [2.11.1]

uint **CreateShader**(enum *type*);
type: VERTEX_SHADER, FRAGMENT_SHADER

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

void **CompileShader**(uint *shader*);

void **ReleaseShaderCompiler**(void);

void **DeleteShader**(uint *shader*);

Loading Shader Binaries [2.11.2]

void **ShaderBinary**(sizei *count*, const uint **shaders*, enum *binaryformat*, const void **binary*, sizei *length*);

Program Objects [2.11.3-4]

uint **CreateProgram**(void);

void **AttachShader**(uint *program*, uint *shader*);

void **DetachShader**(uint *program*, uint *shader*);

void **LinkProgram**(uint *program*);

void **UseProgram**(uint *program*);

void **ProgramParameteri**(uint *program*, enum *pname*, int *value*);
pname: PROGRAM_BINARY_RETRIEVABLE_HINT

void **DeleteProgram**(uint *program*);

void **GetProgramBinary**(uint *program*, sizei *bufSize*, sizei **length*, enum **binaryFormat*, void **binary*);

void **ProgramBinary**(uint *program*, enum *binaryFormat*, const void **binary*, sizei *length*);

Vertex Attributes [2.11.5]

void **GetActiveAttrib**(uint *program*, uint *index*, sizei *bufSize*, sizei **length*, int **size*, enum **type*, char **name*);
**type* returns: FLOAT, FLOAT_VEC{2,3,4}, FLOAT_MAT{2,3,4}, FLOAT_MAT{2x3, 2x4, 3x2, 3x4, 4x2, 4x3}, {UNSIGNED_}INT, {UNSIGNED_}INT_VEC{2,3,4}

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

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

Uniform Variables [2.11.6]

int **GetUniformLocation**(uint *program*, const char **name*);

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

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

void **GetActiveUniformBlockiv**(uint *program*, uint *uniformBlockIndex*, enum *pname*, int **params*);
pname: UNIFORM_BLOCK_{BINDING, DATA_SIZE}, UNIFORM_BLOCK_{NAME_LENGTH}, UNIFORM_BLOCK_ACTIVE_{UNIFORMS, UNIFORM_INDICES}, UNIFORM_BLOCK_ REFERENCED_BY_{VERTEX,FRAGMENT}_SHADER

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

void **GetActiveUniform**(uint *program*, uint *uniformIndex*, sizei *bufSize*, sizei **length*, int **size*, enum **type*, char **name*);
**type* returns: FLOAT, BOOL, {FLOAT, BOOL}_VEC{2, 3, 4}, {UNSIGNED_}INT, {UNSIGNED_}INT_VEC{2, 3, 4}, FLOAT_MAT{2, 3, 4}, FLOAT_MAT{2x3, 2x4, 3x2, 3x4, 4x2, 4x3}, SAMPLER_{2D, 3D, CUBE_SHADOW}, SAMPLER_2D{_ARRAY}_SHADOW, {UNSIGNED_}INT_SAMPLER_{2D, 3D, CUBE}, {{UNSIGNED_}INT_}SAMPLER_2D_ARRAY

void **GetActiveUniformsiv**(uint *program*, sizei *uniformCount*, const uint **uniformIndices*, enum *pname*, int **params*);
pname: UNIFORM_TYPE, UNIFORM_SIZE, UNIFORM_NAME_LENGTH, UNIFORM_BLOCK_INDEX, UNIFORM_{OFFSET, ARRAY_STRIDE}, UNIFORM_MATRIX_STRIDE, UNIFORM_IS_ROW_MAJOR

(Continued on next page >)

Shaders and Programs (Cont'd)

void **Uniform{1234}{if}**(int *location*, T *value*);

void **Uniform{1234}{if}v**(int *location*, sizei *count*, const T *value*);

void **Uniform{1234}ui**(int *location*, T *value*);

void **Uniform{1234}uiv**(int *location*, sizei *count*, const T *value*);

void **UniformMatrix{234}fv**(int *location*, sizei *count*, boolean *transpose*, const float **value*);

void **UniformMatrix{ 2x3,3x2,2x4,4x2,3x4,4x3}fv**(int *location*, sizei *count*, boolean *transpose*, const float **value*);

void **UniformBlockBinding**(uint *program*, uint *uniformBlockIndex*, uint *uniformBlockBinding*);

Output Variables [2.11.8]

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

bufferMode: {INTERLEAVED, SEPARATE}_ATTRIBS

void **GetTransformFeedbackVarying**(uint *program*, uint *index*, sizei *bufSize*, sizei **length*, sizei **size*, enum **type*, char **name*);

**type* returns any of the scalar, vector, or matrix attribute types returned by GetActiveAttrib().

Shader Execution [2.11.9, 3.9.2]

void **ValidateProgram**(uint *program*);

int **GetFragDataLocation**(uint *program*, const char **name*);

Shader Queries

Shader Queries [6.1.12]

boolean **IsShader**(uint *shader*);

void **GetShaderiv**(uint *shader*, enum *pname*, int **params*);

pname: SHADER_TYPE, {VERTEX, FRAGMENT_SHADER}, {DELETE, COMPILE}_STATUS, INFO_LOG_LENGTH, SHADER_SOURCE_LENGTH

void **GetAttachedShaders**(uint *program*, sizei *maxCount*, sizei **count*, uint **shaders*);

void **GetShaderInfoLog**(uint *shader*, sizei *bufSize*, sizei **length*, char **infoLog*);

void **GetShaderSource**(uint *shader*, sizei *bufSize*, sizei **length*, char **source*);

void **GetShaderPrecisionFormat**(enum *shadertype*, enum *precisiontype*, int **range*, int **precision*);

shadertype: VERTEX_SHADER, FRAGMENT_SHADER

precision: LOW_FLOAT, MEDIUM_FLOAT, HIGH_FLOAT, LOW_INT, MEDIUM_INT, HIGH_INT

void **GetVertexAttribfv**(uint *index*, enum *pname*, float **params*);

pname: CURRENT_VERTEX_ATTRIB , VERTEX_ATTRIB_ARRAY_*x* (where *x* may be BUFFER_BINDING, DIVISOR, ENABLED, INTEGER, SIZE, STRIDE, TYPE, NORMALIZED)

void **GetVertexAttribiv**(uint *index*, enum *pname*, int **params*);

pname: See ***GetVertexAttribfv()***

void **GetVertexAttribIiv**(uint *index*, enum *pname*, int **params*);

pname: See ***GetVertexAttribfv()***

void **GetVertexAttribIuiv**(uint *index*, enum *pname*, uint **params*);

pname: See ***GetVertexAttribfv()***

void **GetVertexAttribPointerv**(uint *index*, enum *pname*, void ***pointer*);

pname: VERTEX_ATTRIB_ARRAY_POINTER

void **GetUniformfv**(uint *program*, int *location*, float **params*);

void **GetUniformiv**(uint *program*, int *location*, int **params*);

void **GetUniformuiv**(uint *program*, int *location*, uint **params*);

Program Queries [6.1.12]

boolean **IsProgram**(uint *program*);

void **GetProgramiv**(uint *program*, enum *pname*, int **params*);

pname: {DELETE, LINK, VALIDATE}_STATUS, INFO_LOG_LENGTH, ACTIVE_UNIFORM_BLOCKS, TRANSFORM_[FEEDBACK_]VARYINGS, TRANSFORM_FEEDBACK_BUFFER_MODE, TRANSFORM_FEEDBACK_VARYING_MAX_LENGTH, ATTACHED_SHADERS, ACTIVE_ATTRIBUTES, ACTIVE_UNIFORMS, ACTIVE_{ATTRIBUTE, UNIFORM}_MAX_LENGTH, ACTIVE_UNIFORM_BLOCK_MAX_NAME_LENGTH, PROGRAM_BINARY_RETRIEVABLE_HINT

void **GetProgramInfoLog**(uint *program*, sizei *bufSize*, sizei **length*, char **infoLog*);

