Chapter 5: Cg and NVIDIA

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This chapter covers both Cg and NVIDIA's mainstream GPU shading and rendering hardware.

First the chapter explains NVIDIA's Cg Programming Language for programmable graphics hardware. Cg provides broad shader portability across a range of graphics hardware functionality (supporting programmable GPUs spanning the DirectX 8 and DirectX 9 feature sets). Shaders written in Cg can be used with OpenGL or Direct3D; Cg is API-neutral and does not tie your shader to a particular 3D API or platform. For example, Direct3D programmers can re-compile Cg programs with Microsoft's HLSL language implementation. Cg supports all versions of Windows (including legacy NT 4.0 and Windows 95 versions), Linux, Apple's OS X for the Macintosh, Sun's Solaris, and Sony's PlayStation 3.

Collected in this chapter are the following Cg-related articles:

- *Cg in Two Pages*: As the title indicates, this article summaries Cg in just two pages, including one vertex and one fragment program example.

- *Cg: A system for programming graphics hardware in a C-like language*: This longer SIGGRAPH 2002 paper explains the design rationale for Cg.

- *A Follow-up Cg Runtime Tutorial for Readers of The Cg Tutorial*: This article presents a complete but simple ANSI C program that uses OpenGL, GLUT, and the Cg runtime to render a bump-mapped torus using Cg vertex and fragment shaders from Chapter 8 of *The Cg Tutorial*. It's easier than you think to integrate Cg into your application; this article explains how!

- *Re-implementing the Follow-up Cg Runtime Tutorial with CgFX*: This follow-up to the previous article re-implements the bump-mapped torus using the CgFX shading system. Learn how to decouple your shading content from application code. NEW

- *Comparison Tables for HLSL, OpenGL Shading Language, and Cg*: Are you looking for a side-by-side comparison of the various features of the several different hardware-accelerated shading languages available to you today? UPDATED

Second this chapter provides details about NVIDIA's GPU hardware architecture and API support. NVIDIA's latest GPUs are designed to fully support the rendering and shading features of both DirectX 9.0c and OpenGL 2.0. NVIDIA provides 3D game and application developers your choice of high-level shading languages (Cg, OpenGL Shading Language, or DirectX 9 HLSL) as well as full support for low-level assembly interfaces to shading.

Collected in this chapter are the following NVIDIA GPU-related articles:

- *GeForce 6 Architecture*: This paper, re-printed from *GPU Gems 2*, is the most detailed publicly available description of NVIDIA GeForce 6 Series of GPUs.

- *NVIDIA GPU Historical Data*: This two page table collects performance data over a 7-year period on NVIDIA GPUs. This table presents the historical basis for expecting continuing graphics hardware performance improvements. What do the financial types always say? Past performance is not a guarantee of future return. UPDATED

- *NVIDIA OpenGL 2.0 Support:* The GeForce 6 Series has the broadest hardware support for OpenGL 2.0 available at the time these notes were prepared. Key OpenGL 2.0 hardware-accelerated features include fully-general non-power-of-two textures, multiple draw buffers (also known as multiple render targets or MRT), two-sided stencil testing, OpenGL Shading Language (GLSL), GLSL support for vertex textures, GLSL support for both per-vertex *and* per-fragment dynamic branching, separate blend equations, and points sprites.

Cg in Two Pages

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1. Cg by Example

Cg is a language for programming GPUs. Cg programs look a lot like C programs. Here is a Cg vertex program:

```
void simpleTransform(float4 objectPosition : POSITION,
                     float4 color          : COLOR,
                     float4 decalCoord     : TEXCOORD0,
                     float4 lightMapCoord  : TEXCOORD1,
                 out float4 clipPosition   : POSITION,
                 out float4 oColor         : COLOR,
                 out float4 oDecalCoord    : TEXCOORD0,
                 out float4 oLightMapCoord : TEXCOORD1,
             uniform float brightness,
             uniform float4x4 modelViewProjection)
{
  clipPosition = mul(modelViewProjection, objectPosition);
  oColor = brightness * color;
  oDecalCoord = decalCoord;
  oLightMapCoord = lightMapCoord;
}
```

1.1 Vertex Program Explanation

The program transforms an object-space position for a vertex by a 4x4 matrix containing the concatenation of the modeling, viewing, and projection transforms. The resulting vector is output as the clip-space position of the vertex. The per-vertex color is scaled by a floating-point parameter prior to output. Also, two texture coordinate sets are passed through unperturbed.

Cg supports scalar data types such as `float` but also has first-class support for vector data types. `float4` represents a vector of four floats. `float4x4` represents a matrix. `mul` is a standard library routine that performs matrix by vector multiplication. Cg provides function overloading like C++; `mul` is an overloaded function so it can be used to multiply all combinations of vectors and matrices.

Cg provides the same operators as C. Unlike C however, Cg operators accept and return vectors as well as scalars. For example, the scalar, `brightness`, scales the vector, `color`, as you would expect.

In Cg, declaring a parameter with the `uniform` modifier indicates that its value is initialized by an external source that will not vary over a given batch of vertices. In this respect, the `uniform` modifier in Cg is different from the `uniform` modifier in RenderMan but used in similar contexts. In practice, the external source is some OpenGL or Direct3D state that your application takes care to load appropriately. For example, your application must supply the `modelViewProjection` matrix and the `brightness` scalar. The Cg runtime library provides an API for loading your application state into the appropriate API state required by the compiled program.

The `POSITION`, `COLOR`, `TEXCOORD0`, and `TEXCOORD1` identifiers following the `objectPosition`, `color`, `decalCoord`, and `lightMapCoord` parameters are input semantics. They indicate how their parameters are initialized by per-vertex varying data. In OpenGL, `glVertex` commands feed the `POSITION` input semantic; `glColor` commands feed the `COLOR` semantic; glMultiTexCoord commands feed the `TEXCOORD`*n* semantics.

The `out` modifier indicates that `clipPosition`, `oColor`, oDecalCoord, and `oLightMapCoord` parameters are output by the program. The semantics that follow these parameters are therefore output semantics. The respective semantics indicate the program outputs a transformed clip-space position and a scaled color. Also, two sets of texture coordinates are passed through. The resulting vertex is feed to primitive assembly to eventually generate a primitive for rasterization.

Compiling the program requires the program source code, the name of the entry function to compile (`simpleTransform`), and a profile name (`vs_1_1`).

The Cg compiler can then compile the above Cg program into the following DirectX 8 vertex shader:

```
vs.1.1
mov oT0, v7
mov oT1, v8
dp4 oPos.x, c1, v0
dp4 oPos.y, c2, v0
dp4 oPos.z, c3, v0
dp4 oPos.w, c4, v0
mul oD0, c0.x, v5
```

The profile indicates for what API execution environment the program should be compiled. This same program can be compiled for the DirectX 9 vertex shader profile (`vs_2_0`), the multi-vendor OpenGL vertex program extension (`arbvp1`), or NVIDIA-proprietary OpenGL extensions (`vp20` & `vp30`).

The process of compiling Cg programs can take place during the initialization of your application using Cg. The Cg runtime contains the Cg compiler as well as API-dependent routines that greatly simplify the process of configuring your compiled program for use with either OpenGL or Direct3D.

1.2 Fragment Program Explanation

In addition to writing programs to process vertices, you can write programs to process fragments. Here is a Cg fragment program:

```
float4 brightLightMapDecal(float4 color         : COLOR,
                           float4 decalCoord    : TEXCOORD0,
                           float4 lightMapCoord : TEXCOORD1,
                   uniform sampler2D decal,
                   uniform sampler2D lightMap) : COLOR
{
  float4 d = tex2Dproj(decal, decalCoord);
  float4 lm = tex2Dproj(lightMap, lightMapCoord);
  return 2.0 * color * d * lm;
}
```

The input parameters correspond to the interpolated color and two texture coordinate sets as designated by their input semantics.

The `sampler2D` type corresponds to a 2D texture unit. The Cg standard library routine `tex2Dproj` performs a projective 2D texture lookup. The two `tex2Dproj` calls sample a decal and light map texture and assign the result to the local variables, `d` and `lm`, respectively.

The program multiplies the two textures results, the interpolated color, and the constant 2.0 together and returns this RGBA color.

The program returns a `float4` and the semantic for the return value is `COLOR`, the final color of the fragment.

The Cg compiler generates the following code for `brightLightMapDecal` when compiled with the `arbfp1` multi-vendor OpenGL fragment profile:

```
!!ARBfp1.0
PARAM c0 = {2, 2, 2, 2}; TEMP R0; TEMP R1; TEMP R2;
TXP R0, fragment.texcoord[0], texture[0], 2D;
TXP R1, fragment.texcoord[1], texture[1], 2D;
MUL R2, c0.x, fragment.color.primary;
MUL R0, R2, R0;
MUL result.color, R0, R1;
END
```

This same program also compiles for the DirectX 8 and 9 profiles (`ps_1_3` & `ps_2_x`) and NVIDIA-proprietary OpenGL extensions (`fp20` & `fp30`).

2. Other Cg Functionality

2.1 Features from C

Cg provides structures and arrays, including multi-dimensional arrays. Cg provides all of C's arithmetic operators (`+`, `*`, `/`, etc.). Cg provides a `boolean` type and boolean and relational operators (`||`, `&&`, `!`, etc.). Cg provides increment/decrement (`++`/`--`) operators, the conditional expression operator (`?:`), assignment expressions (`+=`, etc.), and even the C comma operator.

Cg provides user-defined functions (in addition to pre-defined standard library functions), but recursive functions are not allowed. Cg provides a subset of C's control flow constructs (`do`, `while`, `for`, `if`, `break`, `continue`); other constructs such as `goto` and `switch` are not supported in current the current Cg implementation but the necessary keywords are reserved.

Like C, Cg does not mandate the precision and range of its data types. In practice, the profile chosen for compilation determines the concrete representation for each data type. `float`, `half`, and `double` are meant to represent continuous values, ideally in floating-point, but this can depend on the profile. `half` is intended for a 16-bit half-precision floating-point data type. (NVIDIA's CineFX architecture provides such a data type.) `int` is an integer data type, usually used for looping and indexing. `fixed` is an additional data type intended to represent a fixed-point continuous data type that may not be floating-point.

Cg provides `#include`, `#define`, `#ifdef`, etc. matching the C preprocessor. Cg supports C and C++ comments.

2.2 Additional Features Not in C

Cg provides built-in constructors (similar to C++ but not user-defined) for vector data types:

```
float4 vec1 = float4(4.0, -2.0, 5.0, 3.0);
```

Swizzling is a way of rearranging components of vector values and constructing shorter or longer vectors. Example:

```
float2 vec2 = vec1.yx;        // vec2 = (-2.0, 4.0)
float scalar = vec1.w;        // scalar = 3.0
float3 vec3 = scalar.xxx;     // vec3 = (3.0, 3.0, 3.0)
```

More complicated swizzling syntax is available for matrices. Vector and matrix elements can also be accessed with standard array indexing syntax as well.

Write masking restricts vector assignments to indicated components. Example:

```
vec1.xw = vec3;  // vec1 = (3.0, -2.0, 5.0, 3.0)
```

Use either `.xyzw` or `.rgba` suffixes swizzling and write masking.

The Cg standard library includes a large set of built-in functions for mathematics (`abs`, `dot`, `log2`, `reflect`, `rsqrt`, etc.) and texture access (`texCUBE`, `tex3Dproj`, etc.). The standard library makes extensive use of function overloading (similar to C++) to support different vector lengths and data types. There is no need to use `#include` to obtain prototypes for standard library routines as in C; Cg standard library routines are automatically prototyped.

In addition to the `out` modifier for *call-by-result* parameter passing, the `inout` modifier treats a parameter as both a *call-by-value* input parameter and a *call-by-result* output parameter.

The `discard` keyword is similar to `return` but aborts the processing without returning a transformed fragment.

2.3 Features Not Supported

Cg has no support currently for pointers or bitwise operations (however, the necessary C operators and keywords are reserved for this purpose). Cg does not (currently) support unions and function variables.

Cg lacks C++ features for "programming in the large" such as classes, templates, operator overloading, exception handling, and namespaces.

The Cg standard library lacks routines for functionality such as string processing, file input/output, and memory allocation, which is beyond the specialized scope of Cg.

However, Cg reserves all C and C++ keywords so that features from these languages could be incorporated into future implementations of Cg as warranted.

3. Profile Dependencies

When you compile a C or C++ program, you expect it to compile without regard to how big (within reason) the program is or what the program does. With Cg, a syntactically and semantically correct program may still not compile due to limitations of the profile for which you are compiling the program.

For example, it is currently an error to access a texture when compiling with a vertex profile. Future vertex profiles may well allow texture accesses, but existing vertex profiles do not. Other errors are more inherent. For example, a fragment profile should not output a parameter with a `TEXCOORD0` semantic. Other errors may be due to exceeding a capacity limit of current GPUs such as the maximum number of instructions or the number of texture units available.

Understand that these profile dependent errors do not reflect limitations of the Cg language, but rather limitations of the current implementation of Cg or the underlying hardware limitations of your target GPU.

4. Compatibility and Portability

NVIDIA's Cg implementation and Microsoft's High Level Shader Language (HLSL) are very similar as they were co-developed. HLSL is integrated with DirectX 9 and the Windows operating system. Cg provides support for multiple APIs (OpenGL, Direct X 8, and Direct X 9) and multiple operating systems (Windows, Linux, and Mac OS X). Because Cg interfaces to multi-vendor APIs, Cg runs on GPUs from multiple vendors.

