OpenGL® Shading Language

Third Edition

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Foreword to the Second Edition

To me, graphics shaders are about the coolest things to ever happen in computer graphics. I grew up in graphics in the 1970s, watching the most amazing people do the most amazing things with the mathematics of graphics. I remember Jim Blinn's bump-mapping technique, for instance, and what effects it was able to create. The method was deceptively simple, but the visual impact was momentous. True, it took a substantial amount of time for a computer to work through the pixel-by-pixel software process to make that resulting image, but we cared about that only a little bit. It was the effect that mattered.

My memory now fast-forwards to the 1980s. Speed became a major issue, with practitioners like Jim Clark working on placing graphics algorithms in silicon. This resulted in the blossoming of companies such as Evans & Sutherland and Silicon Graphics. They brought fast, interactive 3D graphics to the masses, but the compromise was that they forced us into doing our work using standard APIs that could easily be hardware supported. Deep-down procedural techniques such as bump mapping could not follow where the hardware was leading.

But the amazing techniques survived in software. Rob Cook's classic paper on shade trees brought attention to the idea of using software "shaders" to perform the pixel-by-pixel computations that could deliver the great effects. This was embodied by the Photorealistic RenderMan rendering software. The book *RenderMan Companion* by Steve Upstill is still the first reference that I point my students to when they want to learn about the inner workings of shaders. The ability to achieve such fine-grained control over the graphics rendering process gave RenderMan users the ability to create the

dazzling, realistic effects seen in Pixar animation shorts and TV commercials. The process was still miles away from real time, but the seed of the idea of giving an *interactive* application developer that type of control was planted. And it was such a powerful idea that it was only a matter of time until it grew.

Now, fast-forward to the start of the new millennium. The major influence on graphics was no longer science and engineering applications. It had become games and other forms of entertainment. (Nowhere has this been more obvious than in the composition of the SIGGRAPH Exhibition.) Because games live and die by their ability to deliver realistic effects at interactive speeds, the shader seed planted a few years earlier was ready to flourish in this new domain. The capacity to place procedural graphics rendering algorithms into the graphics hardware was definitely an idea whose time had come. Interestingly, it brought the graphics community full circle. We searched old SIGGRAPH proceedings to see how pixel-by-pixel scene control was performed in software then, so we could "re-invent" it using interactive shader code.

So, here we are in the present, reading Randi Rost's *OpenGL Shading Language*. This is the next book I point my shader-intrigued students to, after Upstill's. It is also the one that I, and they, use most often day to day. By now, my first edition is pretty worn.

But great news—I have an excuse to replace it! This second edition is a *major* enhancement over the first. This is more than just errata corrections. There is substantial new material in this book. New chapters on lighting, shadows, surface characteristics, and RealWorldz are essential for serious effects programmers. There are also 18 new shader examples. The ones I especially like are shadow mapping, vertex noise, image-based lighting, and environmental mapping with cube maps. But they are all really good, and you will find them all useful.

The OpenGL Shading Language is now part of standard OpenGL. It will be used everywhere. There is no reason not to. Anybody interested in effects graphics programming will want to read this book cover to cover. There are many nuggets to uncover. But GLSL is useful even beyond those borders. For example, we use it in our visualization research here at OSU (dome transformation, line integral convolution, image compression, terrain data mapping, etc.). I know that GLSL will find considerable applications in many other non-game areas as well.

I want to express my appreciation to Randi, who obviously started working on the first edition of this book even before the GLSL specification was fully decided upon. This must have made the book extra difficult to write, but it let the rest of us jump on the information as soon as it was stable. Thanks, too, for this second edition. It will make a significant contribution to the shader-programming community, and we appreciate it.

—Mike Bailey, Ph.D.
Professor, Computer Science
Oregon State University

Foreword to the First Edition

This book is an amazing measure of how far and how fast interactive shading has advanced. Not too many years ago, procedural shading was something done only in offline production rendering, creating some of the great results we all know from the movies, but were not anywhere close to interactive. Then a few research projects appeared, allowing a slightly modified but largely intact type of procedural shading to run in real time. Finally, in a rush, widely accessible commercial systems started to support shading. Today, we've come to the point where a real-time shading language developed by a cross-vendor group of OpenGL participants has achieved official designation as an OpenGL Architecture Review Board approved extension. This book, written by one of those most responsible for spearheading the development and acceptance of the OpenGL shading language, is your guide to that language and the extensions to OpenGL that let you use it.

I came to my interest in procedural shading from a strange direction. In 1990, I started graduate school at the University of North Carolina in Chapel Hill because it seemed like a good place for someone whose primary interest was interactive 3D graphics. There, I started working on the Pixel-Planes project. This project had produced a new graphics machine with several interesting features beyond its performance at rendering large numbers of polygons per second. One feature in particular had an enormous impact on the research directions I've followed for the past 13 years. Pixel-Planes 5 had programmable pixel processors—lots of them. Programming these processors was similar in many ways to the assembly-language fragment programs that have burst onto the graphics scene in the past few years.

Programming them was exhilarating, yet also thoroughly exasperating.

I was far from the only person to notice both the power and pain of writing low-level code to execute per-pixel. Another group within the Pixel-Planes team built an assembler for shading code to make it a little easier to write, although it was still both difficult to write a good shader and ever-so-rewarding once you had it working. The shaders produced will be familiar to anyone who has seen demos of any of the latest graphics products, and not surprisingly you'll find versions of many of them in this book: wood, clouds, brick, rock, reflective wavy water, and (of course) the Mandelbrot fractal set.

The rewards and difficulties presented by Pixel-Planes 5 shaders guided many of the design decisions behind the next machine, PixelFlow. PixelFlow was designed and built by a university/industry partnership with industrial participation first by Division, then by Hewlett-Packard. The result was the first interactive system capable of running procedural shaders compiled from a high-level shading language. PixelFlow was demonstrated at the SIGGRAPH conference in 1997. For a few years thereafter, if you were fortunate enough to be at UNC-Chapel Hill, you could write procedural shaders and run them in real time when no one else could. And, of course, the only way to see them in action was to go there.

I left UNC for a shading project at SGI, with the hopes of providing a commercially supported shading language that could be used on more than just one machine at one site. Meanwhile, a shading language research project started up at Stanford, with some important results for shading on PC-level graphics hardware. PC graphics vendors across the board started to add low-level shading capabilities to their hardware. Soon, people everywhere could write shading code similar in many ways to that which had so inspired me on the Pixel-Planes 5 machine. And, not surprisingly, soon people everywhere also knew that we were going to need a higher-level language for interactive shading.