Texturing [3.8]

Shaders support texturing using at least MAX_VERTEX_TEXTURE_IMAGE_UNITS images for vertex shaders and at least MAX_TEXTURE_IMAGE_UNITS images for fragment shaders.

void **ActiveTexture**(enum *texture*);

texture: [TEXTURE0..TEXTURE*i*] where *i* = [MAX_COMBINED_TEXTURE_IMAGE_UNITS-1]

void **GenTextures**(sizei *n*, uint **textures*);

void **BindTexture**(enum *target*, uint *texture*);

void **DeleteTextures**(sizei *n*, const uint **textures*);

Sampler Objects [3.8.2]

void **GenSamplers**(sizei *count*, uint **samplers*);

void **BindSampler**(uint *unit*, uint *sampler*);

void **SamplerParameter{if}**(uint *sampler*, enum *pname*, T *param*);

pname: TEXTURE_WRAP_{S, T, R}, TEXTURE_{MIN, MAG}_FILTER, TEXTURE_{MIN, MAX}_LOD, TEXTURE_COMPARE_{MODE, FUNC}

void **SamplerParameter{if}v**(uint *sampler*, enum *pname*, const T **params*);

pname: See ***SamplerParameter{if}***

void **DeleteSamplers**(sizei *count*, const uint **samplers*);

Sampler Queries [6.1.5]

boolean **IsSampler**(uint *sampler*);

void **GetSamplerParameter{if}v**(uint *sampler*, enum *pname*, T **params*);

pname: See ***SamplerParameter{if}***

Texture Image Specification [3.8.3, 3.8.4]

void **TexImage3D**(enum *target*, int *level*, int *internalformat*, sizei *width*, sizei *height*, sizei *depth*, int *border*, enum *format*, enum *type*, const void **data*);

target: TEXTURE_3D, TEXTURE_2D_ARRAY

format: ALPHA, RGBA, RGB, RG, RED, {RGBA, RGB, RG, RED}_INTEGER, DEPTH_{COMPONENT, STENCIL}, LUMINANCE_ALPHA, LUMINANCE

type: {UNSIGNED_}BYTE, {UNSIGNED_}SHORT, {UNSIGNED_}INT, UNSIGNED_SHORT_5_6_5, UNSIGNED_SHORT_4_4_4_4, UNSIGNED_SHORT_5_5_5_1, {HALF_}FLOAT, UNSIGNED_INT_2_10_10_10_REV, UNSIGNED_INT_24_8, UNSIGNED_INT_10F_11F_11F_REV, UNSIGNED_INT_5_9_9_9_REV, FLOAT_32_UNSIGNED_INT_24_8_REV

internalformat: R8, R8I, R8UI, R8_SNORM, R16I, R16UI, R16F, R32I, R32UI, R32F, RG8, RG8I, RG8UI, RG8_SNORM, RG16I, RG16UI, RG16F, RG32I, RG32UI, RG32F, RGB, RGB5_A1, RGB565, RGB8, RGB8I, RGB8UI, RGB8_SNORM, RGB9_E5, RGB10_A2, RGB10_A2UI, RGB16I, RGB16UI, RGB16F, RGB32I, RGB32UI, RGB32F, SRGB8, RGBA, RGBA4, RGBA8, RGBA8I, RGBA8UI, RGBA8_SNORM, RGBA16I, RGBA16UI, RGBA16F, RGBA32I, RGBA32UI, RGBA32F, SRGB8_ALPHA8, R11F_G11F_B10F, DEPTH_COMPONENT16, DEPTH_COMPONENT24, DEPTH_COMPONENT32F, DEPTH24_STENCIL8, DEPTH32F_STENCIL8, LUMINANCE_ALPHA, LUMINANCE, ALPHA

void **TexImage2D**(enum *target*, int *level*, int *internalformat*, sizei *width*, sizei *height*, int *border*, enum *format*, enum *type*, void **data*);

target: TEXTURE_2D, TEXTURE_CUBE_MAP_POSITIVE_{X, Y, Z}, TEXTURE_CUBE_MAP_NEGATIVE}{X, Y, Z}

internalformat: See ***TexImage3D***

format, type: See ***TexImage3D***

void **TexStorage2D**(enum *target*, sizei *levels*, enum *internalformat*, sizei *width*, sizei *height*);

target: TEXTURE_CUBE_MAP, TEXTURE_2D

internalformat: See ***TexImage3D*** except for unsized base internal formats in [Table 3.3]

void **TexStorage3D**(enum *target*, sizei *levels*, enum *internalformat*, sizei *width*, sizei *height*, sizei *depth*);

target: TEXTURE_3D, TEXTURE_2D_ARRAY

internalformat: See ***TexImage3D*** except for unsized base internal formats in [Table 3.3]

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Texturing (continued)

Alt. Texture Image Specification Commands [3.8.5]

Texture images may also be specified using image data taken directly from the framebuffer, and rectangular subregions of existing texture images may be respecified.

void **CopyTexImage2D**(enum *target*, int *level*, enum *internalformat*, int *x*, int *y*, sizei *width*, sizei *height*, int *border*);

target: TEXTURE_2D, TEXTURE_CUBE_MAP_POSITIVE_{X, Y, Z}, TEXTURE_CUBE_MAP_NEGATIVE_{X, Y, Z}

internalformat: See ***TexImage3D,*** except for DEPTH* values

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*);

target: TEXTURE_3D, TEXTURE_2D_ARRAY

format, type: See ***TexImage3D***

void **TexSubImage2D**(enum *target*, int *level*, int *xoffset*, int *yoffset*, sizei *width*, sizei *height*, enum *format*, enum *type*, const void **data*);

target: TEXTURE_2D, TEXTURE_CUBE_MAP_POSITIVE_{X, Y, Z}, TEXTURE_CUBE_MAP_NEGATIVE_{X, Y, Z}

format, type: See ***TexImage3D***

void **CopyTexSubImage3D**(enum *target*, int *level*, int *xoffset*, int *yoffset*, int *zoffset*, int *x*, int *y*, sizei *width*, sizei *height*);

target: TEXTURE_3D, TEXTURE_2D_ARRAY

void **CopyTexSubImage2D**(enum *target*, int *level*, int *xoffset*, int *yoffset*, int *x*, int *y*, sizei *width*, sizei *height*);

target: See ***TexSubImage2D***

Compressed Texture Images [3.8.6]

void **CompressedTexImage2D**(enum *target*, int *level*, enum *internalformat*, sizei *width*, sizei *height*, int *border*, sizei *imageSize*, const void **data*);

target: See ***TexImage2D***

internalformat: COMPRESSED_RGBA8_ETC2_EAC, COMPRESSED_{R{G}11, SIGNED_R{G}11}_EAC, COMPRESSED_SRGB8_ALPHA8_ETC2_EAC, COMPRESSED_{S}RGB8{_PUNCHTHROUGH_ALPHA1}_ETC2 [Table 3.16]

void **CompressedTexImage3D**(enum *target*, int *level*, enum *internalformat*, sizei *width*, sizei *height*, sizei *depth*, int *border*, sizei *imageSize*, const void **data*);

target: see ***TexImage3D***

internalformat: See ***TexImage2D***

void **CompressedTexSubImage2D**(enum *target*, int *level*, int *xoffset*, int *yoffset*, sizei *width*, sizei *height*, enum *format*, sizei *imageSize*, const void **data*);

target: See ***TexSubImage2D***

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*);

target: See ***TexSubImage2D***

Texture Parameters [3.8.7]

void **TexParameter{if}**(enum *target*, enum *pname*, T *param*);

void **TexParameter{if}v**(enum *target*, enum *pname*, const T **params*);

target: TEXTURE_{2D, 3D}, TEXTURE_2D_ARRAY, TEXTURE_CUBE_MAP

pname: TEXTURE_{BASE, MAX}_LEVEL, TEXTURE_{MIN, MAX}_LOD, TEXTURE_{MIN, MAG}_FILTER, TEXTURE_COMPARE_{MODE,FUNC}, TEXTURE_SWIZZLE_{R,G,B,A}, TEXTURE_WRAP_{S,T,R}