5. More Information

Read the *The Cg Tutorial: The Definitive Guide to Programmable Real-Time Graphics* (ISBN 0321194969) published by Addison-Wesley.

Cg: A system for programming graphics hardware in a C-like language

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Abstract

The latest real-time graphics architectures include programmable floating-point vertex and fragment processors, with support for data-dependent control flow in the vertex processor. We present a programming language and a supporting system that are designed for programming these stream processors. The language follows the philosophy of C, in that it is a hardware-oriented, general-purpose language, rather than an application-specific shading language. The language includes a variety of facilities designed to support the key architectural features of programmable graphics processors, and is designed to support multiple generations of graphics architectures with different levels of functionality. The system supports both of the major 3D graphics APIs: OpenGL and Direct3D. This paper identifies many of the choices that we faced as we designed the system, and explains why we made the decisions that we did.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture; D.3.4 [Programming Languages]: Processors – Compilers and code generation I.3.1 [Computer Graphics]: Hardware Architecture—Graphics processors; I.3.6 [Computer Graphics]: Methodology and Techniques—Languages

1 Introduction

Graphics architectures are now highly programmable, and support application-specified assembly language programs for both vertex processing and fragment processing. But it is already clear that the most effective tool for programming these architectures is a high level language. Such languages provide the usual benefits of program portability and improved programmer productivity, and they also make it easier develop programs incrementally and interactively, a benefit that is particularly valuable for shader programs.

In this paper we describe a system for programming graphics hardware that supports programs written in a new C-like language named Cg. The Cg language is based on both the syntax and the philosophy of C [Kernighan and Ritchie 1988]. In particular, Cg is intended to be general-purpose (as much as is possible on graphics hardware), rather than application specific, and is a hardware-oriented language. As in C, most data types and operators have an obvious mapping to hardware operations, so that it is easy to write high-performance code. Cg includes a variety of new features designed to efficiently support the unique architectural characteristics of programmable graphics processors. Cg also adopts a few features from C++ [Stroustrup 2000] and Java [Joy et al. 2000], but unlike these languages Cg is intended to be a language for "programming in the small," rather than "programming in the large."

Cg is most commonly used for implementing shading algorithms (Figure 1), but Cg is not an application-specific shading language in the sense that the RenderMan shading language [Hanrahan and Lawson 1990] or the Stanford real-time shading language (RTSL) [Proudfoot et al. 2001] are. For example, Cg omits high-level shading-specific facilities such as built-in support for separate surface and light shaders. It also omits specialized data types for colors and points, but supports general-purpose user-defined compound data types such as structs and arrays.

As is the case for almost all system designs, most features of the Cg language and system are not novel when considered individually. However, when considered as a whole, we believe that the system and its design goals are substantially different from any previously-implemented system for programming graphics hardware.

The design, implementation, and public release of the Cg system has occurred concurrently with the design and development of similar systems by 3Dlabs [2002], the OpenGL ARB [Kessenich et al. 2003], and Microsoft [2002b]. There has been significant cross-pollination of ideas between the different efforts, via both public and private channels, and all four systems have improved as a result of this exchange. We will discuss some of the remaining similarities and differences between these systems throughout this paper.

This paper discusses the Cg programmer interfaces (i.e. Cg language and APIs) and the high-level Cg system architecture. We focus on describing the key design choices that we faced and on explaining why we made the decisions we did, rather than providing a language tutorial or describing the system's detailed implementation and internal architecture. More information about the Cg language is available in the language specification [NVIDIA Corp. 2003a] and tutorial [Fernando and Kilgard 2003].

Figure 1: *Screen captures from a real-time Cg demo running on an NVIDIA GeForce™FX. The procedural paint shader makes the car's surface rustier as time progresses.*

2 Background

Off-line rendering systems have supported user-programmable components for many years. Early efforts included Perlin's pixel-stream editor [1985] and Cook's shade-tree system [1984].

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Today, most off-line rendering systems use the RenderMan shading language, which was specifically designed for procedural computation of surface and light properties.

In real-time rendering systems, support for user programmability has evolved with the underlying graphics hardware. The UNC PixelFlow architecture [Molnar et al. 1992] and its accompanying PFMan procedural shading language [Olano and Lastra 1998] and rendering API [Leech 1998] demonstrated the utility of real-time procedural shading capabilities. Commercial systems are only now reaching similar levels of flexibility and performance.

For many years, mainstream commercial graphics hardware was configurable, but not user programmable (e.g. RealityEngine [Akeley 1993]). SGI's OpenGL shader system [Peercy et al. 2000] and Quake III's shading language [Jaquays and Hook 1999] targeted the fragment-processing portion of this hardware using multipass rendering techniques, and demonstrated that mainstream developers would use higher-level tools to program graphics hardware.

Although multipass rendering techniques can map almost any computation onto hardware with just a few basic capabilities [Peercy et al. 2000], to perform well multipass techniques require hardware architectures with a high ratio of memory bandwidth to arithmetic units. But VLSI technology trends are driving systems in the opposite direction: arithmetic capability is growing faster than off-chip bandwidth [Dally and Poulton 1998].

In response to this trend, graphics architects began to incorporate programmable processors into both the vertex-processing and fragment-processing stages of single-chip graphics architectures [Lindholm et al. 2001]. The Stanford RTSL system [Proudfoot et al. 2001] was designed for this type of programmable graphics hardware. Earlier real-time shading systems had focused on fragment computations, but RTSL supports vertex computations as well. Using RTSL, a user writes a single program, but may specify whether particular computations should be mapped to the vertex processor or the fragment processor by using special data-type modifiers.

The most recent generation of PC graphics hardware (*DirectX 9* or *DX9* hardware, announced in 2002), continues the trend of adding additional programmable functionality to both the fragment and the vertex processors (Figure 2). The fragment processor adds flexible support for floating-point arithmetic and computed texture coordinates [Mitchell 2002; NVIDIA Corp. 2003b]. Of greater significance for languages and compilers, the vertex processor in some of these architectures departs from the previous SIMD programming model, by adding conditional branching functionality [NVIDIA Corp. 2003c]. This branching capability cannot be easily supported by RTSL for reasons that we will discuss later.

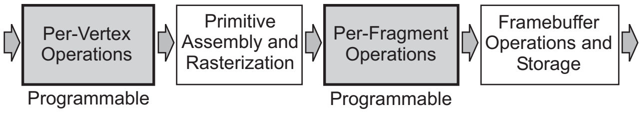

Figure 2: *Current graphics architectures* (DX9-class architectures) *include programmable floating-point vertex and fragment processors.*

Despite these advances in PC graphics architectures, they cannot yet support a complete implementation of C, as the SONY PlayStation 2 architecture does for its vertex processor that resides on a separate chip [Codeplay Corporation 2003].

Thus, by early 2001, when our group at NVIDIA began to experiment with programming languages for graphics hardware, it was clear that developers would need a high-level language to use future hardware effectively, but that each of the existing languages had significant shortcomings. Microsoft was interested in addressing this same problem, so the two companies collaborated on the design of a new language. NVIDIA refers to its implementation of the language, and the system that supports it, as Cg. In this paper, we consider the design of the Cg language and the design of the system that surrounds and supports it.

3 Design Goals

The language and system design was guided by a handful of high-level goals:

- **Ease of programming.**
  Programming in assembly language is slow and painful, and discourages the rapid experimentation with ideas and the easy reuse of code that the off-line rendering community has already shown to be crucial for shader design.
- **Portability.**
  We wanted programs to be portable across hardware from different companies, across hardware generations (for DX8-class hardware or better), across operating systems (Windows, Linux, and MacOS X), and across major 3D APIs (OpenGL [Segal and Akeley 2002] and DirectX [Microsoft Corp. 2002a]). Our goal of portability across APIs was largely motivated by the fact that GPU programs, and especially "shader" programs, are often best thought of as art assets – they are associated more closely with the 3D scene model than they are with the actual application code. As a result, a particular GPU program is often used by multiple applications (e.g. content-creation tools), and on different platforms (e.g. PCs and entertainment consoles).
- **Complete support for hardware functionality.**
  We believed that developers would be reluctant to use a high-level language if it blocked access to functionality that was available in assembly language.
- **Performance.**
  End users and developers pay close attention to the performance of graphics systems. Our goal was to design a language and system architecture that could provide performance equal to, or better than, typical hand-written GPU assembly code. We focused primarily on interactive applications.
- **Minimal interference with application data.**
  When designing any system layered between applications and the graphics hardware, it is tempting to have the system manage the scene data because doing so facilitates resource virtualization and certain global optimizations. Toolkits such as SGI's Performer [Rohlf and Helman 1994] and Electronic Arts's EAGL [Lalonde and Schenk 2002] are examples of software layers that successfully manage scene data, but their success depends on both their domain-specificity and on the willingness of application developers to organize their code in conforming ways. We wanted Cg to be usable in existing applications, without the need for substantial reorganization. And we wanted Cg to be applicable to a wide variety of interactive and non-interactive application categories. Past experience suggests that these goals are best achieved by avoiding management of scene data.
- **Ease of adoption.**
  In general, systems that use a familiar programming model and can be adopted incrementally are accepted more rapidly than systems that must be adopted on an all-or-nothing basis. For example, we wanted the Cg system to support integration of a vertex program written in Cg with a fragment program written in assembly language, and vice-versa.
- **Extensibility for future hardware.**
  Future programmable graphics architectures will be more flexible than today's architectures, and they will require

additional language functionality. We wanted to design a language that could be extended naturally without breaking backward compatibility.

- **Support for non-shading uses of the GPU.**

  Graphics processors are rapidly becoming sufficiently flexible that they can be used for tasks other than programmable transformation and shading (e.g. [Boltz et al. 2003]). We wanted to design a language that could support these new uses of GPUs.

Some of these goals are in partial conflict with each other. In cases of conflict, the goals of high performance and support for hardware functionality took precedence, as long as doing so did not fundamentally compromise the ease-of-use advantage of programming in a high-level language.

Often system designers must preserve substantial compatibility with old system interfaces (e.g. OpenGL is similar to IRIS GL). In our case, that was a non-goal because most pre-existing high level shader code (e.g. RenderMan shaders) must be modified anyway to achieve real-time performance on today's graphics architectures.

4 Key Design Decisions

4.1 A "general-purpose language", not a domain-specific "shading language"

Computer scientists have long debated the merits of domain-specific languages vs. general-purpose languages. We faced the same choice – should we design a language specifically tailored for shading computations, or a more general-purpose language intended to expose the fundamental capabilities of programmable graphics architectures?

Domain-specific languages have the potential to improve programmer productivity, to support domain-specific forms of modularity (such as surface and light shaders), and to use domain-specific information to support optimizations (e.g. disabling lights that are not visible from a particular surface). Most of these advantages are obtained by raising the language's abstraction level with domain-specific data types, operators, and control constructs.

These advantages are counterbalanced by a number of disadvantages that typically accompany a language based on higher-level abstractions. First, in contrast to a low-level language such as C, the run-time cost of language operators may not be obvious. For example, the RenderMan system may compute coordinate transformations that are not explicitly requested. Second, the language's abstraction may not match the abstraction desired by the user. For example, neither RenderMan nor RTSL can easily support OpenGL's standard lighting model because the OpenGL model uses separate light colors for the diffuse and specular light terms. Finally, if the domain-specific language abstraction does not match the underlying hardware architecture well, the language's compiler and runtime system may have to take complete control of the underlying hardware to translate between the two abstractions.

These issues – when considered with our design goals of high performance, minimal management of application data, and support for non-shading uses of GPU's – led us to develop a hardware-focused general-purpose language rather than a domain-specific shading language.

We were particularly inspired by the success of the C language in achieving goals for performance, portability, and generality of CPU programs that were very similar to our goals for a GPU language. One of C's designers, Dennis Ritchie, makes this point well [Ritchie 1993]:

> "C is quirky, flawed, and an enormous success. While accidents of history surely helped, it evidently satisfied a need for a system implementation language efficient enough to displace assembly language, yet sufficiently abstract and fluent to describe algorithms and interactions in a wide variety of environments."

These reasons, along with C's familiarity for developers, led us to use C's syntax, semantics, *and* philosophy as the initial basis for Cg's language specification. It was clear, however, that we would need to extend and modify C to support GPU architectures effectively.

Using C as the basis for a GPU language has another advantage: It provides a pre-defined evolutionary path for supporting future graphics architectures, which may include CPU-like features such as general-purpose indirect addressing. Cg reserves all C and C++ keywords so that features from these languages can be incorporated into future implementations of Cg as needed, without breaking backward compatibility.

As will become evident, Cg also selectively uses ideas from C++, Java, RenderMan, and RTSL. It has also drawn ideas from and contributed ideas to the contemporaneously-developed C-like shading languages from 3Dlabs (hereafter *3DLSL*), the OpenGL ARB (*GLSL*), and Microsoft (*HLSL*).