Research continues into the use, improvement, and abuse of these languages at my lab at University of Maryland, Baltimore County; and at many, many others. However, the mere existence of real-time high-level shading languages is no longer the subject of that research. Interactive shading languages have moved from the research phase to wide availability. There are a number of options for anyone wanting to develop an application using the shading capabilities of modern graphics hardware. The principal choices are Cg, HLSL, and the OpenGL Shading Language. The last of which has the distinction of being the only one that has been through a rigorous

multivendor review process. I participated in that process, as did more than two dozen representatives from a dozen companies and universities.

This brings us back full circle to this book. If you are holding this book now, you are most likely interested in some of the same ideals that drove the creation of the OpenGL Shading Language, the desire for a cross-OS, cross-platform, robust and standardized shading language. You want to learn how to use all of that? Open up and start reading. Then get shading!

—Marc Olano
University of Maryland
Baltimore County, MD
September 2003

Preface

For just about as long as there has been graphics hardware, there has been programmable graphics hardware. Over the years, building flexibility into graphics hardware designs has been a necessary way of life for hardware developers. Graphics APIs continue to evolve, and because a hardware design can take two years or more from start to finish, the only way to guarantee a hardware product that can support the then current graphics APIs at its release is to build in some degree of programmability from the very beginning.

Until recently, the realm of programming graphics hardware belonged to just a few people, mainly researchers and graphics hardware driver developers. Research into programmable graphics hardware has been taking place for many years, but the point of this research has not been to produce viable hardware and software for application developers and end users. The graphics hardware driver developers have focused on the immediate task of providing support for the important graphics APIs of the time: PHIGS, PEX, Iris GL, OpenGL, Direct3D, and so on. Until recently, none of these APIs exposed the programmability of the underlying hardware, so application developers have been forced into using the fixed functionality provided by traditional graphics APIs.

Hardware companies have not exposed the programmable underpinnings of their products because of the high cost of educating and supporting customers to use low-level, device-specific interfaces and because these interfaces typically change quite radically with each new generation of graphics hardware. Application developers who use such a device-specific interface to a piece of graphics hardware face the daunting task of updating their software

for each new generation of hardware that comes along. And forget about supporting the application on hardware from multiple vendors!

As we moved into the 21st century, some of these fundamental tenets about graphics hardware were challenged. Application developers pushed the envelope as never before and demanded a variety of new features in hardware in order to create more and more sophisticated onscreen effects. As a result, new graphics hardware designs became more programmable than ever before. Standard graphics APIs were challenged to keep up with the pace of hardware innovation. For OpenGL, the result was a spate of extensions to the core API as hardware vendors struggled to support a range of interesting new features that their customers were demanding.

The creation of a standard, cross-platform, high-level shading language for commercially available graphics hardware was a watershed event for the graphics industry. A paradigm shift occurred, one that took us from the world of rigid, fixed functionality graphics hardware and graphics APIs to a brave new world where the graphics processing unit, or GPU (i.e., graphics hardware), is as important as the central processing unit, or CPU. The GGU is optimized for processing dynamic media such as 3D graphics and video. Highly parallel processing of floating-point data is the primary task for GPUs, and the flexibility of the GPU means that it can also be used to process data other than a stream of traditional graphics commands. Applications can take advantage of the capabilities of both the CPU and the GPU, using the strengths of each to optimally perform the task at hand.

This book describes how graphics hardware programmability is exposed through a high-level language in the leading cross-platform 3D graphics API: OpenGL. This language, the OpenGL Shading Language, lets applications take total control over the most important stages of the graphics processing pipeline. No longer restricted to the graphics rendering algorithms and formulas chosen by hardware designers and frozen in silicon, software developers are beginning to use this programmability to create stunning effects in real time.

Intended Audience

The primary audience for this book is application programmers who want to write shaders. This book can be used as both a tutorial and a reference book by people interested in learning to write shaders with the OpenGL Shading Language. Some will use the book in one fashion, and some in the other. The organization is amenable to both uses and is based on the

assumption that most people won't read the book in sequential order from back to front (but some intrepid readers of the first edition reported that they did just that!).

Readers do not need previous knowledge of OpenGL to absorb the material in this book, but such knowledge is very helpful. A brief review of OpenGL is included, but this book does not attempt to be a tutorial or reference book for OpenGL. Anyone attempting to develop an OpenGL application that uses shaders should be armed with OpenGL programming documentation in addition to this book.

Computer graphics has a mathematical basis, so some knowledge of algebra, trigonometry, and calculus will help readers understand and appreciate some of the details presented. With the advent of programmable graphics hardware, key parts of the graphics processing pipeline are once again under the control of software developers. To develop shaders successfully in this environment, developers must understand the mathematical basis of computer graphics.

About This Book

This book has three main parts. Chapters 1 through 8 teach the reader about the OpenGL Shading Language and how to use it. This part of the book covers details of the language and details of the OpenGL commands that create and manipulate shaders. To supply a basis for writing shaders, Chapters 9 through 19 contain a gallery of shader examples and some explanation of the underlying algorithms. This part of the book is both the baseline for a reader's shader development and a springboard for inspiring new ideas. Finally, Chapter 20 compares other notable commercial shading languages, and Appendixes A and B contain reference material for the language and the API entry points that support it.

The chapters are arranged to suit the needs of the reader who is least familiar with OpenGL and shading languages. Certain chapters can be skipped by readers who are more familiar with both topics. This book has somewhat compartmentalized chapters in order to allow such usage.

- Chapter 1 reviews the fundamentals of the OpenGL API. Readers already familiar with OpenGL may skip to Chapter 2.
- Chapter 2 introduces the OpenGL Shading Language and the OpenGL entry points that have been added to support it. If you want to know what the OpenGL Shading Language is all about and you have time to read only two chapters of this book, this chapter and Chapter 3 are the ones to read.