Manual Mipmap Generation [3.8.9]

void **GenerateMipmap**(enum *target*);

target: TEXTURE_{2D,3D}, TEXTURE_{2D_ARRAY, CUBE_MAP}

Enumerated Queries [6.1.3]

void **GetTexParameter{if}v**(enum *target*, enum *value*, T *data*);

target: TEXTURE_{2D, 3D}, TEXTURE_{2D_ARRAY, CUBE_MAP}

value: TEXTURE_{BASE, MAX}_LEVEL, TEXTURE_{MIN, MAX}_LOD, TEXTURE_{MIN, MAG}_FILTER, TEXTURE_IMMUTABLE_FORMAT, TEXTURE_COMPARE_{FUNC, MODE}, TEXTURE_WRAP_{S, T, R}, TEXTURE_SWIZZLE_{R, G, B, A}

Texture Queries [6.1.4]

boolean **IsTexture**(uint *texture*);

Per-Fragment Operations

Scissor Test [4.1.2]

Enable/Disable(SCISSOR_TEST);

void **Scissor**(int *left*, int *bottom*, sizei *width*, sizei *height*);

Multisample Fragment Operations [4.1.3]

Enable/Disable(*cap*);

cap: SAMPLE{_ALPHA_TO}_COVERAGE

void **SampleCoverage**(float *value*, boolean *invert*);

Stencil Test [4.1.4]

Enable/Disable(STENCIL_TEST);

void **StencilFunc**(enum *func*, int *ref*, uint *mask*);

func: NEVER, ALWAYS, LESS, GREATER, {L, G}EQUAL, {NOT}EQUAL

void **StencilFuncSeparate**(enum *face*, enum *func*, int *ref*, uint *mask*);

face, func: See ***StencilOpSeparate***

void **StencilOp**(enum *sfail*, enum *dpfail*, enum *dppass*);

sfail, dpfail, and *dppass*: KEEP, ZERO, REPLACE, INCR, DECR, INVERT, INCR_WRAP, DECR_WRAP

void **StencilOpSeparate**(enum *face*, enum *sfail*, enum *dpfail*, enum *dppass*);

face: FRONT, BACK, FRONT_AND_BACK

sfail, dpfail, and *dppass*: KEEP, ZERO, REPLACE, INCR, DECR, INVERT, INCR_WRAP, DECR_WRAP

func: NEVER, ALWAYS, LESS, GREATER, {L, G}EQUAL, {NOT}EQUAL

Depth Buffer Test [4.1.5]

Enable/Disable(DEPTH_TEST);

void **DepthFunc**(enum *func*);

func: NEVER, ALWAYS, LESS, LEQUAL, EQUAL, GREATER, GEQUAL, NOTEQUAL

Blending [4.1.7]

Enable/Disable(BLEND); *(all draw buffers)*

void **BlendEquation**(enum *mode*);

void **BlendEquationSeparate**(enum *modeRGB*, enum *modeAlpha*);

mode, modeRGB, and *modeAlpha*: FUNC_ADD, FUNC[_REVERSE]_SUBTRACT, MIN, MAX

void **BlendFuncSeparate**(enum *srcRGB*, enum *dstRGB*, enum *srcAlpha*, enum *dstAlpha*);

srcRGB, dstRGB, srcAlpha, and *dstAlpha*: ZERO, ONE, {ONE_MINUS_}SRC_COLOR, {ONE_MINUS_}DST_COLOR, {ONE_MINUS_}SRC_ALPHA, {ONE_MINUS_}DST_ALPHA, {ONE_MINUS_}CONSTANT_COLOR, {ONE_MINUS_}CONSTANT_ALPHA, SRC_ALPHA_SATURATE

void **BlendFunc**(enum *src*, enum *dst*);

src, dst: See ***BlendFuncSeparate***

void **BlendColor**(float *red*, float *green*, float *blue*, float *alpha*);

Dithering [4.1.9]

Enable/Disable(DITHER);

Whole Framebuffer

Selecting a Buffer for Writing [4.2.1]

void **DrawBuffers**(sizei *n*, const enum **bufs*);

bufs points to an array of *n* BACK, NONE, or COLOR_ATTACHMENT*i* where *i* = [0,MAX_COLOR_ATTACHMENTS - 1].

Fine Control of Buffer Updates [4.2.2]

void **ColorMask**(boolean *r*, boolean *g*, boolean *b*, boolean *a*);

void **DepthMask**(boolean *mask*);

void **StencilMask**(uint *mask*);

void **StencilMaskSeparate**(enum *face*, uint *mask*);

face: FRONT, BACK, FRONT_AND_BACK

Clearing the Buffers [4.2.3]

void **Clear**(bitfield *buf*);

buf: Bitwise OR of COLOR_BUFFER_BIT, DEPTH_BUFFER_BIT, STENCIL_BUFFER_BIT

void **ClearColor**(float *r*, float *g*, float *b*, float *a*);

void **ClearDepthf**(float *d*);

void **ClearStencil**(int *s*);

void **ClearBuffer{if ui}v**(enum *buffer*, int *drawbuffer*, const T **value*);

buffer: COLOR, DEPTH, STENCIL

void **ClearBufferfi**(enum *buffer*, int *drawbuffer*, float *depth*, int *stencil*);

buffer: DEPTH_STENCIL

drawbuffer: 0

Pixel Rectangles [3.7.1]

void **PixelStorei**(enum *pname*, T *param*);
pname: {UN}PACK_ROW_LENGTH,
{UN}PACK_ALIGNMENT,
{UN}PACK_SKIP_{ROWS,PIXELS},
{UN}PACK_IMAGE_HEIGHT,
{UN}PACK_SKIP_IMAGES

Framebuffer Objects

Binding/Managing Framebuffer [4.4.1]

void **GenFramebuffers**(sizei *n*,
uint **framebuffers*);

void **BindFramebuffer**(enum *target*,
uint *framebuffer*);

void **DeleteFramebuffers**(sizei *n*,
const uint **framebuffers*);