4.2 A program for each pipeline stage

The user-programmable processors in today's graphics architectures use a stream-processing model [Herwitz and Pomerene 1960; Stephens 1997; Kapasi et al. 2002], as shown earlier in Figure 2. In this model, a processor reads one element of data from an input stream, executes a program (*stream kernel)* that operates on this data, and writes one element of data to an output stream. For example, the vertex processor reads one untransformed vertex, executes the vertex program to transform the vertex, and writes the resulting transformed vertex to an output buffer. The output stream from the vertex processor passes through a non-programmable part of the pipeline (including primitive assembly, rasterization, and interpolation), before emerging as a stream of interpolated fragments that form the input stream to the fragment processor.

Choosing a programming model to layer on top of this stream-processing architecture was a major design question. We initially considered two major alternatives. The first, illustrated by RTSL and to a lesser extent by RenderMan, is to require that the user write a single program, with some auxiliary mechanism for specifying whether particular computations should be performed on the vertex processor or the fragment processor. The second, illustrated by the assembly-level interfaces in OpenGL and Direct3D, is to use two separate programs. In both cases, the programs consume an element of data from one stream, and write an element of data to another stream.

The unified vertex/fragment program model has a number of advantages. It encapsulates all of the computations for a shader in one piece of code, a feature that is particularly comfortable for programmers who are already familiar with RenderMan. It also allows the compiler to assist in deciding which processor will perform a particular computation. For example, in RTSL, if the programmer does not explicitly specify where a particular computation will be performed, the compiler infers the location using a set of well-defined rules. Finally, the single-program model facilitates source code modularity by allowing a single function to include related vertex and fragment computations.

However, the single-program model is not a natural match for the underlying dual-processor architecture. If the programmable processors omit support for branch instructions, the model can be effective, as RTSL demonstrated. But if the processors support branch instructions, the single-program model becomes very awkward. For example, this programming model allows arbitrary mixing of vertex and fragment operations within data-dependent loops, but the architecture can support only fragment operations within fragment loops, and only vertex operations within vertex loops. It would be possible to define auxiliary language rules that forbid intermixed loop operations, but we concluded that the result would be an unreasonably confusing programming model that would eliminate many of the original advantages of the single-program model.

As a result, we decided to use a multi-program model for Cg. Besides eliminating the difficulties with data-dependent control flow, this model's closer correspondence to the underlying GPU architecture makes it easier to for users to estimate the performance of code, and allows the use of a less-intrusive compiler and runtime system. The multi-program model also allows applications to choose the active vertex program independently from the active fragment program. This capability had been requested by application developers.

A language for expressing stream kernels

After we made the decision to use a multi-program model for Cg, we realized that we had the opportunity to both simplify and generalize the language by eliminating most of the distinctions between vertex programs and fragment programs. We developed a single language specification for writing a stream kernel (i.e. vertex program or fragment program), and then allowed particular processors to omit support for some capabilities of the language. For example, although the core language allows the use of texture lookups in any program, the compiler will issue an error if the program is compiled for any of today's vertex processors since today's vertex processors don't support texture lookups. We will explain this mechanism in more detail later, in our discussion of Cg's general mechanism for supporting different graphics architectures.

The current Cg system can be thought of as a specialized stream processing system [Stephens 1997]. Unlike general stream processing languages such as StreamIt [Thies et al. 2002] or Brook [Buck and Hanrahan 2003], the Cg system does not provide a general mechanism for specifying how to connect stream processing kernels together. Instead, the Cg system relies on the established graphics pipeline dataflow of GPUs. Vertex data sent by the application is processed by the vertex kernel (i.e. the vertex program). The results of the vertex program are passed to primitive assembly, rasterization, and interpolation. Then the resulting interpolated fragment parameters are processed by the fragment kernel (i.e. the fragment program) to generate data used by the framebuffer-test unit to update the fragment's corresponding pixel. Cg's focus on kernel programming is similar to that of Imagine KernelC [Mattson 2001]. However, if the Cg language is considered separately from the rest of the Cg system, it is only mildly specialized for stream-kernel programming and could be extended to support other parallel programming models.

A data-flow interface for program inputs and outputs

For a system with a programming model based on separate vertex and fragment programs, a natural question arises: Should the system allow any vertex program to be used with any fragment program? Since the vertex program communicates with the fragment program (via the rasterizer/interpolator), how should the vertex program outputs and fragment program inputs be defined to ensure compatibility? In effect, this communication constitutes a user-defined interface between the vertex program and the fragment program, but the interface is a data-flow interface rather than a procedural interface of the sort that C programmers are accustomed to. A similar data-flow interface exists between the application and inputs to the vertex program (i.e. vertex arrays map to vertex program input registers).

When programming GPUs at the assembly level, the interface between fragment programs and vertex programs is established at the register level. For example, the user can establish a convention that the vertex program should write the normal vector to the `TEXCOORD3` output register, so that it is available to the fragment program (after being interpolated) in its `TEXCOORD3` input register. These registers may be physical registers or virtual registers (i.e. API resources that are bound to physical registers by the driver), but in either case the binding names must be chosen from a predefined namespace with predefined data types.

Cg and HLSL support this same mechanism, which can be considered to be a modified bind-by-name scheme in which a predefined auxiliary namespace is used instead of the user-defined identifier name. This approach provides maximum control over the generated code, which is crucial when Cg is used for the program on one side of the interface but not for the program on the other side. For example, this mechanism can be used to write a fragment program in Cg that will be compatible with a vertex program written in assembly language.

Cg (but not HLSL) also supports a bind-by-position scheme. Bind-by-position requires that data be organized in an ordered list (e.g. as a function-parameter list, or a list of structure members), with the outputs in a particular position mapping to inputs in that same position. This scheme avoids the need to refer to a predefined auxiliary namespace.

GLSL uses a third scheme, pure bind-by-name, that is not supported by either Cg or HLSL. In the pure bind-by-name scheme, the binding of identifiers to actual hardware registers must be deferred until after the vertex program and fragment program have been paired, which may not happen until link time or run time. In contrast, the bind-by-position approach allows the binding to be performed at compile time, without any knowledge of the program at the other side of the interface. For this reason, performance-oriented languages such as C that are designed for separate compile and link steps have generally chosen bind-by-position instead of bind-by-name.

4.3 Permit subsetting of language

Striking a balance between the often-conflicting goals of portability and comprehensive support for hardware functionality was a major design challenge. The functionality of GPU processors is growing rapidly, so there are major differences in functionality between the different graphics architectures that Cg supports. For example, DX9-class architectures support floating-point fragment arithmetic while most DX8-class architectures do not. Some DX9-class hardware supports branching in the vertex processor while other DX9-class hardware does not. Similarly, on all recent architectures the vertex processor and fragment processor support different functionality.

We considered a variety of possible approaches to hiding or exposing these differences. When minor architectural differences could be efficiently hidden by the compiler, we did so. However, since performance is important in graphics, major architectural differences cannot reasonably be hidden by a compiler. For example, floating-point arithmetic could be emulated on a fixed-point architecture but the resulting performance would be so poor that the emulation would be worthless for most applications.

A different approach is to choose a particular set of capabilities, and mandate that any implementation of the language support all of those capabilities and no others. If the *only* system-design goal had been to maximize portability, this approach would have been the right one. GLSL currently follows this approach, although it specifies a different set of capabilities for the vertex and fragment processor. However, given our other design goals, there was no reasonable point at which we could set the feature bar. We wanted both to support the existing installed base of DX8-class hardware, and to provide access to the capabilities of the latest hardware. It could be argued that the presence of significant feature disparities is a one-time problem, but we disagree – feature disparities will persist as long as the capabilities of graphics hardware continue to improve, as we expect will happen.

Our remaining choice was to expose major architectural differences as differences in language capabilities. To minimize the impact on portability, we exposed the differences using a subsetting mechanism. Each processor is defined by a *profile* that specifies which subset of the full Cg specification is supported on that processor. Thus, program compatibility is only compromised for programs that use a feature that is not supported by all processors. For example, a program that uses texture mapping cannot be compiled with any current vertex profile. The explicit existence of this mechanism is one of the major differences between Cg and GLSL, and represents a significant difference in design philosophy. However, hardware vendors are free to implement subsets and supersets of GLSL using the OpenGL extension mechanism, potentially reducing the significance of this difference in practice.

The NVIDIA Cg compiler currently supports 18 different profiles, representing vertex and fragment processors for the DirectX 8, DirectX 9, and OpenGL APIs, along with various extensions and capability bits representing the functionality of different hardware. Although one might be concerned that this profile mechanism would make it difficult to write portable Cg programs, it is surprisingly easy to write a single Cg program that will run on all vertex profiles, or on all DX9-class fragment profiles. With care, it is even possible to write a single Cg program that will run on any fragment profile; the extra difficulty is caused by the idiosyncratic nature of DX8-class fragment hardware.

4.4 Modular system architecture

Any system has a variety of modules connected by internal and external interfaces. Taken as a whole, these constitute the system architecture. Cg's system architecture (Figure 3) includes much more than the language itself. More specifically, it includes an API that applications can use to compile and manage Cg programs (the *Cg runtime*), and several modules layered on top of existing graphics APIs.

Cg's architecture is more modular than that of the SGI, GLSL and RTSL systems but similar to that of HLSL. The architecture provides a high degree of flexibility for developers in deciding which parts of the system to use. For example, it is easy to use the complete Cg system to program the fragment processor while relying on the OpenGL API's conventional fixed-function routines to control the vertex processor. The modular nature of the system does makes it difficult to implement some optimizations that would cross module boundaries; this tradeoff is a classic one in systems design.

Metaprogramming systems (e.g. [McCool et al. 2002]), which use operator overloading to embed one language within another, have a very different system architecture. In metaprogramming systems, there is no clear boundary between the host CPU language, the embedded GPU language, and the mechanism for passing data between the two. This tight integration has some advantages, but we chose a more modular, conventional architecture for Cg. The two classes of system architectures are sufficiently different that we do not attempt to compare them in detail in this paper.

4.4.1 No mandatory virtualization

The most contentious system design question we faced was whether or not to automatically virtualize hardware resources using software-based multi-pass techniques. Current hardware limits the number of instructions, live temporary registers, bound textures, program inputs, and program outputs used by a program. Thus, without software-assisted virtualization a sufficiently complex program will exceed these limits and fail to compile. The limits on instruction count and temporary register count are potentially the most serious because the consumption of these resources is not clearly defined in a high-level language and may depend on compiler optimizations.

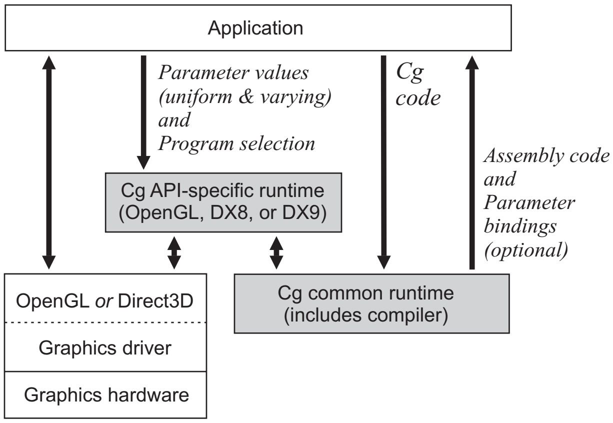

Figure 3: *Cg system architecture*

The SGI and RTSL systems demonstrated that it is possible to use multi-pass techniques to virtualize some resources for pre-DX8 hardware [Peercy et al. 2000; Proudfoot et al. 2001] and for later hardware [Chan et al. 2002]. However, we consider it to be impossible to efficiently, correctly, and automatically virtualize most DX8 architectures because the architectures use high-precision data types internally, but do not provide a high-precision framebuffer to store these data types between passes.

Despite the apparent advantages of automatic virtualization, we do not require it in the Cg language specification, and we do not support it in the current release of the Cg system. Several factors led to this decision. First, virtualization is most valuable on hardware with the fewest resources – DX8-class hardware in this case – but we had already concluded that effective virtualization of this hardware was impossible. Second, the resource limits on newer DX9-class hardware are set high enough that most programs that exceed the resource limits would run too slowly to be useful in a real-time application. Finally, virtualization on current hardware requires global management of application data and hardware resources that conflicted with our design goals. More specifically, the output from the vertex processor must be fed to the fragment processor, so multi-pass virtualization requires the system to manage simultaneously the vertex program and the fragment program, as well as all program parameters and various non-programmable graphics state. For example, when RTSL converts a long fragment program into multiple passes, it must also generate different vertex processor code for each pass.

Although Cg's language specification does not require virtualization, we took care to define the language so that it does not preclude virtualization. As long as the user avoids binding inputs and outputs to specific hardware registers, the language itself is virtualizable. For example, Cg adopts RTSL's approach of representing textures using identifiers (declared with special `sampler` types), rather than texture unit numbers, which are implicitly tied to a single rendering pass. Virtualization is likely to be useful for applications that can tolerate slow frame rates (e.g. 1 frame/sec), and for non-rendering uses of the GPU. Future hardware is likely to include better support for resource virtualization, at which point it would be easier for either the hardware driver or the Cg system to support it.

Of the systems contemporary with Cg, HLSL neither requires nor implements virtualization, and GLSL requires it only for resources whose usage is not directly visible in the language (i.e. instructions and temporary registers).

4.4.2 Layered above an assembly language interface

High level languages are generally compiled to a machine/assembly language that runs directly on the hardware. The system designers must decide whether or not to expose this machine/assembly language as an additional interface for system users. If this interface is not exposed, the high level language serves as the only interface to the programmable hardware.