- Chapter 3 thoroughly describes the OpenGL Shading Language. This material is organized to present the details of a programming language. This section serves as a useful reference section for readers who have developed a general understanding of the language.
- Chapter 4 discusses how the newly defined programmable parts of the rendering pipeline interact with each other and with OpenGL's fixed functionality. This discussion includes descriptions of the built-in variables defined in the OpenGL Shading Language.
- Chapter 5 describes the built-in functions that are part of the OpenGL Shading Language. This section is a useful reference section for readers with an understanding of the language.
- Chapter 6 presents and discusses a fairly simple shader example. People who learn best by diving in and studying a real example will benefit from the discussion in this chapter.
- Chapter 7 describes the entry points that have been added to OpenGL to support the creation and manipulation of shaders. Application programmers who want to use shaders in their application must understand this material.
- Chapter 8 presents some general advice on shader development and describes the shader development process. It also describes tools that are currently available to aid the shader development process.
- Chapter 9 begins a series of chapters that present and discuss shaders with a common characteristic. In this chapter, shaders that duplicate some of the fixed functionality of the traditional OpenGL pipeline are presented.
- Chapter 10 presents a few shaders that are based on the capability to store data in and retrieve data from texture maps.
- Chapter 11 is devoted to shaders that are procedural in nature; that is, effects are computed algorithmically rather than being based on information stored in textures.
- Chapter 12 presents several alternative lighting models that can be implemented with OpenGL shaders.
- Chapter 13 discusses algorithms and shaders for producing shadows.
- Chapter 14 delves into the details of shaders that implement more realistic surface characteristics, including refraction, diffraction, and more realistic reflection.

- Chapter 15 describes noise and the effects that can be achieved with its proper use.
- Chapter 16 contains examples of how shaders can create rendering effects that vary over time.
- Chapter 17 contains a discussion of the aliasing problem and how shaders can be written to reduce the effects of aliasing.
- Chapter 18 illustrates shaders that achieve effects other than photorealism. Such effects include technical illustration, sketching or hatching effects, and other stylized rendering.
- Chapter 19 presents several shaders that modify images as they are being drawn with OpenGL.
- Chapter 20 compares the OpenGL Shading Language with other notable commercial shading languages.
- Appendix A contains the language grammar that more clearly specifies the OpenGL Shading Language.
- Appendix B contains reference pages for the API entry points that are related to the OpenGL Shading Language.
- Finally, the Glossary collects terms defined in the book, Further Reading gathers all the chapter references and adds more, and the Index ends the book.

About the Shader Examples

The shaders contained in this book are primarily short programs that illustrate the capabilities of the OpenGL Shading Language. None of the example shaders should be presumed to illustrate the "best" way of achieving a particular effect. (Indeed, the "best" way to implement certain effects may have yet to be discovered through the power and flexibility of programmable graphics hardware.) Performance improvements for each shader are possible for any given hardware target. For most of the shaders, image quality may be improved if greater care is taken to reduce or eliminate causes of aliasing.

The source code for these shaders is written in a way that I believe represents a reasonable trade-off between source code clarity, portability, and performance. Use them to learn the OpenGL Shading Language, and improve on them for use in your own projects.

I have taken as much care as possible to present shaders that are done "the right way" for the OpenGL Shading Language rather than those with idiosyncrasies from their development on specific implementations of the OpenGL Shading Language. Electronic versions of most of these shaders are available through a link at this book's Web site at http://3dshaders.com.

Errata

I know that this book contains some errors, but I've done my best to keep them to a minimum. If you find any errors, please report them to me (randi@3dshaders.com), and I will keep a running list on this book's Web site at http://3dshaders.com.

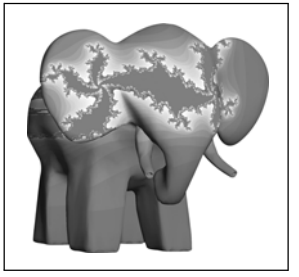
Typographical Conventions

This book contains a number of typographical conventions to enhance readability and understanding.

- SMALL CAPS are used for the first occurrence of defined terms.
- *Italics* are used for emphasis, document titles, and coordinate values such as *x*, *y*, and *z*.
- **Bold serif** is used for language keywords.
- Sans serif is used for macros and symbolic constants that appear in the text.
- **Bold sans serif** is used for function names.
- *Italic sans serif* is used for variables, parameter names, spatial dimensions, and matrix components.
- `Fixed width` is used for code examples.

Chapter 6

Simple Shading Example



Now that we've described the OpenGL Shading Language, let's look at a simple example. In this example, we apply a brick pattern to an object. The brick pattern is calculated entirely within a fragment shader. If you'd prefer to skip ahead to the next chapter for a more in-depth discussion of the API that allows shaders to be defined and manipulated, feel free to do so.

The shader for rendering a procedural brick pattern was the first interesting shader ever executed by the OpenGL Shading Language on programmable graphics hardware. It ran for the first time in March 2002, on the 3Dlabs Wildcat VP graphics accelerator. Dave Baldwin published the first GLSL brick fragment shader in a white paper that described the language destined to become the OpenGL Shading Language. His GLSL shader was based on a RenderMan shader by Darwyn Peachey that was published in the book *Texturing and Modeling: A Procedural Approach*. Steve Koren and John Kessenich adapted Dave's shader to get it working on real hardware for the first time, and it has subsequently undergone considerable refinement for inclusion in this book.

This example, like most of the others in this book, consists of three essential components: the source code for the vertex shader, the source code for the fragment shader, and the application code that initializes and uses these shaders. This chapter focuses on the vertex and fragment shaders. The application code for using these shaders is discussed in Section 7.13, after the details of the OpenGL Shading Language API have been discussed.

With this first example, we take a little more time discussing the details in order to give you a better grasp of what's going on. In examples later in the book, we focus mostly on the details that differ from previous examples.

6.1 Brick Shader Overview

One approach to writing shaders is to come up with a description of the effect that you're trying to achieve and then decide which parts of the shader need to be implemented in the vertex shader, which need to be implemented in the fragment shader, and how the application will tie everything together.

In this example, we develop a shader that applies a computed brick pattern to all objects that are drawn. We don't attempt the most realistic-looking brick shader, but rather a fairly simple one that illustrates many of the concepts we introduced in the previous chapters. We don't use textures for this brick pattern; the pattern itself is generated algorithmically. We can build a lot of flexibility into this shader by parameterizing the different aspects of our brick algorithm.

Let's first come up with a description of the overall effect we're after. We want

- A single light source
- Diffuse and specular reflection characteristics
- A brick pattern based on the position in modeling coordinates of the object being rendered—where the *x* coordinate is related to the brick horizontal position and the *y* coordinate is related to the brick vertical position
- Alternate rows of bricks offset by one-half the width of a single brick
- Easy-to-modify colors and ratios: brick color, mortar color, brick-to-brick horizontal distance, brick-to-brick vertical distance, brick width fraction (ratio of the width of a brick to the overall horizontal distance between two adjacent bricks), and brick height fraction (ratio of the height of a brick to the overall vertical distance between two adjacent bricks)

The brick geometry parameters that we use to control geometry and color are illustrated in Figure 6.1. Brick size and brick percentage parameters are both stored in user-defined uniform variables of type **vec2**. The horizontal distance between two bricks, including the width of the mortar, is provided by *BrickSize.x*. The vertical distance between two rows of bricks, including the height of the mortar, is provided by *BrickSize.y*. These two values are given in units of modeling coordinates. The fraction of *BrickSize.x* represented by the brick only is provided by *BrickPct.x*. The fraction of *BrickSize.y* represented by the brick only is provided by *BrickPct.y*. These two values are in the range [0,1]. Finally, the brick color and the mortar color are represented by the variables *BrickColor* and *MortarColor*.