Renderbuffer Objects [4.4.2]

void **GenRenderbuffers**(sizei *n*,
uint **renderbuffers*);

void **BindRenderbuffer**(enum *target*,
uint *renderbuffer*);
target: RENDERBUFFER

void **DeleteRenderbuffers**(sizei *n*,
const uint **renderbuffers*);

void **RenderbufferStorageMultisample**(
enum *target*, sizei *samples*,
enum *internalformat*, sizei *width*,
sizei *height*);
target: RENDERBUFFER
internalformat: {R,RG,RGB}8,
RGB{565, A4, 5_A1, 10_A2},
RGB{10_A2UI}, R{8,16,32}I, RG{8,16,32}I,
R{8,16,32}UI, RG{8,16,32}UI, RGBA,
RGBA{8, 8I, 8UI, 16I, 16UI, 32I, 32UI},
SRGB8_ALPHA8, STENCIL_INDEX8,
DEPTH{24, 32F}_STENCIL8,
DEPTH_COMPONENT{16, 24, 32F}

void **RenderbufferStorage**(enum *target*,
enum *internalformat*, sizei *width*,
sizei *height*);
target: RENDERBUFFER
internalformat: See
RenderbufferStorageMultisample

Attach Renderbuffer Images to Framebuffer

void **FramebufferRenderbuffer**(enum *target*,
enum *attachment*,
enum *renderbuffertarget*,
uint *renderbuffer*);
target: FRAMEBUFFER,
{DRAW, READ}_FRAMEBUFFER
attachment: DEPTH_ATTACHMENT,
{DEPTH_}STENCIL_ATTACHMENT,
COLOR_ATTACHMENT*i*
(*i* = [0, MAX_COLOR_ATTACHMENTS-1])
renderbuffertarget: RENDERBUFFER

Attaching Texture Images to a Framebuffer

void **FramebufferTexture2D**(enum *target*,
enum *attachment*, enum *textarget*,
uint *texture*, int *level*);
textarget: TEXTURE_2D,
TEXTURE_CUBE_MAP_POSITIVE{X, Y, Z},
TEXTURE_CUBE_MAP_NEGATIVE{X, Y, Z}
target: FRAMEBUFFER,
{DRAW, READ}_FRAMEBUFFER
attachment: See ***FrameBufferRenderbuffer***

void **FramebufferTextureLayer**(enum *target*,
enum *attachment*, uint *texture*, int *level*,
int *layer*);
target: TEXTURE_2D_ARRAY, TEXTURE_3D
attachment: See ***FrameBufferRenderbuffer***

Framebuffer Completeness [4.4.4]

enum **CheckFramebufferStatus**(
enum *target*);
target: FRAMEBUFFER,
{DRAW, READ}_FRAMEBUFFER
returns: FRAMEBUFFER_COMPLETE or a constant
indicating which value violates framebuffer
completeness

Invalidating Framebuffer Contents [4.5]

void **InvalidateSubFramebuffer**(
enum *target*, sizei *numAttachments*,
const enum **attachments*, int *x*,
int *y*, sizei *width*, sizei *height*);
target: FRAMEBUFFER
attachments: points to an array of COLOR, STENCIL,
{DEPTH, STENCIL}_ATTACHMENT,
COLOR_ATTACHMENT*i*

void **InvalidateFramebuffer**(enum *target*,
sizei *numAttachments*,
const enum **attachments*);

Renderbuffer Object Queries [6.1.14]

boolean **IsRenderbuffer**(uint *renderbuffer*);

void **GetRenderbufferParameteriv**(
enum *target*, enum *pname*, int **params*);
target: RENDERBUFFER
pname: RENDERBUFFER_*x*, where *x* may be
WIDTH, HEIGHT, {RED, GREEN, BLUE}_SIZE,
{ALPHA, DEPTH, STENCIL}_SIZE, SAMPLES,
INTERNAL_FORMAT

Framebuffer Object Queries [6.1.13]

boolean **IsFramebuffer**(uint *framebuffer*);

void
GetFramebufferAttachmentParameteriv(
enum *target*, enum *attachment*,
enum *pname*, int **params*);
target: FRAMEBUFFER, {DRAW, READ}_FRAMEBUFFER
attachment: BACK, STENCIL, COLOR_ATTACHMENT*i*,
{DEPTH, STENCIL, DEPTH_STENCIL}_ATTACHMENT
pname: FRAMEBUFFER_ATTACHMENT_*x*,
where *x* may be one of OBJECT_{TYPE, NAME},
COMPONENT_TYPE, COLOR_ENCODING,
{RED, GREEN, BLUE, ALPHA}_SIZE,
{DEPTH, STENCIL}_SIZE, TEXTURE_{LEVEL, LAYER},
TEXTURE_CUBE_MAP_FACE

void **GetInternalformativ**(enum *target*,
enum *internalformat*, enum *pname*,
sizei *bufSize*, int **params*);
internalformat:
See ***RenderbufferStorageMultisample***
target: RENDERBUFFER
pname: NUM_SAMPLE_COUNTS, SAMPLES

Special Functions

Flush and Finish [5.1]

Flush guarantees that commands issued so far will eventually complete. **Finish** blocks until all commands issued so far have completed.

void **Flush**(void);

void **Finish**(void);

Sync Objects and Fences [5.2]

sync **FenceSync**(enum *condition*,
bitfield *flags*);
condition: SYNC_GPU_COMMANDS_COMPLETE
flags: 0

enum **ClientWaitSync**(sync *sync*, bitfield *flags*,
uint64 *timeout*);
flags: 0 or SYNC_FLUSH_COMMANDS_BIT
timeout: nanoseconds

void **WaitSync**(
sync *sync*, bitfield *flags*, uint64 *timeout*);
flags: 0
timeout: TIMEOUT_IGNORED

void **DeleteSync**(sync *sync*);

Hints [5.3]

void **Hint**(enum *target*, enum *hint*);
target: GENERATE_MIPMAP_HINT,
FRAGMENT_SHADER_DERIVATIVE_HINT
hint: FASTEST, NICEST, DONT_CARE

Sync Object Queries [6.1.8]

sync **GetSynciv**(sync *sync*, enum *pname*,
sizei *bufSize*, sizei **length*, int **values*);
pname: OBJECT_TYPE, SYNC_{STATUS, CONDITION,
FLAGS}

boolean **IsSync**(sync *sync*);

State and State Requests

A complete list of symbolic constants for states is shown in the tables in [6.2].

Simple Queries [6.1.1]

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 **GetIntegeri_v**(enum *target*, uint *index*,
int **data* ;

void **GetInteger64i_v**(enum *target*,
uint *index*, int64 **data*);

boolean **IsEnabled**(enum *cap*);

String Queries [6.1.6]

ubyte ***GetString**(enum *name*);
name: VENDOR, RENDERER, EXTENSIONS,
{SHADING_LANGUAGE_}VERSION

ubyte ***GetStringi**(enum *name*, uint *index*);
name: EXTENSIONS

The OpenGL® ES Shading Language is two closely-related languages which are used to create shaders for the vertex and fragment processors contained in the OpenGL ES processing pipeline.

[n.n.n] and [Table n.n] refer to sections and tables in the OpenGL ES Shading Language 3.0 specification at www.khronos.org/registry/gles/

Preprocessor [3.4]

Preprocessor Directives

The number sign (#) can be immediately preceded or followed in its line by spaces or horizontal tabs.

#	*#define*	*#undef*
#if	*#ifdef*	*#ifndef*
#else	*#elif*	*#endif*
#error	*#pragma*	*#extension*
#line		

Examples of Preprocessor Directives

- "#version 300 es" must appear in the first line of a shader program written in GLSL ES version 3.00. If omitted, the shader will be treated as targeting version 1.00.
- #extension *extension_name* : *behavior*, where *behavior* can be require, enable, warn, or disable; and where *extension_name* is the extension supported by the compiler
- #pragma optimize({on, off}) - enable or disable shader optimization (default on)
- #pragma debug({on, off}) - enable or disable compiling shaders with debug information (default off)

Predefined Macros

__LINE__	Decimal integer constant that is one more than the number of preceding newlines in the current source string
__FILE__	Decimal integer constant that says which source string number is currently being processed.
__VERSION__	Decimal integer, e.g.: 300
GL_ES	Defined and set to integer 1 if running on an OpenGL-ES Shading Language.