With a separate assembly language interface, the system is more modular. The compiler and associated run-time system may be distributed separately from the driver, or even shipped with the application itself. Users can choose between running the compiler as a command-line tool, or invoking it through an API at application run time. By providing access to the assembly code, the system allows users to tune their code by studying the compiler output, by manually editing the compiler output, or even by writing programs entirely in assembly language. All of these capabilities can be useful for maximizing performance, although they are less important if the compiler optimizes well.

In contrast, if the high-level language is the only interface to the hardware then the compiler must be integrated into the driver. This approach allows graphics architects to change the hardware instruction set in the future. Also, by forcing the user to compile via the driver, the system can guarantee that old applications will use compiler updates included in new drivers. However, the application developer loses the ability to guarantee that a particular pre-tested version of the compiler will be used. Since optimizing compilers are complex and frequently exhibit bugs at higher optimization levels, we considered this issue to be significant. Similarly, if the developer cannot control the compiler version, there is a risk that a program's use of non-virtualized resources could change and trigger a compilation failure where there was none before.

These and other factors led us to layer the Cg system above the low-level graphics API, with an assembly language serving as the interface between the two layers. RTSL and HLSL take this same approach, while GLSL takes the opposite approach of integrating the high-level language into the graphics API and driver.

4.4.3 Explicit program parameters

All input parameters to a Cg program must be explicitly declared using non-`static` global variables or by including the parameters on the entry function's parameter list. Similarly, the application is responsible for explicitly specifying the values for the parameters. Unlike GLSL, the core Cg specification does not include pre-defined global variables such as `gl_ModelViewMatrix` that are automatically filled from classical graphics API state. Such pre-defined variables are contrary to the philosophy of C and are not portable across 3D APIs with different state. We believe that even in shading programs all state used by vertex and fragment programs ought to be programmer-defined rather than mediated by fixed API-based definitions. However, pre-defined variables can be useful for retrofitting programmability into old applications, and for that reason some Cg profiles support them.

At the assembly language level, program inputs are passed in registers or, in some cases, named parameters. In either case, the parameter passing is untyped. For example, in the `ARB_vertex_program` assembly language each program parameter consists of four floating-point values. Because the Cg system is layered on top of the assembly-language level, developers may pass parameters to Cg programs in this manner if they wish.

However, Cg also provides a set of runtime API routines that allow parameters to be passed using their true names and types. GLSL uses a similar mechanism. In effect, this mechanism allows applications to pass parameters using Cg semantics rather than assembly-language semantics. Usually, this approach is easier and less error-prone than relying on the assembly-level parameter-passing mechanisms. These runtime routines make use of a header provided by the Cg compiler on its assembly language output that specifies the mapping between Cg parameters and registers (Figure 4). There are three versions of these runtime libraries – one for OpenGL, one for DirectX 8, and one for DirectX 9. Separate libraries were necessary to accommodate underlying API differences and to match the style of the respective APIs.

```
#profile arbvp1
#program simpleTransform
#semantic simpleTransform.brightness
#semantic simpleTransform.modelViewProjection
#var float4 objectPosition : $vin.POSITION : POSITION : 0 : 1
#var float4 color : $vin.COLOR : COLOR : 1 : 1
...
#var float brightness : : c[0] : 8 : 1
#var float4x4 modelViewProjection : : c[1], 4 : 9 : 1
```

Figure 4: *The Cg compiler prepends a header to its assembly code output to describe the mapping between program parameters and registers.*

5 Cg Language Summary

Although this paper is not intended to be a tutorial on the Cg language, we describe the language briefly. This description illustrates some of our design decisions and facilitates the discussions later in this paper.

5.1 Example program

Figure 5 shows a Cg program for a vertex processor. The program transforms an object-space position for a vertex by a four-by-four matrix containing the concatenation of the modeling, viewing, and projection transforms. The resulting vector is output as the clip-space position of the vertex. The per-vertex color is scaled by a floating-point parameter prior to output. Also, a texture coordinate set is passed through without modification.

```
void simpleTransform(float4 objectPosition :  POSITION,
                     float4 color          :  COLOR,
                     float4 decalCoord     :  TEXCOORD0,
                 out float4 clipPosition   :  POSITION,
                 out float4 oColor         :  COLOR,
                 out float4 oDecalCoord    :  TEXCOORD0,
             uniform float  brightness,
             uniform float4x4 modelViewProjection)

{
  clipPosition = mul(modelViewProjection, objectPosition);
  oColor = brightness * color;
  oDecalCoord = decalCoord;
}
```

Figure 5: *Example Cg Program for Vertex Processor*

Cg supports scalar data types such as `float` but also has first-class support for vector and matrix data types. The identifier `float4` represents a vector of four floats, and `float4x4` represents a matrix. The `mul` function is a standard library routine that performs matrix by vector multiplication. Cg provides function overloading like C++; `mul` is overloaded and may be used to multiply various combinations of vectors and matrices.

Cg provides the same operators as C. Unlike C, however, Cg operators accept and return vectors as well as scalars. For example, the scalar, brightness, scales the vector, color, as you would expect.

In Cg, declaring a vertex program parameter with the uniform modifier indicates that its value will not vary over a batch of vertices. The application must provide the value of such parameters. For example, the application must supply the modelViewProjection matrix and the brightness scalar, typically by using the Cg runtime library's API.

The POSITION, COLOR, and TEXCOORD0 identifiers following the objectPosition, color, and decalCoord parameters specify how these parameters are bound to API resources. In OpenGL, glVertex commands feed POSITION; glColor commands feed COLOR; and glMultiTexCoord commands feed TEXCOORDn.

The out modifier indicates that clipPosition, oColor, and oDecalCoord parameters are output by the program. The identifier following the colon after each of these parameters specifies how the output is fed to the primitive assembly and rasterization stages of the graphics pipeline.

5.2 Other Cg functionality

Cg provides structures and arrays, including multi-dimensional arrays; all of C's arithmetic operators (+, *, /, etc.); a boolean type and boolean and relational operators (||, &&, !, etc.); increment/decrement (++/- -) operators; the conditional expression operator (?:); assignment expressions (+=, etc.); and even the C comma operator.

Cg supports programmer-defined functions (in addition to pre-defined standard library functions), but recursive functions are not allowed. Cg provides only a subset of C's control flow constructs: (do, while, for, if, break, and continue). Other constructs, such as goto and switch, are not supported in the current Cg implementation, but the necessary keywords are reserved.

Cg provides built-in constructors for vector data types (similar to C++ but not user-definable): e.g. float4 a = float4(4.0, -2.0, 5.0, 3.0);

Swizzling is a way of rearranging components of vector values and constructing shorter or longer vectors. For example:

```
float2 b = a.yx;          // b = (-2.0, 4.0)
```

Cg does not currently support pointers or bitwise operations. Cg lacks most C++ features for "programming in the large" such as full classes, templates, operator overloading, exception handling, and namespaces. Cg supports #include, #define, #ifdef, etc. matching the C preprocessor.

6 Design Issues

6.1 Support for hardware

By design, the C language is close to the level of the hardware – it exposes the important capabilities of CPU hardware in the language. For example, it exposes hardware data types (with extensions such as long long if necessary) and the existence of pointers. As a result, the C language provides performance transparency – programmers have straightforward control over machine-level operations, and thus the performance of their code.

When designing Cg, we followed this philosophy. The discussion below is organized around the characteristics of GPU hardware that led to differences between Cg and C.

6.1.1 Stream processor

The stream processing model used by the programmable processors in graphics architectures is significantly different from the purely sequential programming model used on CPUs. Much of the new functionality in Cg (as compared to C) supports this stream programming model. In particular, a GPU program is executed many times – once for each vertex or fragment. To efficiently accommodate this repeated execution, the hardware provides two kinds of inputs to the program. The first kind of input changes with each invocation of the program and is carried in the incoming stream of vertices or fragments. An example is the vertex position. The second kind of input may remain unchanged for many invocations of the program; its value persists until a new value is sent from the CPU as an update to the processor state. An example is the modelview matrix. At the hardware level, these two types of inputs typically reside in different register sets.

A GPU language compiler must know the category to which an input belongs before it can generate assembly code. Given the hardware-oriented philosophy of Cg, we decided that the distinction should be made in the Cg source code. We adapted RenderMan's terminology for the two kinds of inputs: a *varying* input is carried with the incoming stream of data, while a uniform input is updated by an explicit state change. Consistent with the general-purpose stream-processor orientation of Cg, this same terminology is used for any processor within the GPU (i.e. vertex or fragment), unlike the scheme used in GLSL, which uses different terminology (and keywords) for varying-per-vertex and varying-per-fragment variables.

Cg uses the uniform type qualifier differently than RenderMan. In RenderMan, it may be used in any variable declaration and specifies a general property of the variable, whereas in Cg it may only be applied to program inputs and it specifies initialization behavior for the variable. In the RenderMan interpretation, all Cg temporary variables would be considered to be varying, and even a uniform input variable becomes varying once it has been rewritten within the program. This difference reflects the difference in the processor models assumed by RenderMan and Cg: RenderMan is designed for a SIMD processor, where many invocations of the program are executing in lockstep and temporary results can be shared, while Cg is designed for a stream processor in which each invocation of the program may execute asynchronously from others, and no sharing of temporary results is possible.

Computations that depend only on uniform parameters do not need to be redone for every vertex or fragment, and could be performed just once on the CPU with the result passed as a new uniform parameter. RTSL can perform this optimization, which may add or remove uniform parameters at the assembly language level. The current Cg compiler does not perform this optimization; if it did, applications would be required to pass uniform parameters through the Cg runtime system rather than passing them directly through the 3D API because the original inputs might no longer exist at the 3D API level. This optimization is an example of a global optimization that crosses system modules. We expect that the Cg system will support optimizations of this type in the future, but only when the application promises that it will pass all affected parameters using the Cg runtime API.

6.1.2 Data types

The data types supported by current graphics processors are different from those supported by standard CPUs, thus motivating corresponding adjustments in the Cg language.

Some graphics architectures support just one numeric data type, while others support multiple types. For example, the NVIDIA GeForce FX supports three different numeric data types in its fragment processor – 32-bit floating-point, 16-bit floating-point, and 12-bit fixed-point. In general, operations that use the lower-precision types are faster, so we wanted to provide some mechanism for using these data types. Several alternatives were possible. The first was to limit the language to a single float data type, and hope that the compiler could perform interval and/or precision analysis to map some computations to the lower-precision types. This strategy is at odds with the philosophy of C, and has not proven to be successful in the past. The second alternative (used in GLSL) was to specify precision using hints, rather than first-class data types. This approach makes it impossible to overload functions based on the data types, a capability that we considered important for supporting high-performance library functions. The third alternative, used by Cg, is to include multiple numeric data types in the language. Cg includes `float`, `half`, and `fixed` data types.

Just as C provides some flexibility in the precision used for its different data types, the core Cg specification provides profiles with flexibility to specify the format used for each of the data types, within certain ranges. For example, in a profile that targets an architecture with just one floating-point type, `half` precision may be the same as `float` precision. For a few types (e.g. `fixed` and `sampler`), profiles are permitted to omit support when appropriate. In particular, the `sampler` types are used to represent textures, and thus are of no use in profiles that do not support texture lookups. However, to allow source code and data structures targeted at different profiles to be mixed in a single source file, the Cg specification requires that all profiles support definitions and declarations of all Cg data types, and to support corresponding assignment statements. The first two requirements are necessary because of a quirk of C syntax: correct parsing of C requires that the parser know whether an identifier was previously defined as a type or as a variable. The third requirement makes it easier to share data structures between different profiles.

In 3D rendering algorithms, three- and four-component vector and four-by-four matrix operations are common. As a result, most past and present graphics architectures directly support four-component vector arithmetic (see e.g. [Levinthal et al. 1987; Lindholm et al. 2001]). C's philosophy of exposing hardware data types suggests that these vector data types should be exposed, and there is precedent for doing so in both shading languages [Levinthal et al. 1987; Hanrahan and Lawson 1990] and in extensions to C [Motorola Corp. 1999]. Despite these precedents, we initially tried to avoid exposing these types by representing them indirectly with C's arrays-of-float syntax. This strategy failed because it did not provide a natural mechanism for programmers or the compiler to distinguish between the architecture's vectors (now `float4 x`), and an indirectly addressable array of scalars (now `float x[4]`). These two types must be stored differently and support different operations because current graphics architectures are restricted to 128-bit granularity for indirect addressing. Thus, Cg and GLSL include vector data types and operators, up to length four.

It would be possible to take the opposite approach to supporting short vector hardware, by omitting short vector data types from the language, and relying on the compiler to automatically combine scalar operations to form vectorized assembly code [Larsen and Amarasinghe 2000; Codeplay Corporation 2003]. This approach requires sophisticated compiler technology to achieve acceptable vectorization and obscures from the programmer the difference between code that will run fast and code that will not. At best, this fully automatic approach to vectorization can only hope to match the performance of languages such as Cg that allow both manual and automatic vectorization.

As a convenience for programmers, Cg also supports built-in matrix types and operations, up to size four by four. This decision was a concession to the primary use of Cg for rendering computations.