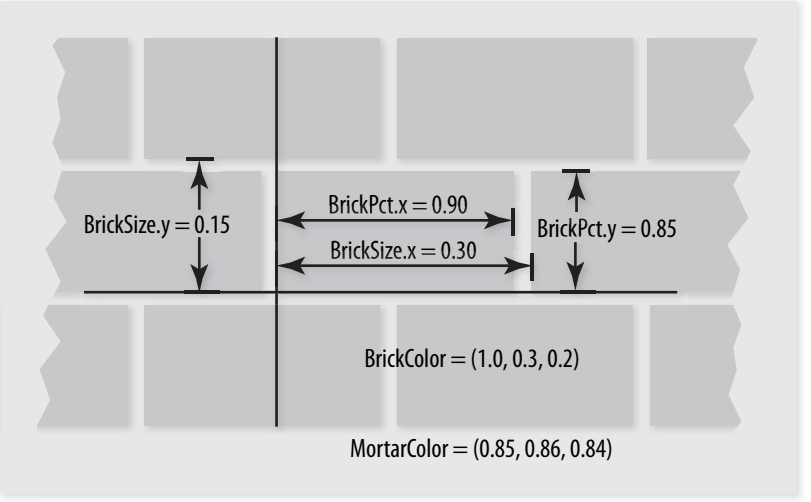


Figure 6.1 Parameters for defining brick

Now that we're armed with a firm grasp of our desired outcome, we'll design our vertex shader, then our fragment shader, and then the application code that will tie it all together.

6.2 Vertex Shader

The vertex shader embodies the operations that occur on each vertex that is provided to OpenGL. To define our vertex shader, we need to answer three questions.

- What data must be passed to the vertex shader for every vertex (i.e., generic attribute variables or in variables)?
- What global state is required by the vertex shader (i.e., uniform variables)?
- What values are computed by the vertex shader (i.e., out variables)?

Let's look at these questions one at a time.

We can't draw any geometry at all without specifying a value for each vertex position. Furthermore, we can't do any lighting unless we have a surface normal for each location for which we want to apply a lighting computation. So at the very least, we need a vertex position and a normal for every

incoming vertex. We'll define a global in-qualified variable to hold the MCvertex (vertex in model coordinates), and a global in-qualified variable to hold the MCnormal (normal in model coordinates):

```
in vec4      MCvertex;
in vec3      MCnormal;
```

We need access to several matrices for our brick algorithm. We need to access the current modelview-projection matrix (*MVPMatrix*) in order to transform our vertex position into the clipping coordinate system. We need to access the current modelview matrix (*MVMatrix*) in order to transform the vertex position into eye coordinates for use in the lighting computation. And we also need to transform our incoming normals into eye coordinates by using OpenGL's normal transformation matrix (*NormalMatrix*, which is just the inverse transpose of the upper-left 3×3 subset of *MVMatrix*).

```
uniform mat4 MVMatrix;
uniform mat4 MVPMatrix;
uniform mat3 NormalMatrix;
```

In addition, we need the position of a single light source. We define the light source position as a uniform variable like this:[1]

```
uniform vec3 LightPosition;
```

We also need values for the lighting calculation to represent the contribution from specular reflection and the contribution from diffuse reflection. We could define these as uniform variables so that they could be changed dynamically by the application, but to illustrate some additional features of the language, we define them as constants like this:

```
const float SpecularContribution = 0.3;
const float DiffuseContribution  = 1.0 - SpecularContribution;
```

Finally, we need to define the values that are passed on to the fragment shader. Every vertex shader must compute the homogeneous vertex position and store its value in the standard variable *gl_Position*, so we know that our brick vertex shader must do likewise. On the fly, we compute the brick pattern in the fragment shader as a function of the incoming geometry's *x* and *y* values in modeling coordinates, so we define an out variable called *MCposition* for this purpose. To apply the lighting effect on top of our brick, we do part of the lighting computation in the fragment shader and apply

1. The shaders in this book observe the convention of capitalizing the first letter of user-specified uniform, in, out, and nonqualified global variable names to set them apart from local variables.

the final lighting effect after the brick/mortar color has been computed in the fragment shader. We do most of the lighting computation in the vertex shader and simply pass the computed light intensity to the fragment shader in an out variable called *LightIntensity*. These two out variables are defined like this:

```
out float    LightIntensity;
out vec2     MCposition;
```

We're now ready to get to the meat of our brick vertex shader. We begin by declaring a main function for our vertex shader and computing the vertex position in eye coordinates:

```
void main()
{
    vec3 ecPosition = vec3(MVMatrix * MCvertex);;
```

In this first line of code, our vertex shader defines a variable called *ecPosition* to hold the eye coordinate position of the incoming vertex. We compute the eye coordinate position by transforming the vertex position (*MCvertex*) by the current modelview matrix (*MVMatrix*). Because one of the operands is a matrix and the other is a vector, the * operator performs a matrix multiplication operation rather than a component-wise multiplication.

The result of the matrix multiplication is a **vec4**, but *ecPosition* is defined as a **vec3**. There is no automatic conversion between variables of different types in the OpenGL Shading Language, so we convert the result to a **vec3** by using a constructor. This causes the fourth component of the result to be dropped so that the two operands have compatible types. (Constructors provide an operation that is similar to type casting, but it is much more flexible, as discussed in Section 3.3.) As we'll see, the eye coordinate position is used a couple of times in our lighting calculation.

The lighting computation that we perform is a simple one. Some light from the light source is reflected in a diffuse fashion (i.e., in all directions). Where the viewing direction is very nearly the same as the reflection direction from the light source, we see a specular reflection. To compute the diffuse reflection, we need to compute the angle between the incoming light and the surface normal. To compute the specular reflection, we need to compute the angle between the reflection direction and the viewing direction. First, we transform the incoming normal:

```
    vec3 tnorm      = normalize(NormalMatrix * MCnormal);
```

This line defines a new variable called *tnorm* for storing the transformed normal (remember, in the OpenGL Shading Language, variables can be declared when needed). The incoming surface normal (*MCnormal*, a

user-defined in variable for accessing the normal value through a generic vertex attribute) is transformed by the current normal transformation matrix (*NormalMatrix*). The resulting vector is normalized (converted to a vector of unit length) by the built-in function **normalize**, and the result is stored in *tnorm*.