Operators and Expressions

Operators [5.1]

Numbered in order of precedence. The relational and equality operators > < <= >= == != evaluate to a Boolean. To compare vectors component-wise, use functions such as lessThan(), equal(), etc. [8.7].

	Operator	Description	Assoc.
1.	( )	parenthetical grouping	N/A
2.	[ ] ( ) . ++ --	array subscript function call & constructor structure field or method selector, swizzler postfix increment and decrement	L - R
3.	++ -- + - ~ !	prefix increment and decrement unary	R - L
4.	* % /	multiplicative	L - R
5.	+ -	additive	L - R
6.	<< >>	bit-wise shift	L - R
7.	< > <= >=	relational	L - R
8.	== !=	equality	L - R
9.	&	bit-wise and	L - R
10.	^	bit-wise exclusive or	L - R
11.	|	bit-wise inclusive or	L - R
12.	&&	logical and	L - R
13.	^^	logical exclusive or	L - R
14.	||	logical inclusive or	L - R
15.	? :	selection (Selects an entire operand. Use mix() to select individual components of vectors.)	L - R
16.	= += -= *= /= %= <<= >>= &= ^= |=	assignment arithmetic assignments	L - R L - R
17.	,	sequence	L - R

Vector Components [5.5]

In addition to array numeric subscript syntax, names of vector components are denoted by a single letter. Components can be swizzled and replicated, e.g.: pos.xx, pos.zy

{x, y, z, w}	Use when accessing vectors that represent points or normals
{r, g, b, a}	Use when accessing vectors that represent colors
{s, t, p, q}	Use when accessing vectors that represent texture coordinates

Types [4.1]

A shader can aggregate these using arrays and structures to build more complex types. There are no pointer types.

Basic Types

void	no function return value or empty parameter list
bool	Boolean
int, uint	signed, unsigned integer
float	floating scalar
vec2, vec3, vec4	n-component floating point vector
bvec2, bvec3, bvec4	Boolean vector
ivec2, ivec3, ivec4	signed integer vector
uvec2, uvec3, uvec4	unsigned integer vector
mat2, mat3, mat4	2x2, 3x3, 4x4 float matrix
mat2x2, mat2x3, mat2x4	2x2, 2x3, 2x4 float matrix
mat3x2, mat3x3, mat3x4	3x2, 3x3, 3x4 float matrix
mat4x2, mat4x3, mat4x4	4x2, 4x3, 4x4 float matrix

Floating Point Sampler Types (opaque)

sampler2D, sampler3D	access a 2D or 3D texture
samplerCube	access cube mapped texture
samplerCubeShadow	access cube map depth texture with comparison
sampler2DShadow	access 2D depth texture with comparison
sampler2DArray	access 2D array texture
sampler2DArrayShadow	access 2D array depth texture with comparison

Signed Integer Sampler Types (opaque)

isampler2D, isampler3D	access an integer 2D or 3D texture
isamplerCube	access integer cube mapped texture
isampler2DArray	access integer 2D array texture

Unsigned Int Sampler Types (opaque)

usampler2D, usampler3D	access unsigned integer 2D or 3D texture
usamplerCube	access unsigned integer cube mapped texture
usampler2DArray	access unsigned integer 2D array texture

Structures and Arrays [4.1.8, 4.1.9]

Structures	struct *type-name* {
	  members
	} *struct-name*[]; // optional variable // declaration or array

Arrays	float foo[3];
	  structures, blocks, and structure members can be arrays
	  only 1-dimensional arrays supported

Qualifiers

Storage Qualifiers [4.3]

Variable declarations may be preceded by one storage qualifier.

none	(Default) local read/write memory, or input parameter
const	Compile-time constant, or read-only function parameter.
in **centroid in**	linkage into a shader from a previous stage
out **centroid out**	linkage out of a shader to a subsequent stage
uniform	Value does not change across the primitive being processed, uniforms form the linkage between a shader, OpenGL ES, and the application

The following interpolation qualifiers for shader outputs and inputs may procede **in**, **centroid in**, **out**, or **centroid out**.

smooth	perspective correct interpolation
flat	no interpolation

(Continued on next page >)

Qualifiers (continued)

Interface Blocks [4.3.7]

Uniform variable declarations can be grouped into named interface blocks, for example:

```
uniform Transform {
   mat4 ModelViewProjectionMatrix;
   uniform mat3 NormalMatrix;    // restatement
of qualifier
   float Deformation;
}
```

Layout Qualifiers [4.3.8]

layout(*layout-qualifier*) *block-declaration*
layout(*layout-qualifier*) **in**/**out**/**uniform**
layout(*layout-qualifier*) **in**/**out**/**uniform**
   declaration

Input Layout Qualifiers [4.3.8.1]

For all shader stages:
location = *integer-constant*

Output Layout Qualifiers [4.3.8.2]

For all shader stages:
location = *integer-constant*

Uniform Block Layout Qualifiers [4.3.8.3]

Layout qualifier identifiers for uniform blocks:
shared, packed, std140, {row, column}_major

Parameter Qualifiers [4.4]

Input values are copied in at function call time, output values are copied out at function return time.

none	(Default) same as **in**
in	For function parameters passed into a function
out	For function parameters passed back out of a function, but not initialized for use when passed in
inout	For function parameters passed both into and out of a function

Precision and Precision Qualifiers [4.5]

Any floating point, integer, or sampler declaration can have the type preceded by one of these precision qualifiers:

highp	Satisfies minimum requirements for the vertex language.
mediump	Range and precision is between that provided by **lowp** and **highp**.
lowp	Range and precision can be less than **mediump**, but still represents all color values for any color channel.

A precision statement establishes a default precision qualifier for subsequent int, float, and sampler declarations, e.g.:

```
precision highp int;
```

Ranges & precisions for precision qualifiers (FP=floating point):

				Integer Range	
	FP Range	FP Magnitude Range	FP Precision	Signed	Unsigned
highp	$(-2^{126}, 2^{127})$	$0.0, (2^{-126}, 2^{127})$	Relative 2^{-24}	$[-2^{31}, 2^{31}-1]$	$[0, 2^{32}-1]$
mediump	$(-2^{14}, 2^{14})$	$(2^{-14}, 2^{14})$	Relative 2^{-10}	$[-2^{15}, 2^{15}-1]$	$[0, 2^{16}-1]$
lowp	$(-2, 2)$	$(2^{-8}, 2)$	Absolute 2^{-8}	$[-2^{7}, 2^{7}-1]$	$[0, 2^{8}-1]$

Invariant Qualifiers Examples [4.6]

#pragma STDGL **invariant**(all)	Force all output variables to be invariant
invariant gl_Position;	Qualify a previously declared variable
invariant centroid out vec3 Color;	Qualify as part of a variable declaration

Order of Qualification [4.7]

When multiple qualifications are present, they must follow a strict order. This order is one of the following:

invariant, interpolation, storage, precision
storage, parameter, precision

Aggregate Operations and Constructors

Matrix Constructor Examples [5.4.2]

```
mat2(float)                  // init diagonal
mat2(vec2, vec2);            // column-major order
mat2(float, float, float, float);
                             // column-major order
```