Current graphics processors do not support integer data types, but they do support boolean operations using condition codes and predicated instructions. Thus, we initially decided to omit support for the C `int` data type, but to add a `bool` data type for conditional operations. This change was partly inspired by the `bool` type in the latest C++ standard. We adjusted the data types expected by C's boolean operators and statements accordingly, so that most common C idioms work with no change. Because some graphics hardware supports highly-efficient vector operations on booleans, we extended C's boolean operations (`&&`, `||`, `?:`, etc.) to support `bool` vectors. For example, the expression `bool2(true,false) ? float2(1,1) : float2(0,0)` yields `float2(1,0)`. Later, for better compatibility with C, we restored the `int` type to the Cg specification, but retained the `bool` type for operations that are naturally boolean and thus can be mapped to hardware condition-code registers.

6.1.3 Indirect addressing

CPUs support indirect addressing (i.e. pointer dereferencing) for reads or writes anywhere in memory. Current graphics processors have very limited indirect addressing capability – indirect addressing is available only when reading from the uniform registers, or sampling textures. Unfortunately, programs written in the C language use pointers frequently because C blurs the distinction between pointer types and array types.

Cg introduces a clear distinction between these two types, both syntactically and semantically. In particular, an array assignment in Cg semantically performs a copy of the entire array. Of course, if the compiler can determine that a full copy is unnecessary, it may (and often does) omit the copy operation from the generated code. Cg currently forbids the use of pointer types and operators, although we expect that as graphics processors become more general, Cg will re-introduce support for pointer types using the C pointer syntax.

To accommodate the limitations of current architectures, Cg permits profiles to impose significant restrictions on the declaration and use of array types, particularly on the use of computed indices (i.e. indirect addressing). However, these restrictions take the form of profile-dependent prohibitions, rather than syntactic changes to the language. Thus, these prohibitions can be relaxed or removed in the future, allowing future Cg profiles to support general array operations without syntactic changes. In contrast, 3DLSL used special syntax and function calls (e.g. `element`) for the array operations supported by current architectures, although its descendent GLSL switched to C-like array notation.

The lack of hardware support for indirect addressing of a read/write memory makes it impossible to implement a runtime stack to hold temporary variables, so Cg currently forbids recursive or co-recursive function calls. With this restriction, all temporary storage can be allocated statically by the compiler.

Read/write parameters to a C function must be declared using pointer types. We needed a different mechanism in Cg, and considered two options. The first was to adopt the C++ call-by-reference syntax and semantics, as 3DLSL did. However, call-by-reference semantics are usually implemented using indirect addressing, to handle the case of parameter aliasing by the calling function. On current architectures it is possible for a compiler to support these semantics without the use of indirect addressing, but this technique precludes separate compilation of different functions (i.e. compile and link), and we were concerned that this technique might not be adequate on future architectures. Instead, we decided to support call-by-value-result semantics, which can be implemented without the use of indirect addressing. We support these semantics using a notation that is new to C/C++ (`in` and `out` parameter modifiers, taken from Ada), thus leaving the C++ `&` notation available to support call-by-reference semantics in the future. GLSL takes this same approach.

6.1.4 Interaction with the rest of the graphics pipeline

In current graphics architectures, some of the input and output registers for the programmable processors are used to control the non-programmable parts of the graphics pipeline, rather than to pass general-purpose data. For example, the vertex processor must store a position vector in a particular output register, so that it may be used by the rasterizer. Likewise, if the fragment processor modifies the depth value, it must write the new value to a particular output register that is read by the framebuffer depth-test unit. We could have chosen to pre-define global variables for these inputs and outputs, but instead we treat them as much as possible like other varying inputs and outputs. However, these inputs and outputs are only available by using the language's syntax for binding a parameter to a register, which is optional in other cases. To ensure program portability, the Cg specification mandates that certain register identifiers (e.g. POSITION) be supported as an output by all vertex profiles, and that certain other identifiers be supported by all fragment profiles.

6.1.5 Shading-specific hardware functionality

The latest generation of graphics hardware includes a variety of capabilities specialized for shading. For example, although texture sampling instructions can be thought of as memory-read instructions, their addressing modes and filtering are highly specialized for shading. The GeForce FX fragment processor also includes built-in discrete-differencing instructions [NVIDIA Corp. 2003b], which are useful for shader anti-aliasing.

We chose to expose these capabilities via Cg's standard library functions, rather than through the language itself. This approach maintains the general-purpose nature of the language, while supporting functionality that is important for shading. Thus, many of Cg's standard library functions are provided for more than just convenience – they are mechanisms for accessing particular hardware capabilities that would otherwise be unavailable.

In other cases, such as the lit function, library functions represent common shading idioms that may be implemented directly in the language, but can be more easily optimized by the compiler and hardware if they are explicitly identified.

Although we do not discuss the details of the Cg standard library in this paper, significant care went into its design. It supports a variety of mathematical, geometric, and specialized functions. When possible, the definitions were chosen to be the same as those used by the corresponding C standard library and/or RenderMan functions.

6.2 User-defined interfaces between modules

The RenderMan shading language and RTSL include support for separate surface and light shaders, and the classical fixed-function OpenGL pipeline does too, in a limited manner. However, these shaders don't actually execute independently; computing the color of any surface point requires binding the light shaders to the surface shader either explicitly or implicitly. In RenderMan and fixed-function OpenGL, the binding is performed implicitly by changing the current surface or light shaders. In RTSL, the application must explicitly bind the shaders at compile time.

Considered more fundamentally, this surface/light modularity consists of built-in surface and light object types that communicate across a built-in interface between the two types of objects. In this conceptual framework, a complete program is constructed from one surface object that invokes zero or more light objects via the built-in interface. There are several subtypes of light objects corresponding to directional, positional, etc. lights. Light objects of different subtypes contain different data (e.g. positional lights have a "light position" but directional lights do not).

It would have run contrary to the C-like philosophy of Cg to include specialized surface/light functionality in the language. However, the ability to write separate surface and light shaders has proven to be valuable, and we wanted to support it with more general language constructs.

The general-purpose solution we chose is adopted from Java and C#.[1] The programmer may define an interface, which specifies one or more function prototypes.[2] For example, an interface may define the prototypes for functions used to communicate between a surface shader and a light shader. An interface may be treated as a generic object type so that one routine (e.g. the surface shader) may call a method from another object (e.g. an object representing a light) using the function prototypes defined in the interface. The programmer implements the interface by defining a struct (i.e. class) that contains definitions for the interface's functions (i.e. methods). This language feature may be used to create programmer-defined categories of interoperable modules; Figure 6 shows how it may be used to implement separate surface and light shaders, although it is useful for other purposes too. GLSL and HLSL do not currently include any mechanism – either specialized or general-purpose – that provides equivalent functionality.

All current Cg language profiles require that the binding of interfaces to actual functions be resolvable at Cg compile time. This binding may be specified either in the Cg language (as would be done in Java), or via Cg runtime calls prior to compilation. Future profiles could relax the compile-time binding requirement, if the corresponding graphics instruction sets include an indirect jump instruction.

6.3 Other language design decisions

6.3.1 Function overloading by types and by profile

Our decision to support a wide variety of data types led us to conclude that we should support function overloading by data type. In particular, most of Cg's standard library functions have at least twelve variants for different data types, so following C's approach of specifying parameter types in function name suffixes would have been unwieldly.

Cg's function overloading mechanism is similar to that of C++, although Cg's matching rules are less complex. For simple cases, Cg's matching rules behave intuitively. However, since matching is performed in multiple dimensions (base type, vector length, etc.) and implicit type promotion is allowed, it is still possible to construct complex cases for which it is necessary to understand the matching rules to determine which overloaded function will be chosen.

Cg also permits functions to be overloaded by profile. Thus, it is possible to write multiple versions of a function that are optimized for different architectures, and the compiler will automatically chose the version for the current profile. For example, one version of a function might use standard arithmetic operations, while a second version uses a table lookup from a texture (Figure 7). This capability is useful for writing portable programs that include optimizations for particular architectures. Some wildcarding of profiles is supported – for example, it is possible to specify just vertex and fragment versions of a function, rather than specifying a version for every possible vertex and fragment profile. The overloading rules cause more-specific profile matches to be preferred over less-specific matches, so program portability can be ensured by defining one lowest-common-denominator version of the function.

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[1] Unlike the other Cg features described in this paper, this capability is not yet supported in a public release (as of April 2003). It is currently being implemented and will be supported in a future Cg release.

[2] C++ provides a similar capability via pure virtual base classes. We chose Java's approach because we consider it to be cleaner and easier to understand.

```
// Declare interface to lights
interface Light {
  float3 direction(float3 from);
  float4 illuminate(float3 p, out float3 lv);
};

// Declare object type (light shader) for point lights
struct PointLight : Light {
  float3 pos, color;
  float3 direction(float3 p) { return pos - p; }
  float3 illuminate(float3 p, out float3 lv) {
    lv = normalize(direction(p));
    return color;
  }
};

// Declare object type (light shader) for directional lights
struct DirectionalLight : Light {
  float3 dir, color;
  float3 direction(float3 p) { return dir; }
  float3 illuminate(float3 p, out float3 lv) {
    lv = normalize(dir);
    return color;
  }
};

// Main program (surface shader)
float4 main(appin IN, out float4 COUT,
            uniform Light lights[]) {
  ...
  for (int i=0; i < lights.Length; i++) { // for each light
    Cl = lights[i].illuminate(IN.pos, L); // get dir/color
    color += Cl * Plastic(texcolor, L, Nn, In, 30); // apply
  }
  COUT = color;
}
```

Figure 6: *Cg's* interface *functionality may be used to implement separate surface and light shaders. The application must bind the light objects to the main program prior to compilation. In this example, the application would perform the binding by making Cg runtime API calls to specify the size and contents of the* lights *array, which is a parameter to* main.

6.3.2 Constants are typeless

In C, if x is declared as float, then the expression 2.0*x is evaluated at double precision. Often, this type promotion is not what the user intended, and it may cause an unintended performance penalty. In our experience, it is usually more natural to think of floating-point constants as being typeless.

This consideration led us to change the type promotion rules for constants. In Cg, a constant is either integer or floating-point, and otherwise has no influence on type promotion of operators. Thus, if y is declared as half, the expression 2.0*y is evaluated at half precision. Users may still explicitly assign types to constants with a suffix character (e.g. 2.0f), in which case the type promotion rules are identical to those in C. Internally, the new constant promotion rules are implemented by assigning a different type (cfloat or cint) to constants that do not have an explicit type suffix. These types always take lowest precedence in the operator type-promotion rules.

These new rules are particularly useful for developing a shader using float variables, then later tuning the performance by selectively changing float variables to half or fixed. This process does not require changes to the constants used by the program.

6.3.3 No type checking for textures

The Cg system leaves the responsibility for most texture management (e.g. loading textures, specifying texture formats, etc.) with the underlying 3D API. Thus, the Cg system has very little information about texture types – e.g. is a particular texture an RGB (float3) texture, or an RGBA (float4) texture? Since compile-time type checking is not possible in this situation, the user is responsible for insuring that Cg texture lookups are used in manner that is consistent with the way the application loads and binds the corresponding textures at run time. Stronger type checking would be possible by integrating the Cg system more tightly with the 3D API.

```
uniform samplerCUBE norm_cubemap;

// For ps_1_1 profile, use cubemap to normalize
ps_1_1 float3 mynormalize(float3 v) {
  return texCUBE(norm_cubemap, v.xyz).xyz;
}

// For ps_2_0 profile, use stdlib routine to normalize
ps_2_0 float3 mynormalize(float3 v) {
  return normalize(v);
}
```

Figure 7: *Function overloading by hardware profile facilitates the use of optimized versions of a function for particular hardware platforms.*

6.4 Runtime API

As described earlier, the Cg runtime API is composed of two parts. The first part is independent of the 3D API and provides a procedural interface to the compiler and its output. The second part is layered on top of the 3D API and is used to load and bind Cg programs, to pass uniform and varying parameters to them, and to perform miscellaneous housekeeping tasks. These interfaces are crucial for system usability since they provide the primary interface between the application and the Cg system. In this section, we discuss a few of the more interesting questions that arose in the design of the runtime API.

6.4.1 Compound types are exploded to cross API

Cg programs may declare uniform parameters with compound types such as structures and arrays. Typically, the application passes the values of these parameters to the Cg program by using the Cg runtime API. Unfortunately, most operating systems do not specify and/or require a standard binary format for compound data types. For example, a data structure defined in a FORTRAN program does not have the same memory layout as the equivalent data structure defined in a C program. Thus, it is difficult to define a natural binary format for passing compound data structures across an API. This problem has plagued API designers for a long time; OpenGL finessed one aspect of it by specifying 2D matrices in terms of 1D arrays.

There are several possible approaches to this issue. The first is to choose a particular binary format, presumably the one used by the dominant C/C++ compiler on the operating system. This approach makes it difficult to use the API from other languages, and invites cross-platform portability issues (e.g. between 32-bit and 64-bit machines). The second is to use Microsoft's .NET common type system [Microsoft Corp. 2003], which directly addresses this problem, but would have restricted the use of the Cg APIs to the .NET platform. We chose a third approach, which is to explode compound data structures into their constituent parts to pass them across the API. For example, a struct consisting of a float3 and a float must be passed using one API call for the float3, and a second API call for the float. Although this approach imposes some overhead, it is not generally a performance bottleneck when it is used for passing uniform values.