Next, we need to compute a vector from the current point on the surface of the three-dimensional object we're rendering to the light source position. Both of these should be in eye coordinates (which means that the value for our uniform variable *LightPosition* must be provided by the application in eye coordinates). The light direction vector is computed as follows:

```
vec3 lightVec   = normalize(LightPosition - ecPosition);
```

The object position in eye coordinates was previously computed and stored in *ecPosition*. To compute the light direction vector, we subtract the object position from the light position. The resulting light direction vector is also normalized and stored in the newly defined local variable *lightVec*.

The calculations we've done so far have set things up almost perfectly to call the built-in function **reflect**. Using our transformed surface normal and the computed incident light vector, we can now compute a reflection vector at the surface of the object; however, **reflect** requires the incident vector (the direction from the light to the surface), and we've computed the direction to the light source. Negating *lightVec* gives us the proper vector:

```
vec3 reflectVec = reflect(-lightVec, tnorm);
```

Because both vectors used in this computation were unit vectors, the resulting vector is a unit vector as well. To complete our lighting calculation, we need one more vector—a unit vector in the direction of the viewing position. Because, by definition, the viewing position is at the origin (i.e., (0,0,0)) in the eye coordinate system, we can simply negate and normalize the computed eye coordinate position, *ecPosition:*

```
vec3 viewVec    = normalize(-ecPosition);
```

With these four vectors, we can perform a per-vertex lighting computation. The relationship of these vectors is shown in Figure 6.2.

The modeling of diffuse reflection is based on the assumption that the incident light is scattered in all directions according to a cosine distribution function. The reflection of light is strongest when the light direction vector and the surface normal are coincident. As the difference between the two angles increases to 90°, the diffuse reflection drops off to zero. Because both vectors have been normalized to produce unit vectors, we can determine the cosine of the angle between *lightVec* and *tnorm* by performing a dot

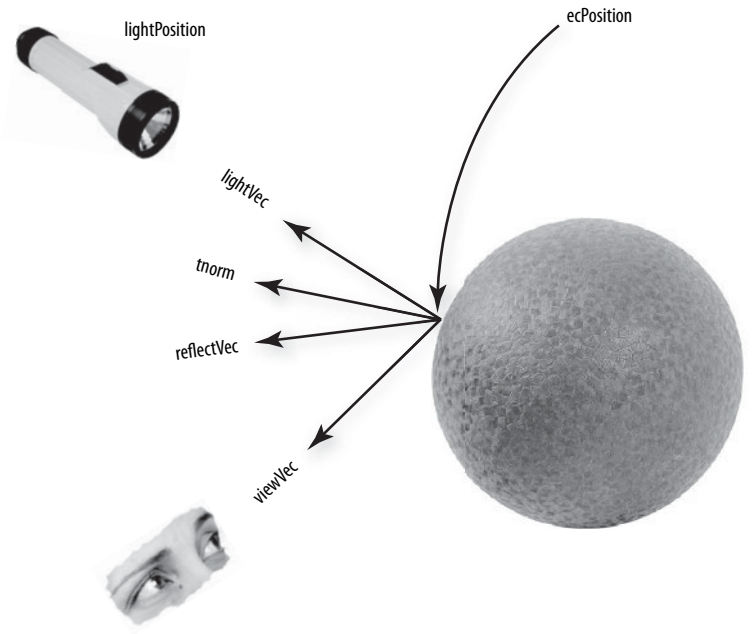


Figure 6.2 Vectors involved in the lighting computation for the brick vertex shader

product operation between those vectors. We want the diffuse contribution to be 0 if the angle between the light and the surface normal is greater than 90° (there should be no diffuse contribution if the light is behind the object), and the **max** function accomplishes this:

```
float diffuse = max(dot(lightVec, tnorm), 0.0);
```

The specular component of the light intensity for this vertex is computed by

```
float spec = 0.0;
if (diffuse > 0.0)
{
    spec = max(dot(reflectVec, viewVec), 0.0);
    spec = pow(spec, 16.0);
}
```

The variable for the specular reflection value is defined and initialized to 0. We compute a specular value other than 0 only if the angle between the light direction vector and the surface normal is less than 90° (i.e., the diffuse value is greater than 0) because we don't want any specular highlights if the light source is behind the object. Because both *reflectVec* and *viewVec* are normalized, computing the dot product of these two vectors gives us the

cosine of the angle between them. If the angle is near zero (i.e., the reflection vector and the viewing vector are almost the same), the resulting value is near 1.0. By raising the result to the 16th power in the subsequent line of code, we effectively "sharpen" the highlight, ensuring that we have a specular highlight only in the region where the reflection vector and the view vector are almost the same. The choice of 16 for the exponent value is arbitrary. Higher values produce more concentrated specular highlights, and lower values produce less concentrated highlights. This value could also be passed in as a uniform variable so that it can be easily modified by the end user.

All that remains is to multiply the computed diffuse and specular reflection values by the *diffuseContribution* and *specularContribution* constants and sum the two values:

```
    LightIntensity = DiffuseContribution * diffuse +
                     SpecularContribution * spec;
```

This value will be assigned to the out variable *LightIntensity* and interpolated between vertices. We also have one other out variable to compute, and we can do that quite easily.

```
    MCposition = MCvertex.xy;
```

When the brick pattern is applied to a geometric object, we want the brick pattern to remain constant with respect to the surface of the object, no matter how the object is moved. We also want the brick pattern to remain constant with respect to the surface of the object, no matter what the viewing position. To generate the brick pattern algorithmically in the fragment shader, we need to provide a value at each fragment that represents a location on the surface. For this example, we provide the modeling coordinate at each vertex by setting our out variable *MCposition* to the same value as our incoming vertex position (which is, by definition, in modeling coordinates).

We don't need the *z* or *w* coordinate in the fragment shader, so we need a way to select just the *x* and *y* components of *MCvertex*. We could have used a constructor here (e.g., **vec2**(*MCvertex*)), but to show off another language feature, we use the component selector **.xy** to select the first two components of *MCvertex* and store them in our out variable *MCposition*.