Structure Constructor Example [5.4.3]

```
struct light {
   float intensity;
   vec3 pos;
};
light lightVar = light(3.0, vec3(1.0, 2.0, 3.0));
```

Matrix Components [5.6]

Access components of a matrix with array subscripting syntax.
For example:

```
mat4 m;            // m represents a matrix
m[1] = vec4(2.0);  // sets second column to
                   // all 2.0
m[0][0] = 1.0;     // sets upper left element
                   // to 1.0
m[2][3] = 2.0;     // sets 4th element of 3rd
                   //  column to 2.0
```

Examples of operations on matrices and vectors:

```
m = f * m;      // scalar * matrix
                // component-wise
v = f * v;      // scalar * vector
                // component-wise
v = v * v;      // vector * vector c
                // component-wise
m = m +/- m;    // matrix component-wise
                // addition/subtraction
m = m * m;      // linear algebraic multiply
m = v * m;      // row vector * matrix linear
                // algebraic multiply
m = m * v;      // matrix * column vector linear
                // algebraic multiply
f = dot(v, v);  // vector dot product
v = cross(v, v); // vector cross product
m = matrixCompMult(m, m);
                // component-wise multiply
```

Structure Operations [5.7]

Select structure fields using the period (.) operator. Valid operators are:

.	field selector
== !=	equality
=	assignment

Array Operations [5.7]

Array elements are accessed using the array subscript operator "[ ]". For example:

```
diffuseColor += lightIntensity[3] * NdotL;
```

The size of an array can be determined using the .**length**() operator. For example:

```
for (i = 0; i < a.length(); i++)
    a[i] = 0.0;
```

Statements and Structure

Iteration and Jumps [6]

Entry	void main()

Iteration	for (;;) { break, continue }
	while ( ) { break, continue }
	do { break, continue } while ( );

Selection	if ( ) { }
	if ( ) { } else { }
	switch ( ) { break, case }

Jump	break, continue, return discard // Fragment shader only

Built-In Inputs, Outputs, and Constants [7]

Shader programs use special variables to communicate with fixed-function parts of the pipeline. Output special variables may be read back after writing. Input special variables are read-only. All special variables have global scope.

Vertex Shader Special Variables [7.1]

Inputs:

```
    int          gl_VertexID;    // integer index
    int          gl_InstanceID;  // instance number
```

Outputs:

```
 out gl_PerVertex {
    vec4         gl_Position;    // transformed vertex position in clip
    coordinates
    float        gl_PointSize;   // transformed point size in pixels (point
                                 // rasterization only)
};
```

Fragment Shader Special Variables [7.2]

Inputs:

```
    highp vec4    gl_FragCoord;    // fragment position within frame buffer
    bool          gl_FrontFacing;  // fragment belongs to a front-facing primitive
    mediump vec2  gl_PointCoord;   // 0.0 to 1.0 for each component
```

Outputs:

```
    highp float    gl_FragDepth;       // depth range
```

Built-In Constants With Minimum Values [7.3]

Built-in Constant	Minimum value
const mediump int gl_MaxVertexAttribs	16
const mediump int gl_MaxVertexUniformVectors	256
const mediump int gl_MaxVertexOutputVectors	16
const mediump int gl_MaxFragmentInputVectors	15
const mediump int gl_MaxVertexTextureImageUnits	16
const mediump int gl_MaxCombinedTextureImageUnits	32
const mediump int gl_MaxTextureImageUnits	16
const mediump int gl_MaxFragmentUniformVectors	224
const mediump int gl_MaxDrawBuffers	4
const mediump int gl_MinProgramTexelOffset	-8
const mediump int gl_MaxProgramTexelOffset	7

Built-In Uniform State [7.4]

As an aid to accessing OpenGL ES processing state, the following uniform variables are built into the OpenGL ES Shading Language.

```
  struct gl_DepthRangeParameters {
     float near;          // n
     float far;           // f
     float diff;          // f - n
  };
  uniform gl_DepthRangeParameters  gl_DepthRange;
```

Built-In Functions

Angle & Trigonometry Functions [8.1]

Component-wise operation. Parameters specified as *angle* are assumed to be in units of radians. T is float, vec2, vec3, vec4.

T **radians** (T *degrees*);	degrees to radians
T **degrees** (T *radians*);	radians to degrees
T **sin** (T *angle*);	sine
T **cos** (T *angle*);	cosine
T **tan** (T *angle*);	tangent
T **asin** (T *x*);	arc sine
T **acos** (T *x*);	arc cosine

T **atan** (T *y*, T *x*);
T **atan** (T *y_over_x*);
	arc tangent

T **sinh** (T *x*);	hyperbolic sine
T **cosh** (T *x*);	hyperbolic cosine
T **tanh** (T *x*);	hyperbolic tangent
T **asinh** (T *x*);	arc hyperbolic sine; inverse of sinh
T **acosh** (T *x*);	arc hyperbolic cosine; non-negative inverse of cosh
T **atanh** (T *x*);	arc hyperbolic tangent; inverse of tanh

Exponential Functions [8.2]

Component-wise operation. T is float, vec2, vec3, vec4.

T **pow** (T *x*, T *y*);	x^y
T **exp** (T *x*);	e^x
T **log** (T *x*);	ln
T **exp2** (T *x*);	2^x
T **log2** (T *x*);	$\log_2$
T **sqrt** (T *x*);	square root
T **inversesqrt** (T *x*);	inverse square root

Common Functions [8.3]

Component-wise operation. T is float and vec*n*, TI is int and ivec*n*, TU is uint and uvec*n*, and TB is bool and bvec*n*, where *n* is 2, 3, or 4.

T **abs**(T *x*);
TI **abs**(TI *x*);
	absolute value

T **sign**(T *x*);
TI **sign**(TI *x*);
	returns -1.0, 0.0, or 1.0

T **floor**(T *x*);	nearest integer <= *x*
T **trunc** (T *x*);	nearest integer a such that |*a*| <= |*x*|
T **round** (T *x*);	round to nearest integer
T **roundEven** (T *x*);	round to nearest integer
T **ceil**(T *x*);	nearest integer >= *x*
T **fract**(T *x*);	*x* - **floor**(*x*)

T **mod**(T *x*, T *y*);
T **mod**(T *x*, float *y*);
T **modf**(T *x*, out T *i*);
	modulus

T **min**(T *x*, T *y*);
TI **min**(TI *x*, TI *y*);
TU **min**(TU *x*, TU *y*);
T **min**(T *x*, float *y*);
TI **min**(TI *x*, int *y*);
TU **min**(TU *x*, uint *y*);
	minimum value

T **max**(T *x*, T *y*);
TI **max**(TI *x*, TI *y*);
TU **max**(TU *x*, TU *y*);
T **max**(T *x*, float *y*);
TI **max**(TI *x*, int *y*);
TU **max**(TU *x*, uint *y*);
	maximum value

T **clamp**(TI *x*, T *minVal*, T *maxVal*);
TI **clamp**(V *x*, TI *minVal*, TI *maxVal*);
TU **clamp**(TU *x*, TU *minVal*, TU *maxVal*);
T **clamp**(T *x*, float *minVal*, float *maxVal*);
TI **clamp**(TI *x*, int *minVal*, int *maxVal*);
TU **clamp**(TU *x*, uint *minVal*, uint *maxVal*);
	min(**max**(*x*, *minVal*), *maxVal*)