6.4.2 Cg system can shadow parameter values

The Cg runtime can manage many Cg programs (both vertex and fragment) at once, each with its own uniform parameters. However, GPU hardware can only hold a limited number of programs and parameters at a time. Thus, the values of the active program's uniform parameters may be lost when a new program is loaded into the hardware. The Cg runtime can be configured to shadow a program's parameters, so that the parameter values persist when the active program is changed. Note that some, but not all, OpenGL extensions already implement this type of shadowing in the driver.

7 CgFX

The Cg language and runtime do not provide facilities for managing the non-programmable parts of the graphics pipeline, such as the framebuffer tests. Since many graphics applications find it useful to group the values for this non-programmable state with the corresponding GPU programs, this capability is supported with a set of language and API extensions to Cg, which we refer to as CgFX. We do not discuss CgFX in detail in this paper, but we will briefly summarize its additional capabilities to avoid confusion with the base Cg language. CgFX can represent and manage:

- Functions that execute on the CPU, to perform setup operations such as computing the inverse-transpose of the modelview matrix
- Multi-pass rendering effects
- Configurable graphics state such as texture filtering modes and framebuffer blend modes
- Assembly-language GPU programs
- Multiple implementations of a single shading effect

8 System Experiences

NVIDIA released a beta version of the Cg system in June 2002, and the 1.0 version of the system in December 2002. Windows and Linux versions of the system and its documentation are available for download [NVIDIA Corp. 2003a]. The system is already widely used.

The modularity of the system has proven to be valuable. From online forums and other feedback, it is clear that some developers use the full system, some use just the off-line compiler, and some use Cg for vertex programs but assembly language for fragment programs. We know that some users examine the assembly language output from the compiler because they complain when the compiler misses optimization opportunities. In some cases, these users have hand-tuned the compiler's assembly-code output to improve performance, typically after they have reached the point where their program produces the desired visual results.

To the best of our knowledge, our decision to omit automatic virtualization from the system has not been a serious obstacle for any developer using DX9-class hardware for an application that requires real-time frame rates. In contrast, we have heard numerous complaints about the resource limits in DX8 fragment hardware, but we still believe that we would not have been able to virtualize DX8 hardware well enough to satisfy developers.

Researchers are already using Cg to implement non-rendering algorithms on GPUs. Examples include fluid dynamics simulations and reaction-diffusion simulations (Figure 8).

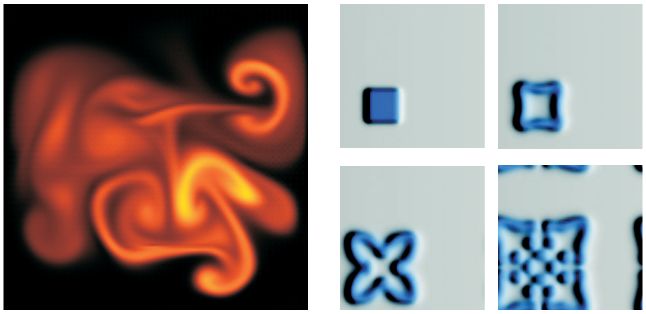

Figure 8: *Cg has been used to compute physical simulations on GPUs. Mark Harris at the University of North Carolina has implemented a Navier-Stokes fluid simulation (left) and a reaction-diffusion simulation (right).*

9 Conclusion

The Cg language is a C-like language for programming GPUs. It extends and restricts C in certain areas to support the stream-processing model used by programmable GPUs, and to support new data types and operations used by GPUs.

Current graphics architectures lack certain features that are standard on CPUs. Cg reflects the limitations of these architectures by restricting the use of standard C functionality, rather than by introducing new syntax or control constructs. As a result, we believe that Cg will grow to support future graphics architectures, by relaxing the current language restrictions and restoring C capabilities such as pointers that it currently omits.

If one considers all of the possible approaches to designing a programming language for GPUs, it is remarkable that the recent efforts originating at three different companies have produced such similar designs. In part, this similarity stems from extensive cross-pollination of ideas among the different efforts. However, we believe that a more significant factor is the de-facto agreement by the different system architects on the best set of choices for a contemporary GPU programming language. Where differences remain between between the contemporary systems, they often stem from an obvious difference in design goals, such as support for different 3D APIs.

We hope that this paper's discussion of the tradeoffs that we faced in the design of Cg will help users to better understand Cg and the other contemporary GPU programming systems, as well as the graphics architectures that they support. We also hope that this distillation of our experiences will be useful for future system architects and language designers, who will undoubtedly have to address many of the same issues that we faced.

10 Acknowledgments

Craig Peeper and Loren McQuade at Microsoft worked closely with us on the design of the Cg/HLSL language. If we had limited this paper to a discussion of the language itself, they probably would have been co-authors.

At NVIDIA, Cass Everitt helped to set the initial design direction for Cg. Craig Kolb designed most of the user-defined interface functionality described in Section 6.2, and Chris Wynn designed the standard library.

We designed and implemented Cg on a very tight schedule, which was only possible because of the highly talented team of people working on the project. Geoff Berry, Michael Bunnell, Chris Dodd, Cass Everitt, Wes Hunt, Craig Kolb, Jayant Kolhe, Rev Lebaredian, Nathan Paymer, Matt Pharr, Doug Rogers, and Chris Wynn developed the Cg compiler, standard library, and runtime technology. These individuals contributed to the language design, the runtime API design, and the implementation of the system. Nick Triantos directed the project. Many other people inside and outside of NVIDIA contributed to the project; the Cg tutorial [Fernando and Kilgard 2003] includes a more complete list of acknowledgments. The Cg compiler backend for DX8-class hardware includes technology licensed from Stanford University [Mark and Proudfoot 2001].

Finally, we thank the anonymous reviewers of this paper for their thoughtful and constructive suggestions.

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A Follow-up Cg Runtime Tutorial for Readers of *The Cg Tutorial*[*]

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April 20, 2005

When Randy and I wrote *The Cg Tutorial*,[†] we wanted a book that would convey our intense enthusiasm for programmable graphics using Cg,[‡] short for C for Graphics. We focused our tutorial on the language itself: What is the Cg language and how do you write Cg programs for programmable graphics hardware?

We chose our language focus for a couple of different reasons.

First off, the language is where all the power and new concepts are. Once you interface Cg into your graphics application, it's the Cg language that really matters. For a conventional CPU programming language, explaining the Cg runtime is somewhat akin to explaining how to edit programs and how to run the compiler. Obviously, you've got to learn these tasks, but there's nothing profound about using an editor or compiler. Likewise, there's nothing deep about the Cg runtime either; it's a fairly straightforward programming interface.

Second, how you interface Cg to your application is a matter of personal design and depends on the nature of your application and your choice of application programming language, operating system, and 3D programming interface. While Randy and I are happy to explain Cg and show how to program your graphics hardware with it, you are the person best able to interface Cg into your application code.

Third, the language shares its design, syntax, and semantics with Microsoft's DirectX 9 High-Level Shader Language (HLSL). This means you can chose whether to use Microsoft's HLSL runtime (ideal for developers focused on DirectX for the Windows

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[†] *The Cg Tutorial* by Randima (Randy) Fernando and Mark J. Kilgard is published by Addison-Wesley (ISBN 0321194969, 336 pages). The book is now available in Japanese translation (ISBN4-939007-55-3).

[‡] *Cg in Two Pages* (http://xxx.lanl.gov/ftp/cs/papers/0302/0302013.pdf) by Mark J. Kilgard is a short overview of the Cg language. *Cg: A System for Programming Graphics Hardware in a C-like Language* (http://www.cs.utexas.edu/users/billmark/papers/Cg) by Bill Mark, Steve Glanville, Kurt Akeley, and Mark J. Kilgard is a SIGGRAPH 2003 paper explaining Cg's design in 12 pages.

platform) or the Cg runtime—supplied by NVIDIA—for those of you who want to support a broad range of operating systems and 3D programming interfaces (such as Linux, Apple's OS X, and OpenGL). Because *The Cg Tutorial* focuses on the Cg language, all the concepts and syntax explained in the book apply whether you choose to use the Cg or HLSL implementation when it comes time to actually write your shader programs. Since there's been some confusion about this point, understand that *The Cg Tutorial* examples in the book compile with *either* language implementation. We hope *The Cg Tutorial* is an instructive book about both Cg *and* HLSL.

To avoid all the mundane details necessary to interface Cg programs to a real application, *The Cg Tutorial* includes an accompanying CD-ROM* with a software framework so you can examine and modify the various Cg programs in the book and see the rendering results without worrying about the mundane details of writing a full application, loading models and textures, and interfacing Cg to your application. Still, the book does provide a brief appendix describing the Cg runtime programming interface for both OpenGL and Direct3D.

Follow-up: A Complete Cg Demo

Still, there's not a *complete* basic example that shows how everything fits together. With that in mind, this article presents a complete graphics demo written in ANSI C that renders a procedurally-generated bump-mapped torus. The demo's two Cg programs are taken directly from the book's Chapter 8 (Bump Mapping). While the Cg programs are reprinted at the end of the article, please consult *The Cg Tutorial* for an explanation of the programs and the underlying bump mapping background and mathematics.

The demo renders with OpenGL and interfaces with the window system via the cross-platform OpenGL Utility Toolkit (GLUT).† To interface the application with the Cg programs, the demo calls the generic Cg and OpenGL-specific CgGL runtime routines.

OpenGL, GLUT, and the Cg and CgGL runtimes are supported on Windows, OS X, and Linux so the demo source code compiles and runs on all these operating systems. The demo automatically selects the most appropriate profile for your hardware. Cg supports multi-vendor OpenGL profiles (namely, **`arbvp1`** and **`arbfp1`**) so the demo works on GPUs from ATI, NVIDIA, or any other OpenGL implementation, such as Brian Paul's open source Mesa library, that exposes the multi-vendor **`ARB_vertex_program`** and **`ARB_fragment_program`** OpenGL extensions.

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* You can download the latest version of the software accompanying *The Cg Tutorial* from http://developer.nvidia.com/object/cg_tutorial_software.html for either Windows or Linux. For best results, make sure you have the latest graphics drivers, latest Cg toolkit, and latest version of *The Cg Tutorial* examples installed.

† Documentation, source code, and pre-compiled GLUT libraries are available from http://www.opengl.org/developers/documentation/glut.html

I verified the demo works on DirectX 9-class hardware including ATI's Radeon 9700 and similar GPUs, NVIDIA's GeForce FX products, and the GeForce 6 Series. The demo even works on older NVIDIA DirectX 8-class hardware such as GeForce3 and GeForce4 Ti GPUs.

So this article's simple Cg-based demo handles multiple operating systems, two different GPU hardware generations (DirectX 8 & DirectX 9), and hardware from the two major GPU vendors (and presumably any other OpenGL implementation exposing OpenGL's standard, multi-vendor vertex and fragment program extensions) with absolutely no GPU-dependent or operating system-dependent code.

To further demonstrate the portability possible by writing shaders in Cg, you can also compile the discussed Cg programs with Microsoft's HLSL runtime with no changes to the Cg programs.

This unmatched level of shader portability is why the Cg language radically changes how graphics applications get at programmable shading hardware today. With one high-level language, you can write high-performance, cross-platform, cross-vendor, and cross-3D API shaders. Just as you can interchange images and textures stored as JPEG, PNG, and Targa files across platforms, you can now achieve a similar level of interoperability with something as seemingly hardware-dependent as a hardware shading algorithm.

Demo Source Code Walkthrough

The demo, named **`cg_bumpdemo`**, consists of the following five source files:

1. **`cg_bumpdemo.c`**—ANSI C source code for the demo.
2. **`brick_image.h`**—Header file containing RGB8 image data for a mipmapped 128x128 normal map for a brick pattern.
3. **`nmap_image.h`**—Header file containing RGB8 image data for a normalization vector cube map with 32x32 faces.
4. **`C8E6v_torus.cg`**—Cg vertex program to generate a torus from a 2D mesh of vertices.
5. **`C8E4f_specSurf.cg`**—Cg fragment program for surface-local specular and diffuse bump mapping.

Later, we will go through **`cg_bumpdemo.c`** line-by-line.

To keep the demo self-contained and maintain the focus on how the Cg runtime loads, compiles, and configures the Cg programs and then renders with them, this demo uses static texture image data included in the two header files.

The data in these header files are used to construct OpenGL texture objects for a brick pattern normal map 2D texture and a "vector normalization" cube map. These texture objects are sampled by the fragment program.

The data in the two headers files consists of hundreds of comma-separated numbers (I'll save you the tedium of publishing all the numbers in this article…). Rather than static data compiled into an executable, a typical application would read normal map textures from on-disk image files or convert a height-field image file to a normal map. Likewise, a "normalization vector" cube map is typically procedurally generated rather than loaded from static data.

The two Cg files each contain a Cg entry function with the same name as the file. These functions are explained in Chapter 8 (Bump Mapping) of *The Cg Tutorial*. These files are read by the demo when the demo begins running. The demo uses the Cg runtime to read, compile, configure, and render with these Cg programs.