All that remains to be done is what all vertex shaders must do: compute the homogeneous vertex position. We do this by transforming the incoming vertex value by the current modelview-projection matrix:

```
    gl_Position     = MVPMatrix * MCvertex;
}
```

For clarity, the code for our vertex shader is provided in its entirety in Listing 6.1.

Listing 6.1 Source code for brick vertex shader

```
#version 140

in vec4      MCvertex;
in vec3      MCnormal;

uniform mat4 MVMatrix;
uniform mat4 MVPMatrix;
uniform mat3 NormalMatrix;

uniform vec3 LightPosition;

const float SpecularContribution = 0.3;
const float DiffuseContribution  = 1.0 - SpecularContribution;

out float    LightIntensity;
out vec2     MCposition;

void main()
{
    vec3 ecPosition = vec3(MVMatrix * MCvertex);
    vec3 tnorm      = normalize(NormalMatrix * MCnormal);
    vec3 lightVec   = normalize(LightPosition - ecPosition);
    vec3 reflectVec = reflect(-lightVec, tnorm);
    vec3 viewVec    = normalize(-ecPosition);
    float diffuse   = max(dot(lightVec, tnorm), 0.0);
    float spec      = 0.0;

    if (diffuse > 0.0)
    {
        spec = max(dot(reflectVec, viewVec), 0.0);
        spec = pow(spec, 16.0);
    }

    LightIntensity  = DiffuseContribution * diffuse +
                      SpecularContribution * spec;

    MCposition      = MCvertex.xy;
    gl_Position     = MVPMatrix * MCvertex;
}
```

6.3 Fragment Shader

The typical purpose of a fragment shader is to compute the color to be applied to a fragment or to compute the depth value for the fragment or

both. In this case (and indeed with most fragment shaders), we're concerned only about the color of the fragment. We're perfectly happy using the depth value that's been computed by the OpenGL rasterization stage. Therefore, the entire purpose of this shader is to compute the color of the current fragment.

Our brick fragment shader starts off by defining a few more uniform variables than did the vertex shader. The brick pattern that will be rendered on our geometry is parameterized to make it easier to modify. The parameters that are constant across an entire primitive can be stored as uniform variables and initialized (and later modified) by the application. This makes it easy to expose these controls to the end user for modification through user interface elements such as sliders and color pickers. The brick fragment shader uses the parameters that are illustrated in Figure 6.1. These are defined as uniform variables as follows:

```
uniform vec3  BrickColor, MortarColor;
uniform vec2  BrickSize;
uniform vec2  BrickPct;
```

We want our brick pattern to be applied consistently to our geometry in order to have the object look the same no matter where it is placed in the scene or how it is rotated. The key to determining the placement of the brick pattern is the modeling coordinate position that is computed by the vertex shader and passed in the in variable *MCposition*:

```
in vec2       MCposition;
```

This variable was computed at each vertex by the vertex shader in the previous section, and it is interpolated across the primitive and made available to the fragment shader at each fragment location. Our fragment shader can use this information to determine where the fragment location is in relation to the algorithmically defined brick pattern. The other in variable that is provided as input to the fragment shader is defined as follows:

```
in float      LightIntensity;
```

This in variable contains the interpolated value for the light intensity that we computed at each vertex in our vertex shader. Note that both of the in variables in our fragment shader are defined with the same type that was used to define them in our vertex shader. A link error would be generated if this were not the case.

The purpose of this fragment shader is to calculate the fragment color. We define an out variable ***FragColor***.

```
out vec4      FragColor;
```

With our uniform, in, and out variables defined, we can begin with the actual code for the brick fragment shader.

```
void main()
{
    vec3  color;
    vec2  position, useBrick;
```

In this shader, we do things more like we would in C and define all our local variables before they're used at the beginning of our **main** function. In some cases, this can make the code a little cleaner or easier to read, but it is mostly a matter of personal preference and coding style. The first actual line of code in our brick fragment shader computes values for the local **vec2** variable *position*:

```
    position = MCposition / BrickSize;
```

This statement divides the fragment's *x* position in modeling coordinates by the brick column width and the *y* position in modeling coordinates by the brick row height. This gives us a "brick row number" (*position.y*) and a "brick number" within that row (*position.x*). Keep in mind that these are signed, floating-point values, so it is perfectly reasonable to have negative row and brick numbers as a result of this computation.

Next, we use a conditional to determine whether the fragment is in a row of bricks that is offset (see Figure 6.3):

```
    if (fract(position.y * 0.5) > 0.5)
        position.x += 0.5;
```

The "brick row number" (*position.y*) is multiplied by 0.5, the integer part is dropped by the **fract** function, and the result is compared to 0.5. Half the time (or every other row), this comparison is true, and the "brick number" value (*position.x*) is incremented by 0.5 to offset the entire row by half the width of a brick. This is illustrated by the graph in Figure 6.3.

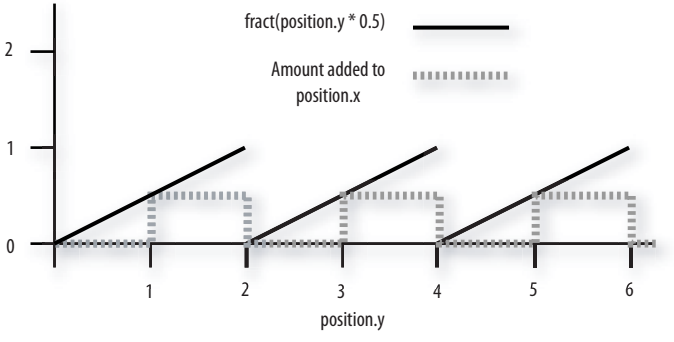


Figure 6.3 A graph of the function **fract**(*position.y* * 0.5) shows how the even/odd row determination is made. The result of this function is compared against 0.5. If the value is greater than 0.5, a value of 0.5 is added to *position.x*; otherwise, nothing is added. The result is that rows whose integer values are 1, 3, 5, …, are shifted half a brick position to the right.

Following this, we compute the fragment's location within the current brick.

```
position = fract(position);
```

This computation gives us the vertical and horizontal position within a single brick. This position serves as the basis for determining whether to use the brick color or the mortar color.

Figure 6.4 shows how we might visualize the results of the fragment shader to this point. If we were to apply this shader to a square with modeling coordinates of (–1.0, –1.0) at the lower-left corner and (1.0, 1.0) at the upper right, our partially completed shader would show the beginnings of the brick pattern we're after. Because the overall width of the square is 2.0 units in modeling coordinates, our division of *MCposition.x* by *BrickSize.x* gives us 2.0 / 0.3, or roughly six and two-thirds bricks across, as we see in Figure 6.4. Similarly, the division of *MCposition.y* by *BrickSize.y* gives us 2.0 / 0.15, or roughly thirteen and two-thirds rows of bricks from top to bottom. For this illustration, we shaded each fragment by summing the fractional part of *position.x* and *position.y*, multiplying the result by 0.5, and then storing this value in the red, green, and blue components of *FragColor*.