T **mix**(T *x*, T *y*, T *a*);
T **mix**(T *x*, T *y*, float *a*);
	linear blend of *x* and *y*

(Continued on next page >)

Built-In Functions (continued)

T **mix**(T *x*, T *y*, TB *a*);	Selects vector source for each returned component

T **step**(T *edge*, T *x*);
T **step**(float *edge*, T *x*);
	0.0 if *x* < *edge*, else 1.0

T **smoothstep**(T *edge0*, T *edge1*, T *x*);
T **smoothstep**(float *edge0*, float *edge1*, T *x*);
	clamp and smooth

TB **isnan**(T *x*);	true if *x* is a NaN
TB **isinf**(T *x*);	true if *x* is positive or negative infinity

TI **floatBitsToInt**(T *value*);
TU **floatBitsToUint**(T *value*);
	highp integer, preserving float bit level representation

T **intBitsToFloat**(TI *value*);
T **uintBitsToFloat**(TU *value*);
	highp float, preserving integer bit level representation

Floating-Point Pack and Unpack [8.4]

uint **packSnorm2x16**(vec2 *v*);
uint **packUnorm2x16**(vec2 *v*);
	convert two floats to fixed point and pack into an integer

vec2 **unpackSnorm2x16**(uint *p*);
vec2 **unpackUnorm2x16**(uint *p*);
	unpack fixed point value pair into floats

uint **packHalf2x16**(vec2 *v*);	convert two floats into half-precision floats and pack into an integer
vec2 **unpackHalf2x16**(uint *v*);	unpack half value pair into full floats

Geometric Functions [8.5]

These functions operate on vectors as vectors, not component-wise. T is float, vec2, vec3, vec4.

float **length**(T *x*);	length of vector
float **distance**(T *p0*, T *p1*);	distance between points
float **dot**(T *x*, T *y*);	dot product
vec3 **cross**(vec3 *x*, vec3 *y*);	cross product
T **normalize**(T *x*);	normalize vector to length 1
T **faceforward**(T *N*, T *I*, T *Nref*);	returns *N* if **dot**(*Nref*, *I*) < 0, else -*N*
T **reflect**(T *I*, T *N*);	reflection direction *I* - 2 * **dot**(*N*,*I*) * *N*
T **refract**(T *I*, T *N*, float *eta*);	refraction vector

Matrix Functions [8.6]

Type mat is any matrix type.

mat **matrixCompMult**(mat *x*, mat *y*);	multiply *x* by *y* component-wise

mat2 **outerProduct**(vec2 *c*, vec2 *r*);
mat3 **outerProduct**(vec3 *c*, vec3 *r*);
mat4 **outerProduct**(vec4 *c*, vec4 *r*);
	linear algebraic column vector * row vector

mat2x3 **outerProduct**(vec3 *c*, vec2 *r*);
mat3x2 **outerProduct**(vec2 *c*, vec3 *r*);
mat2x4 **outerProduct**(vec4 *c*, vec2 *r*);
mat4x2 **outerProduct**(vec2 *c*, vec4 *r*);
mat3x4 **outerProduct**(vec4 *c*, vec3 *r*);
mat4x3 **outerProduct**(vec3 *c*, vec4 *r*);
	linear algebraic column vector * row vector

mat2 **transpose**(mat2 *m*);
mat3 **transpose**(mat3 *m*);
mat4 **transpose**(mat4 *m*);
mat2x3 **transpose**(mat3x2 *m*);
mat3x2 **transpose**(mat2x3 *m*);
mat2x4 **transpose**(mat4x2 *m*);
mat4x2 **transpose**(mat2x4 *m*);
mat3x4 **transpose**(mat4x3 *m*);
mat4x3 **transpose**(mat3x4 *m*);
	transpose of matrix *m*

float **determinant**(mat2 *m*);
float **determinant**(mat3 *m*);
float **determinant**(mat4 *m*);
	determinant of matrix *m*

mat2 **inverse**(mat2 *m*);
mat3 **inverse**(mat3 *m*);
mat4 **inverse**(mat4 *m*);
	inverse of matrix *m*

Vector Relational Functions [8.7]

Compare *x* and *y* component-wise. Input and return vector sizes for a particular call must match. Type bvec is bvec*n*; vec is vec*n*; ivec is ivec*n*; uvec is uvec*n*; (where *n* is 2, 3, or 4). T is union of vec and ivec.

bvec **lessThan**(T *x*, T *y*);
bvec **lessThan**(uvec *x*, uvec *y*);
	x < y

bvec **lessThanEqual**(T *x*, T *y*);
bvec **lessThanEqual**(uvec *x*, uvec *y*);
	x <= y

bvec **greaterThan**(T *x*, T *y*);
bvec **greaterThan**(uvec *x*, uvec *y*);
	x > y

bvec **greaterThanEqual**(T *x*, T *y*);
bvec **greaterThanEqual**(uvec *x*, uvec *y*);
	x >= y

bvec **equal**(T *x*, T *y*);
bvec **equal**(bvec *x*, bvec *y*);
bvec **equal**(uvec *x*, uvec *y*);
	x == y

bvec **notEqual**(T *x*, T *y*);
bvec **notEqual**(bvec *x*, bvec *y*);
bvec **notEqual**(uvec *x*, uvec *y*);
	x!= y

bool **any**(bvec *x*);	true if any component of *x* is true
bool **all**(bvec *x*);	true if all components of *x* are true
bvec **not**(bvec *x*);	logical complement of *x*

Texture Lookup Functions [8.8]

The function textureSize returns the dimensions of level *lod* for the texture bound to sampler, as described in [2.11.9] of the OpenGL ES 3.0 specification, under "Texture Size Query". The initial "g" in a type name is a placeholder for nothing, "i", or "u".

highp ivec{2,3}	**textureSize**(gsampler{2,3}D *sampler*, int *lod*);
highp ivec2	**textureSize**(gsamplerCube *sampler*, int *lod*);
highp ivec2	**textureSize**(sampler2DShadow *sampler*, int *lod*);
highp ivec2	**textureSize**(samplerCubeShadow *sampler*, int *lod*);
highp ivec3	**textureSize**(gsampler2DArray *sampler*, int *lod*);
highp ivec3	**textureSize**(sampler2DArrayShadow *sampler*, int *lod*);

Texture lookup functions using samplers are available to vertex and fragment shaders. The initial "g" in a type name is a placeholder for nothing, "i", or "u".