Rather than rehash the background, theory, and operation of these Cg programs, you should consult Chapter 8 of *The Cg Tutorial*. Pages 200 to 204 explain the construction of the brick pattern normal map. Pages 206 to 208 explain the construction and application of a normalization cube map. Pages 208 to 211 explains specular bump mapping, including the `C8E4f_specSurf` fragment program. Pages 211 to 218 explain texture-space bump mapping. Pages 218 to 224 explain the construction of the per-vertex coordinate system needed for texture-space bump mapping for the special case of an object (the torus) that is generated from parametric equations by the `C8E6v_torus` vertex program.

For your convenience and so you can map Cg parameter names used in the C source file to their usage in the respective Cg programs, the complete contents of `C8E6v_torus.cg` and `C8E4f_specSurf.cg` are presented in Appendix A and Appendix B at the end of this article (the Cg programs are short, so why not).

On to the C Code

Now, it's time to dissect `cg_bumpdemo.c` line-by-line as promised (we'll skip comments in the source code if the comments are redundant with the discussion below).

To help you identify which names are external to the program, the following words are listed in **`boldface`** within the C code: C keywords; C standard library routines and macros; OpenGL, GLU, and GLUT routines, types, and enumerants; and Cg and CgGL runtime routines, types, and enumerants.

Initial Declarations

```
#include <math.h>
#include <stdlib.h>
#include <stdio.h>
#include <GL/glut.h>
#include <Cg/cg.h>
#include <Cg/cgGL.h>
```

The first three includes are basic ANSI C standard library includes. We'll be using **`sin`**, **`cos`**, **`printf`**, **`exit`**, and **`NULL`**. We rely on the GLUT header file to include the necessary OpenGL and OpenGL Utility Library (GLU) headers.

The **`<Cg/cg.h>`** header contains generic routines for loading and compiling Cg programs but does not contain routines that call the 3D programming interface to configure the Cg programs for rendering. The generic Cg routines begin with a **`cg`** prefix; the generic Cg types begin with a **`CG`** prefix; and the generic Cg macros and enumerations begin with a **`CG_`** prefix.

The **`<Cg/cgGL.h>`** contains the OpenGL-specific routines for configuring Cg programs for rendering with OpenGL. The OpenGL-specific Cg routines begin with a **`cgGL`** prefix; the OpenGL-specific Cg types begin with a **`CGGL`** prefix; and the OpenGL-specific Cg macros and enumerations begin with a **`CGGL_`** prefix.

Technically, the **`<Cg/cgGL.h>`** header includes **`<Cg/cg.h>`** so we don't have to explicitly include **`<Cg/cg.h>`** but we include both to remind you that we'll be calling both generic Cg routines and OpenGL-specific Cg routines.

```
/* An OpenGL 1.2 define */
#define GL_CLAMP_TO_EDGE                    0x812F

/* A few OpenGL 1.3 defines */
#define GL_TEXTURE_CUBE_MAP                 0x8513
#define GL_TEXTURE_BINDING_CUBE_MAP         0x8514
#define GL_TEXTURE_CUBE_MAP_POSITIVE_X      0x8515
```

We will use these OpenGL enumerants later when initializing our "normalization vector" cube map. We list them here explicitly since we can't count on **`<GL/gl.h>`** (included by **`<GL/glut.h>`** above) to have enumerants added since OpenGL 1.1 because Microsoft still supplies the dated OpenGL 1.1 header file.

Next, we'll list all global variables we plan to use. We use the **`my`** prefix to indicate global variables that we define (to make it crystal clear what names we are defining rather than those names defined by header files). When we declare a variable of a type defined by the Cg runtime, we use the **`myCg`** prefix to remind you that the variable is for use with the Cg runtime.

Cg Runtime Variables

```
static CGcontext   myCgContext;
static CGprofile   myCgVertexProfile,
                   myCgFragmentProfile;
static CGprogram   myCgVertexProgram,
                   myCgFragmentProgram;
static CGparameter myCgVertexParam_lightPosition,
                   myCgVertexParam_eyePosition,
                   myCgVertexParam_modelViewProj,
                   myCgVertexParam_torusInfo,
                   myCgFragmentParam_ambient,
                   myCgFragmentParam_LMd,
                   myCgFragmentParam_LMs,
                   myCgFragmentParam_normalMap,
                   myCgFragmentParam_normalizeCube,
                   myCgFragmentParam_normalizeCube2;
```

These are the global Cg runtime variables the demo initializes uses. We need a single Cg compilation context named **`myCgContext`**. Think of your Cg compilation context as the "container" for all the Cg handles you manipulate. Typically your program requires just one Cg compilation context.

We need two Cg profile variables, one for our vertex program profile named **`myCgVertexProfile`** and another for our fragment program profile named **`myCgFragmentProfile`**. These profiles correspond to a set of programmable hardware capabilities for vertex or fragment processing and their associated execution environment. Profiles supported by newer GPUs are generally more functional than older profiles. The Cg runtime makes it easy to select the most appropriate profile for your hardware as we'll see when we initialize these profile variables.

Next we need two Cg program handles, one for our vertex program named **`myCgVertexProgram`** and another for our fragment program named **`myCgFragmentProgram`**. When we compile a Cg program successfully, we use these handles to refer to the corresponding compiled program.

We'll need handles to each of the uniform input parameters used by our vertex and fragment programs respectively. We use these handles to match the uniform input parameters in the Cg program text with the opaque OpenGL state used to maintain the corresponding Cg program state. Different profiles can maintain Cg program state with different OpenGL state so these Cg parameter handles abstract away the details of how a particular profile manages a particular Cg parameter.

The **`myCgVertexParam_`** prefixed parameter handles end with each of the four uniform input parameters to the **`C8E6v_torus`** vertex program in Appendix A. Likewise, the **`myCgFragmentParam_`** prefixed parameter handles end with each of the six uniform input parameters to the **`C8E4v_specSurf`** fragment program in Appendix B.

In a real program, you'll probably have more Cg program handles than just two. You may have hundreds depending on how complicated the shading is in your application. And each program handle requires a Cg parameter handle for each input parameter. This means you probably won't want to use global variables to store these handles. You'll probably want to encapsulate your Cg runtime handles within "shader objects" that may well combine vertex and fragment Cg programs and their parameters within the same object for convenience. Keep in mind that this demo is trying to be very simple.

Other Variables

```
static const char *myProgramName = "cg_bumpdemo",
                  *myVertexProgramFileName = "C8E6v_torus.cg",
                  *myVertexProgramName = "C8E6v_torus",
                  *myFragmentProgramFileName = "C8E4f_specSurf.cg",
                  *myFragmentProgramName = "C8E4f_specSurf";
```

We need various string constants to identify our program name (for error messages and the window name), the names of the file names containing the text of the vertex and fragment Cg programs to load, and the names of the entry functions for each of these files.

In Appendix A, you'll find the contents of the **`C8E6v_torus.cg`** file and, within the file's program text, you can find the entry function named **`C8E6v_torus`**. In Appendix B, you'll find the contents of the **`C8E4f_specSurf.cg`** file and, within the file's program text, you can find the entry function name **`C8E4f_specSurf`**.

```
static float myEyeAngle = 0,
             myAmbient[4] = { 0.3f, 0.3f, 0.3f, 0.3f }, /* Dull white */
             myLMd[4] = { 0.9f, 0.6f, 0.3f, 1.0f },     /* Gold */
             myLMs[4] = { 1.0f, 1.0f, 1.0f, 1.0f };     /* Bright white */
```

These are demo variables used to control the rendering of the scene. The viewer rotates around the fixed torus. The angle of rotation and a degree of elevation for the viewer is determined by **`myEyeAngle`**, specified in radians. The other three variables provide lighting and material parameters to the fragment program parameters. With these particular values, the bump-mapped torus has a "golden brick" look.

Texture Data

```
/* OpenGL texture object (TO) handles. */
enum {
  TO_NORMALIZE_VECTOR_CUBE_MAP = 1,
  TO_NORMAL_MAP = 2,
};
```

The **`TO_`** prefixed enumerants provide numbers for use as OpenGL texture object names.

```
static const GLubyte
myBrickNormalMapImage[3*(128*128+64*64+32*32+16*16+8*8+4*4+2*2+1*1)] = {
/* RGB8 image data for mipmapped 128x128 normal map for a brick pattern */
#include "brick_image.h"
};

static const GLubyte
myNormalizeVectorCubeMapImage[6*3*32*32] = {
/* RGB8 image data for normalization vector cube map with 32x32 faces */
#include "normcm_image.h"
};
```

These static, constant arrays include the header files containing the data for the normal map's brick pattern and the "normalization vector" cube map. Each texel is 3 unsigned bytes (one for red, green, and blue). While each byte of the texel format is unsigned, normal map components, as well as the vector result of normalizing an arbitrary direction vector, are logically signed values within the [-1,1] range. To accommodate signed values with OpenGL's conventional **`GL_RGB8`** unsigned texture format, the unsigned [0,1] range is expanded in the fragment program to a signed [-1,1] range. This is the reason for the **`expand`** helper function called by the **`C8E4f_specSurf`** fragment program (see Appendix B).

The normal map has mipmaps so there is data for the 128x128 level, and then, each of the successively downsampled mipmap levels. The "normalization vector" cube map has six 32x32 faces.

Error Reporting Helper Routine

```
static void checkForCgError(const char *situation)
{
  CGerror error;
  const char *string = cgGetLastErrorString(&error);

  if (error != CG_NO_ERROR) {
    printf("%s: %s: %s\n",
      myProgramName, situation, string);
    if (error == CG_COMPILER_ERROR) {
      printf("%s\n", cgGetLastListing(myCgContext));
    }
    exit(1);
  }
}
```

Cg runtime routines report errors by setting a global error value. Calling the **`cgGetLastErrorString`** routine both returns a human-readable string describing the last generated Cg error and writes an error code of type **`CGerror`**. **`CG_NO_ERROR`** (defined to be zero) means there was no error. As a side-effect, **`cgGetLastErrorString`** also resets the global error value to **`CG_NO_ERROR`**. The Cg runtime also includes the simpler function **`cgGetError`** that just returns and then resets the global error code if you just want the error code and don't need a human-readable string too.

The `checkForCgError` routine is used to ensure proper error checking throughout the demo. Rather than cheap out on error checking, the demo checks for errors after essentially every Cg runtime call by calling `checkForCgError`. If an error has occurred, the routine prints an error message including the `situation` string and translated Cg error value string, and then exits the demo.

When the error returned is `CG_COMPILER_ERROR` that means there are compiler error messages too. So `checkForCgError` then calls `cgGetLastListing` to get a listing of the compiler error messages and prints these out too. For example, if your Cg program had a syntax error, you'd see the compiler's error messages including the line numbers where the compiler identified problems.

While "just exiting" is fine for a demo, real applications will want to properly handle any errors generated. In general, you don't have to be so paranoid as to call `cgGetLastErrorString` after every Cg runtime routine. Check the runtime API documentation for each routine for the reasons it can fail; when in doubt, check for failures.

Demo Initialization

```
static void display(void);
static void keyboard(unsigned char c, int x, int y);

int main(int argc, char **argv)
{
  const GLubyte *image;
  unsigned int size, level, face;
```

The `main` entry-point for the demo needs a few local variables to be used when loading textures. We also need to forward declare the `display` and `keyboard` GLUT callback routines for redrawing the demo's rendering window and handling keyboard events.

OpenGL Utility Toolkit Initialization

```
  glutInitWindowSize(400, 400);
  glutInitDisplayMode(GLUT_RGB | GLUT_DOUBLE | GLUT_DEPTH);
  glutInit(&argc, argv);

  glutCreateWindow(myProgramName);
  glutDisplayFunc(display);
  glutKeyboardFunc(keyboard);
```

Using GLUT, we request a double-buffered RGB color 400x400 window with a depth buffer. We allow GLUT to take a pass parsing the program's command line arguments. Then, we create a window and register the `display` and `keyboard` callbacks. We'll explain these callback routines after completely initializing GLUT, OpenGL, and Cg. That's it for initializing GLUT except for calling `glutMainLoop` to start event processing at the very end of `main`.

OpenGL Rendering State Initialization

```
glClearColor(0.1, 0.3, 0.6, 0.0);  /* Blue background */
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
gluPerspective(
  60.0,   /* Field of view in degree */
  1.0,    /* Aspect ratio */
  0.1,    /* Z near */
  100.0); /* Z far */
glMatrixMode(GL_MODELVIEW);
glEnable(GL_DEPTH_TEST);
```

Next, we initialize basic OpenGL rendering state. For better aesthetics, we change the background color to a nice sky blue. We specify a perspective projection matrix and enable depth testing for hidden surface elimination.