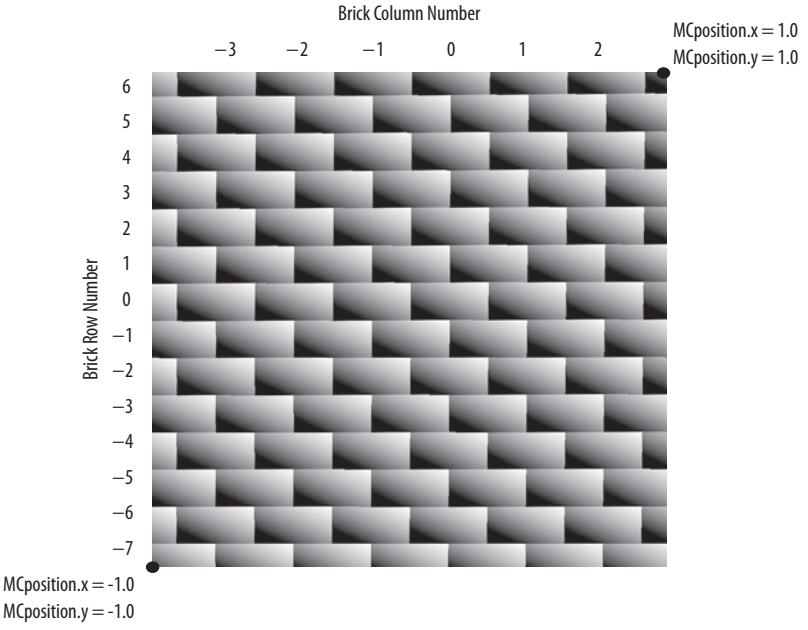


Figure 6.4 Intermediate results of brick fragment shader

To complete our brick shader, we need a function that gives us a value of 1.0 when the brick color should be used and 0 when the mortar color should be used. If we can achieve this, we can end up with a simple way to choose the appropriate color. We know that we're working with a horizontal component of the brick texture function and a vertical component. If we can create the desired function for the horizontal component and the desired function for the vertical component, we can just multiply the two values together to get our final answer. If the result of either of the individual functions is 0 (mortar color), the multiplication causes the final answer to be 0; otherwise, it is 1.0, and the brick color is used.

We use the **step** function to achieve the desired effect. The **step** function takes two arguments, an edge (or threshold) and a parameter to test against that edge. If the value of the parameter to be tested is less than the edge value, the function returns 0; otherwise, it returns 1.0. (Refer to Figure 5.11 for a graph of this function.) In typical use, the **step** function produces a pattern of pulses (i.e., a square wave) whereby the function starts at 0 and rises to 1.0 when the threshold is reached. We can get a function that starts at 1.0 and drops to 0 just by reversing the order of the two arguments provided to this function.

```
    useBrick = step(position, BrickPct);
```

In this line of code, we compute two values that tell us whether we are in the brick or in the mortar in the horizontal direction (*useBrick.x*) and in the vertical direction (*useBrick.y*). The built-in function **step** produces a value of 0 when *BrickPct.x* < *position.x* and a value of 1.0 when *BrickPct.x* >= *position.x*. Because of the **fract** function, we know that *position.x* varies from (0,1). The variable *BrickPct* is a uniform variable, so its value is constant across the primitive. This means that the value of *useBrick.x* is 1.0 when the brick color should be used and 0 when the mortar color should be used as we move horizontally. The same thing is done in the vertical direction, with *position.y* and *BrickPct.y* computing the value for *useBrick.y*. By multiplying *useBrick.x* by *useBrick.y*, we can get a value of 0 or 1.0 that lets us select the appropriate color for the fragment. The periodic step function for the horizontal component of the brick pattern is illustrated in Figure 6.5.

The values of *BrickPct.x* and *BrickPct.y* can be computed by the application to give a uniform mortar width in both directions based on the ratio of column width to row height, or the values can be chosen arbitrarily to give a mortar appearance that looks right.

All that remains is to compute our final color value and store it in the out variable *FragColor*.

```
    color  = mix(MortarColor, BrickColor, useBrick.x * useBrick.y);
    color *= LightIntensity;
    FragColor = vec4(color, 1.0);
}
```

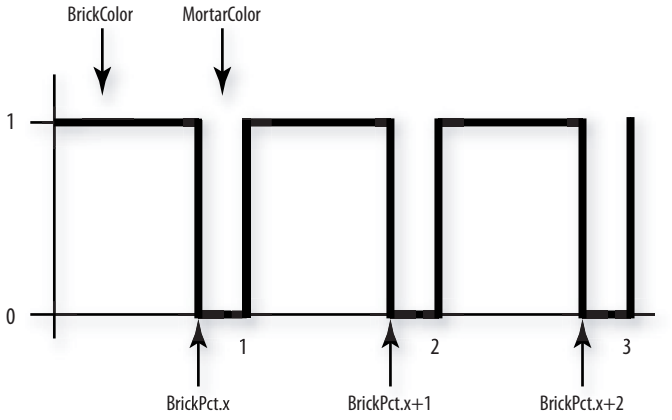


Figure 6.5 The periodic step function that produces the horizontal component of the procedural brick pattern

Here we compute the color of the fragment and store it in the local variable *color*. We use the built-in function **mix** to choose the brick color or the mortar color, depending on the value of *useBrick.x * useBrick.y*. Because *useBrick.x* and *useBrick.y* can have values of only 0 (mortar) or 1.0 (brick), we choose the brick color only if both values are 1.0; otherwise, we choose the mortar color.

The resulting value is then multiplied by the light intensity, and that result is stored in the local variable *color*. This local variable is a **vec3**, and *FragColor* is defined as a **vec4**, so we create our final color value by using a constructor to add a fourth component (alpha) equal to 1.0 and assign the result to the out variable *FragColor*.

The source code for the complete fragment shader is shown in Listing 6.2.