gvec4	**texture**(gsampler{2,3}D *sampler*, vec{2,3} *P* [, float *bias*]);
gvec4	**texture**(gsamplerCube *sampler*, vec3 *P* [, float *bias*]);
float	**texture**(sampler2DShadow *sampler*, vec3 *P* [, float *bias*]);
float	**texture**(samplerCubeShadow *sampler*, vec4 *P* [, float *bias*]);
gvec4	**texture**(gsampler2DArray *sampler*, vec3 *P* [, float *bias*]);
float	**texture**(sampler2DArrayShadow *sampler*, vec4 *P*);
gvec4	**textureProj**(gsampler2D *sampler*, vec{3,4} *P* [, float *bias*]);
gvec4	**textureProj**(gsampler3D *sampler*, vec4 *P* [, float *bias*]);
float	**textureProj**(sampler2DShadow *sampler*, vec4 *P* [, float *bias*]);
gvec4	**textureLod**(gsampler{2,3}D *sampler*, vec{2,3} *P*, float *lod*);
gvec4	**textureLod**(gsamplerCube *sampler*, vec3 *P*, float *lod*);
float	**textureLod**(sampler2DShadow *sampler*, vec3 *P*, float *lod*);
gvec4	**textureLod**(gsampler2DArray *sampler*, vec3 *P*, float *lod*);
gvec4	**textureOffset**(gsampler2D *sampler*, vec2 *P*, ivec2 *offset* [, float *bias*]);
gvec4	**textureOffset**(gsampler3D *sampler*, vec3 *P*, ivec3 *offset* [, float *bias*]);
float	**textureOffset**(sampler2DShadow *sampler*, vec3 *P*, ivec2 *offset* [, float *bias*]);
gvec4	**textureOffset**(gsampler2DArray *sampler*, vec3 *P*, ivec2 *offset* [, float *bias*]);
gvec4	**texelFetch**(gsampler2D *sampler*, ivec2 *P*, int *lod*);
gvec4	**texelFetch**(gsampler3D *sampler*, ivec3 *P*, int *lod*);
gvec4	**texelFetch**(gsampler2DArray *sampler*, ivec3 *P*, int *lod*);
gvec4	**texelFetchOffset**(gsampler2D *sampler*, ivec2 *P*, int *lod*, ivec2 *offset*);
gvec4	**texelFetchOffset**(gsampler3D *sampler*, ivec3 *P*, int *lod*, ivec3 *offset*);
gvec4	**texelFetchOffset**(gsampler2DArray *sampler*, ivec3 *P*, int *lod*, ivec2 *offset*);

(Continued on next page >)

Built-In Functions (continued)

gvec4 **textureProjOffset**(gsampler2D *sampler*, vec3 *P*, ivec2 *offset* [, float *bias*]);
gvec4 **textureProjOffset**(gsampler2D *sampler*, vec4 *P*, ivec2 *offset* [, float *bias*]);
gvec4 **textureProjOffset**(gsampler3D *sampler*, vec4 *P*, ivec3 *offset* [, float *bias*]);
float **textureProjOffset**(sampler2DShadow *sampler*, vec4 *P*, ivec2 *offset* [, float bias]);

gvec4 **textureLodOffset**(gsampler2D *sampler*, vec2 *P*, float *lod*, ivec2 *offset*);
gvec4 **textureLodOffset**(gsampler3D *sampler*, vec3 *P*, float *lod*, ivec3 *offset*);
float **textureLodOffset**(sampler2DShadow *sampler*, vec3 *P*, float *lod*, ivec2 *offset*);
gvec4 **textureLodOffset**(gsampler2DArray *sampler*, vec3 *P*, float *lod*, ivec2 *offset*);

gvec4 **textureProjLod**(gsampler2D *sampler*, vec3 *P*, float *lod*);
gvec4 **textureProjLod**(gsampler2D *sampler*, vec4 *P*, float *lod*);
gvec4 **textureProjLod**(gsampler3D *sampler*, vec4 *P*, float *lod*);
float **textureProjLod**(sampler2DShadow *sampler*, vec4 *P*, float *lod*);

gvec4 **textureProjLodOffset**(gsampler2D *sampler*, vec3 *P*, float *lod*, ivec2 *offset*);
gvec4 **textureProjLodOffset**(gsampler2D *sampler*, vec4 *P*, float *lod*, ivec2 *offset*);
gvec4 **textureProjLodOffset**(gsampler3D *sampler*, vec4 *P*, float *lod*, ivec3 *offset*);
float **textureProjLodOffset**(sampler2DShadow *sampler*, vec4 *P*, float *lod*, ivec2 *offset*);

gvec4 **textureProjGrad**(gsampler2D *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*);
gvec4 **textureProjGrad**(gsampler2D *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*);
gvec4 **textureProjGrad**(gsampler3D *sampler*, vec4 *P*, vec3 *dPdx*, vec3 *dPdy*);
float **textureProjGrad**(sampler2DShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*);

gvec4 **textureGrad**(gsampler2D *sampler*, vec2 *P*, vec2 *dPdx*, vec2 *dPdy*);
gvec4 **textureGrad**(gsampler3D *sampler*, vec3 *P*, vec3 *dPdx*, vec3 *dPdy*);
gvec4 **textureGrad**(gsamplerCube *sampler*, vec3 *P*, vec3 *dPdx*, vec3 *dPdy*);
float **textureGrad**(sampler2DShadow *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*);

float **textureGrad**(samplerCubeShadow *sampler*, vec4 *P*, vec3 *dPdx*, vec3 *dPdy*);
gvec4 **textureGrad**(gsampler2DArray *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*);
float **textureGrad**(sampler2DArrayShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*);

gvec4 **textureGradOffset**(gsampler2D *sampler*, vec2 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);
gvec4 **textureGradOffset**(gsampler3D *sampler*, vec3 *P*, vec3 *dPdx*, vec3 *dPdy*, ivec3 *offset*);
float **textureGradOffset**(sampler2DShadow *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);
gvec4 **textureGradOffset**(gsampler2DArray *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);
float **textureGradOffset**(sampler2DArrayShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);

gvec4 **textureProjGradOffset**(gsampler2D *sampler*, vec3 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);
gvec4 **textureProjGradOffset**(gsampler2D *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);
gvec4 **textureProjGradOffset**(gsampler3D *sampler*, vec4 *P*, vec3 *dPdx*, vec3 *dPdy*, ivec3 *offset*);
float **textureProjGradOffset**(sampler2DShadow *sampler*, vec4 *P*, vec2 *dPdx*, vec2 *dPdy*, ivec2 *offset*);

Fragment Processing Functions [8.9]

Approximated using local differencing.

T **dFdx**(T *p*);	Derivative in *x*
T **dFdy**(T *p*);	Derivative in *y*
T **fwidth**(T *p*);	**abs** (**dFdx** (*p*)) + **abs** (**dFdy** (*p*));

Sample Program

Here is an example of G-buffer construction for deferred lighting using GLSL ES 3.0 with multiple render targets.

Vertex Shader

```
#version 300 es

// inputs
layout (location=0) in vec4 a_position;
layout (location=1) in vec2 a_texCoord;
layout (location=3) in vec3 a_normal;

// outputs
out  vec2 v_texCoord;
out  vec3 v_normal;
out  vec3 v_worldPos;

// uniforms
layout(std140) uniform transforms
{
   mat4 u_modelViewMat;
   mat4 u_modelViewProjMat;
   mat3 u_normalMat;
};

void main()
{
   v_texCoord    = a_texCoord;
   v_normal      = u_normalMat * a_normal;
   v_worldPos    = (u_modelViewMat * a_position).xyz;

   // vertex position calculation
   gl_Position   = u_modelViewProjMat * a_position;
}
```

Fragment Shader

```
#version 300 es

precision mediump float;

// inputs
in   vec2 v_texCoord;
in   vec3 v_normal;
in   vec3 v_worldPos;

// outputs
out vec4 gl_FragData[3];

// uniforms
uniform sampler2D   u_baseTextureSamp;
uniform float       u_specular;

void main()
{
   vec4 baseColor  = texture(u_baseTextureSamp, v_texCoord);

   // Normalize per-pixel vectors
   vec3 normal     = normalize(v_normal);

   // Store material properties into MRTs
   gl_FragData[0]  = baseColor;                      // base color
   gl_FragData[1]  = vec4(normal, u_specular);       // packed: surface
                                                     // normal in xyz, specular exponent in w.
   gl_FragData[2]  = vec4(v_worldPos, 0.0);          // world position
}
```