Listing 6.2 Source code for brick fragment shader

```
#version 140

uniform vec3  BrickColor, MortarColor;
uniform vec2  BrickSize;
uniform vec2  BrickPct;

in vec2       MCposition;
in float      LightIntensity;

out vec4      FragColor;

void main()
{
    vec3  color;
    vec2  position, useBrick;
```

```
    position = MCposition / BrickSize;

    if (fract(position.y * 0.5) > 0.5)
        position.x += 0.5;

    position = fract(position);

    useBrick = step(position, BrickPct);
//
    color  = mix(MortarColor, BrickColor, useBrick.x * useBrick.y);
    color *= LightIntensity;
    FragColor = vec4(color, 1.0);
}
```

When comparing this shader to the vertex shader in the previous example, we notice one of the key features of the OpenGL Shading Language, namely, that the language used to write these two shaders is almost identical. Both shaders have a main function, some uniform variables, and some local variables; expressions are the same; built-in functions are called in the same way; constructors are used in the same way; and so on. The only perceptible differences exhibited by these two shaders are (A) the vertex shader accesses generic attribute variables through user-defined in variables, such as *MCvertex* and *MCnormal*, (B) the vertex shader writes to the built-in variable *gl_Position*, whereas the fragment shader writes to the user-defined out variable *FragColor*, and (C) the out variables ***LightIntensity*** and ***MCposition*** are written by the vertex shader, and the fragment shader reads the in variables ***LightIntensity*** and ***MCposition***.

The application code to create and use these shaders is shown in Section 7.13, after the OpenGL Shading Language API has been presented. The result of rendering some simple objects with these shaders is shown in Figure 6.6. A color version of the result is shown in Color Plate 34.

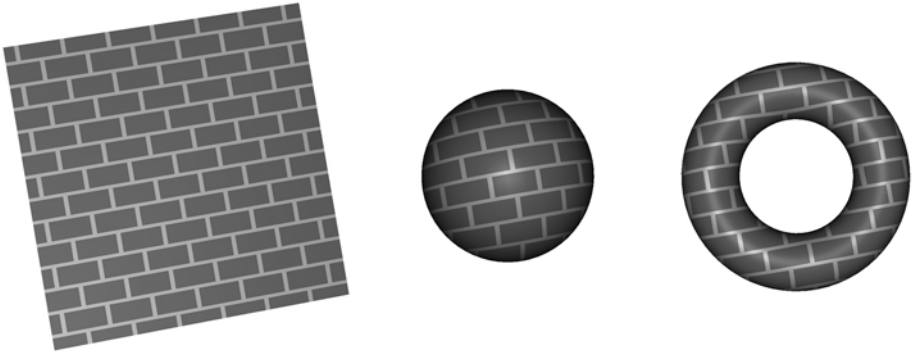


Figure 6.6 A flat polygon, a sphere, and a torus rendered with the brick shaders

6.4 Observations

A couple of problems with our shader make it unfit for anything but the simplest cases. Because the brick pattern is computed with the modeling coordinates of the incoming object, the apparent size of the bricks depends on the size of the object in modeling coordinates. The brick pattern might look fine with some objects, but the bricks may turn out much too small or much too large on other objects. At the very least, we should probably have a uniform variable in the vertex shader to scale the modeling coordinates. The application could allow the end user to adjust the scale factor to make the brick pattern look good on the object being rendered.

Another potential issue is that we've chosen to base the brick pattern on the object's x and y coordinates in modeling space. This can result in some unrealistic-looking effects on objects that aren't as regular as the objects shown in Figure 6.6. By using only the x and y coordinates of the object, we end up modeling bricks that are infinitely deep. The brick pattern looks fine when viewed from the front of the object, but when you look at it from the side, you'll be able to see how the brick extends in depth. To get a truly three-dimensional brick shader, we'd need to add a third dimension to our procedural texture calculation and use the z component of the position in modeling coordinates to determine whether we were in brick or mortar in the z dimension as well (see if you can modify the shaders to do this).

If we look closely at our brick pattern, we also notice aliasing artifacts (jaggies) along the transition from brick color to mortar color. These artifacts are due to the **step** function causing an instantaneous change from 0 to 1.0 (or from 1.0 to 0) when we cross the transition point between brick color and mortar color. Our shader has no alternative but to pick one color or the other for each fragment, and, because we cannot sample at a high enough frequency to represent this instantaneous change at the brick/mortar border, aliasing artifacts occur. Instead of using the **step** function, we could have used the built-in **smoothstep** function. This function is like the **step** function, except that it defines two edges and a smooth interpolation between 0 and 1.0 between those two edges. This would have the effect of blurring the transition between the brick color and the mortar color, thus making the aliasing artifacts much less noticeable. A method for analytically antialiasing the procedural brick texture is described in Section 17.4.5.

Despite these shortcomings, our brick shaders are perfectly good examples of a working OpenGL shader. Together, our brick vertex and fragment shaders illustrate a number of the interesting features of the OpenGL Shading Language.

6.5 Summary

This chapter has applied the language concepts from previous chapters to the development of working shaders that create a procedurally defined brick pattern. The vertex shader is responsible for transforming the vertex position, passing along the modeling coordinate position of the vertex, and computing a light intensity value at each vertex, using a single simulated light source. The fragment shader is responsible for determining whether each fragment should be brick color or mortar color. Once this determination is made, the light intensity value is applied to the chosen color, and the final color value is passed from the fragment shader so that it can ultimately be written in the framebuffer. The source code for these two shaders was discussed line by line to explain clearly how they work. This pair of shaders illustrates many of the features of the OpenGL Shading Language and can be used as a springboard for doing bigger and better things with the language.

6.6 Further Information

This shader and others are available from the 3Dlabs developer Web site. Source code for getting started with OpenGL shaders is also available.

[1] *Former 3Dlabs developer Web site*. Now at http://3dshaders.com.

[2] Baldwin, Dave, *OpenGL 2.0 Shading Language White Paper, Version 1.0*, 3Dlabs, October, 2001.

[3] Ebert, David S., John Hart, Bill Mark, F. Kenton Musgrave, Darwyn Peachey, Ken Perlin, and Steven Worley, *Texturing and Modeling: A Procedural Approach, Third Edition*, Morgan Kaufmann Publishers, San Francisco, 2002. www.texturingandmodeling.com

[4] Kessenich, John, Dave Baldwin, and Randi Rost, *The OpenGL Shading Language, Version 1.40*, 3Dlabs/Intel, March 2008. www.opengl.org/documentation/specs/

[5] Segal, Mark, and Kurt Akeley, *The OpenGL Graphics System: A Specification (Version 3.1)*, Editor (v1.1): Chris Frazier, (v1.2–3.1): Jon Leech, (v2.0): Jon Leech and Pat Brown, March 2008. www.opengl.org/documentation/specs/

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