OpenGL Texture Object Initialization

```
glPixelStorei(GL_UNPACK_ALIGNMENT, 1); /* Tightly packed texture data. */
```

By default, OpenGL's assumes each image scanline is aligned to begin on 4 byte boundaries. However, RGB8 data (3 bytes per pixel) is usually tightly packed to a 1 byte alignment is appropriate. That's indeed the case for the RGB8 pixels in our static arrays used to initialize our textures. If you didn't know about this OpenGL pitfall before, you do now.[‡]

Normal Map 2D Texture Initialization

```
glBindTexture(GL_TEXTURE_2D, TO_NORMAL_MAP);
/* Load each mipmap level of range-compressed 128x128 brick normal
   map texture. */
for (size = 128, level = 0, image = myBrickNormalMapImage;
     size > 0;
     size /= 2, image += 3*size*size, level++) {
  glTexImage2D(GL_TEXTURE_2D, level,
    GL_RGB8, size, size, 0, GL_RGB, GL_UNSIGNED_BYTE, image);
}
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
  GL_LINEAR_MIPMAP_LINEAR);
```

We bind to the texture object for our brick pattern normal map 2D texture and load each of the 7 mipmap levels, starting with the 128x128 base level and working down to the 1x1 level. Each level is packed into the `myBrickNormalMapImage` array right after the

---

[‡] Being aware of pitfalls such as this one can save you a lot of time debugging. This and other OpenGL pitfalls are enumerated in my article "Avoiding 19 Common OpenGL Pitfalls" found here http://developer.nvidia.com/object/Avoiding_Common_ogl_Pitfalls.html An earlier HTML version of the article (with just 16 pitfalls) is found here http://www.opengl.org/developers/code/features/KilgardTechniques/oglpitfall/oglpitfall.html

previous level. So the 64x64 mipmap level immediately follows the 128x128 level, and so on. OpenGL's default minification filter is "nearest mipmap linear" (again, a weird default—it means nearest filtering within a mipmap level and then bilinear filtering between the adjacent mipmap levels) so we switch to higher-quality "linear mipmap linear" filtering.

Normalize Vector Cube Map Texture Initialization

```
glBindTexture(GL_TEXTURE_CUBE_MAP, TO_NORMALIZE_VECTOR_CUBE_MAP);
/* Load each 32x32 face (without mipmaps) of range-compressed "normalize
   vector" cube map. */
for (face = 0, image = myNormalizeVectorCubeMapImage;
     face < 6;
     face++, image += 3*32*32) {
  glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_X + face, 0,
    GL_RGB8, 32, 32, 0, GL_RGB, GL_UNSIGNED_BYTE, image);
}
glTexParameteri(GL_TEXTURE_CUBE_MAP, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
glTexParameteri(GL_TEXTURE_CUBE_MAP, GL_TEXTURE_WRAP_S,
  GL_CLAMP_TO_EDGE);
glTexParameteri(GL_TEXTURE_CUBE_MAP, GL_TEXTURE_WRAP_T,
  GL_CLAMP_TO_EDGE);
```

Next, we bind the texture object for the "normalization vector" cube map[1] intended to quickly normalize the 3D lighting vectors that are passed as texture coordinates. The cube map texture has six faces but there's no need for mipmaps. Each face is packed into the **`myNormalizeVectorCubeMapImage`** array right after the prior face with the faces ordered in the order of the sequential texture cube map face OpenGL enumerants.

Again, the default minification state is inappropriate (this time because we don't have mipmaps) so **`GL_LINEAR`** is specified instead. While the default **`GL_REPEAT`** wrap mode was fine for the brick pattern that we intend to tile over the surface of the torus, the **`GL_CLAMP_TO_EDGE`** wrap mode (introduced by OpenGL 1.2) keeps one edge of a cube map face from bleeding over to the other.

GLUT and OpenGL are now initialized so it is time to begin loading, compiling, and configuring the Cg programs.

Cg Runtime Initialization

```
myCgContext = cgCreateContext();
checkForCgError("creating context");
```

---

[1] Using a "normalization vector" cube map allows our demo to work on older DirectX 8-class GPUs that lacked the shading generality to normalize vectors mathematically. Ultimately as more capable GPUs become ubiquitous, use of normalization cube maps is sure to disappear in favor of normalizing a vector mathematically. See Exercise 5.

Before we can do anything with the Cg runtime, we need to allocate a Cg compilation context with **`cgCreateContext`**. Typically, your application just needs one Cg compilation context unless you have a multi-threaded application that requires using the Cg runtime concurrently in different threads. Think of the Cg context as the context and container for all your Cg programs that are creating, loading (compiling), and configured by the Cg runtime.

Cg Vertex Profile Selection

```
myCgVertexProfile = cgGLGetLatestProfile(CG_GL_VERTEX);
cgGLSetOptimalOptions(myCgVertexProfile);
checkForCgError("selecting vertex profile");
```

We need a profile with which to compile our vertex program. We could hard-code a particular profile (for example, the multi-vendor **`CG_PROFILE_ARBVP1`** profile), but we are better off asking the CgGL runtime to determine the best vertex profile for our current OpenGL context by calling the **`cgGLGetLatestProfile`** routine. (Keep in mind there's a current OpenGL rendering context that GLUT created for us when we called **`glutCreateWindow`**.) **`cgGLGetLatestProfile`** calls OpenGL queries to examine the current OpenGL rendering context. Based on the OpenGL **`GL_EXTENSIONS`** string, this routine can decide what profiles are supported and then which hardware-supported profile offers the most functionality and performance. The **`CG_GL_VERTEX`** parameter says to return the most appropriate vertex profile, but we can also pass **`CG_GL_FRAGMENT`**, as we will do later, to determine the most appropriate fragment profile.

Cg supports a number of vertex profiles. These are the vertex profiles currently supported by Cg 1.4 for OpenGL: **`CG_PROFILE_VP40`** corresponds to the **`vp40`** vertex program profile for the **`NV_vertex_program3`** OpenGL extension (providing full access to the vertex processing features of NVIDIA's GeForce 6 Series GPUs such as vertex textures). **`CG_PROFILE_VP30`** corresponds to the **`vp30`** vertex program profile for the **`NV_vertex_program2`** OpenGL extension (providing full access to the vertex processing features of NVIDIA's GeForce FX GPUs such as per-vertex dynamic branching). **`CG_PROFILE_ARBVP1`** corresponds to the **`arbvp1`** vertex program profile for the **`ARB_vertex_program`** OpenGL extension (a multi-vendor OpenGL standard, supported by both NVIDIA and ATI). **`CG_PROFILE_VP20`** corresponds to the **`vp20`** vertex program profile for the **`NV_vertex_program`** and **`NV_vertex_program1_1`** OpenGL extensions (for NVIDIA's GeForce3, GeForce4 Ti, and later GPUs).

While several GPUs can support the same profile, there may be GPU-specific techniques the Cg compiler can use to make the most of the available functionality and generate better code for your given GPU. By calling **`cgGLSetOptimalOptions`** with the profile we've selected, we ask the compiler to optimize for the specific hardware underlying our OpenGL rendering context.

For example, some vertex profiles such as **`CG_PROFILE_VP40`** support texture fetches but typically support fewer texture image units than the hardware's corresponding fragment-level texture functionality. **`cgGLSetOptimalOptions`** informs the compiler what the hardware's actual vertex texture image unit limit is.

Vertex Program Creation and Loading

```
myCgVertexProgram =
  cgCreateProgramFromFile(
    myCgContext,              /* Cg runtime context */
    CG_SOURCE,                /* Program in human-readable form */
    myVertexProgramFileName,  /* Name of file containing program */
    myCgVertexProfile,        /* Profile to try */
    myVertexProgramName,      /* Entry function name */
    NULL);                    /* No extra compiler options */
checkForCgError("creating vertex program from file");
cgGLLoadProgram(myCgVertexProgram);
checkForCgError("loading vertex program");
```

Now we try to create and load the Cg vertex program. We use the optimal vertex profile for our OpenGL rendering context to compile the vertex program contained in the file named by **`myVertexProgramFileName`**. As it turns out, the **`C8E6v_torus`** vertex program is simple enough that every Cg vertex profile mentioned in the last section is functional enough to compile the **`C8E6v_torus`** program.

The **`cgCreateProgramFromFile`** call reads the file, parses the contents, and searches for the entry function specified by **`myVertexProgramName`** and, if found, creates a vertex program for the profile specified by **`myCgVertexProfile`**. The **`cgCreateProgramFromFile`** routine is a generic Cg runtime routine so it just creates the program without actually translating the program into a form that can be passed to the 3D rendering programming interface.

You don't actually need a current OpenGL rendering context to call **`cgCreateProgramFromFile`**, but you do need a current OpenGL rendering context that supports the profile of the program for **`cgGLLoadProgram`** to succeed.

It is the OpenGL-specific **`cgGLLoadProgram`** routine that translates the program into a profile-dependent form. For example, in the case of the multi-vendor **`arbvp1`** profile, this includes calling the **`ARB_vertex_program`** extension routine **`glProgramStringARB`** to create an OpenGL program object.

We expect **`cgGLLoadProgram`** to "just work" because we've already selected a profile suited for our GPU and **`cgCreateProgramFromFile`** successfully compiled the Cg program into a form suitable for that profile.

Vertex Program Parameter Handles

```
myCgVertexParam_lightPosition =
  cgGetNamedParameter(myCgVertexProgram, "lightPosition");
checkForCgError("could not get lightPosition parameter");

myCgVertexParam_eyePosition =
  cgGetNamedParameter(myCgVertexProgram, "eyePosition");
checkForCgError("could not get eyePosition parameter");

myCgVertexParam_modelViewProj =
  cgGetNamedParameter(myCgVertexProgram, "modelViewProj");
checkForCgError("could not get modelViewProj parameter");

myCgVertexParam_torusInfo =
  cgGetNamedParameter(myCgVertexProgram, "torusInfo");
checkForCgError("could not get torusInfo parameter");
```

Now that the vertex program is created and successfully loaded, we initialize all the Cg parameter handles. Later during rendering in the **`display`** callback, we will use these parameter handles to update whatever OpenGL state the compiled program associates with each parameter.

In this demo, we know *a priori* what the input parameter names are to keep things simple. If we had no special knowledge of the parameter names, we could use Cg runtime routines to iterate over all the parameter names for a given program (see the **`cgGetFirstParameter`**, **`cgGetNextParameter`**, and related routines—use these for Exercise 11 at the end of this article).

Cg Fragment Profile Selection

```
myCgFragmentProfile = cgGLGetLatestProfile(CG_GL_FRAGMENT);
cgGLSetOptimalOptions(myCgFragmentProfile);
checkForCgError("selecting fragment profile");
```

We select our fragment profile in the same manner we used to select our vertex profile. The only difference is we pass the **`CG_GL_FRAGMENT`** parameter when calling **`cgGLGetLatestProfile`**.

Cg supports a number of fragment profiles. These are the fragment profiles currently supported by Cg 1.4 for OpenGL: **`CG_PROFILE_FP40`** corresponds to the **`fp40`** vertex program profile for the **`NV_fragment_program2`** OpenGL extension (providing full access to the fragment processing features of NVIDIA's GeForce 6 Series GPUs such as per-fragment dynamic branching). **`CG_PROFILE_FP30`** corresponds to the **`fp30`** vertex program profile for the **`NV_fragment_program`** OpenGL extension (providing full access to the fragment processing features of NVIDIA's GeForce FX GPUs). **`CG_PROFILE_ARBFP1`** corresponds to the **`arbfp1`** fragment program profile for the **`ARB_fragment_program`** OpenGL extension (a multi-vendor OpenGL standard, supported by both NVIDIA and ATI). **`CG_PROFILE_FP20`** corresponds to the **`fp20`** vertex program profile for the **`NV_texture_shader`**, **`NV_texture_shader2`**,

`NV_register_combiners`, and **`NV_register_combiners2`** OpenGL extensions (for NVIDIA's GeForce3, GeForce4 Ti, and later GPUs).

As in the vertex profile case, **`cgGLSetOptimalOptions`** informs the compiler about specific hardware limits relevant to fragment profiles. For example, when your OpenGL implementation supports the **`ATI_draw_buffers`** extension, the **`cgGLSetOptimalOptions`** informs the compiler of this fact so the compiler can know how many color buffers are actually available when compiling for fragment profiles that support output multiple color buffers. Other limits such as the **`ARB_fragment_program`** limit on texture indirections are likewise queried so the compiler is aware of this limit. The maximum number of texture indirections the GPU can support may require the compiler to re-schedule the generated instructions around this limit. Other profile limits include the number of texture image units available, the maximum number of temporaries and constants allowed, and the static instruction limit.

Fragment Program Creation and Loading

```
myCgFragmentProgram =
  cgCreateProgramFromFile(
    myCgContext,                /* Cg runtime context */
    CG_SOURCE,                  /* Program in human-readable form */
    myFragmentProgramFileName,  /* Name of file containing program */
    myCgFragmentProfile,        /* Profile to try */
    myFragmentProgramName,      /* Entry function name */
    NULL);                      /* No extra compiler options */
checkForCgError("creating fragment program from file");
cgGLLoadProgram(myCgFragmentProgram);
checkForCgError("loading fragment program");
```

We create and load the fragment program in much the same manner as the vertex program.

Fragment Program Parameter Handles

```
myCgFragmentParam_ambient =
  cgGetNamedParameter(myCgFragmentProgram, "ambient");
checkForCgError("getting ambient parameter");

myCgFragmentParam_LMd =
  cgGetNamedParameter(myCgFragmentProgram, "LMd");
checkForCgError("getting LMd parameter");

myCgFragmentParam_LMs =
  cgGetNamedParameter(myCgFragmentProgram, "LMs");
checkForCgError("getting LMs parameter");

myCgFragmentParam_normalMap =
  cgGetNamedParameter(myCgFragmentProgram, "normalMap");
checkForCgError("getting normalMap parameter");

myCgFragmentParam_normalizeCube =
  cgGetNamedParameter(myCgFragmentProgram, "normalizeCube");
checkForCgError("getting normalizeCube parameter");
```

```
myCgFragmentParam_normalizeCube2 =
  cgGetNamedParameter(myCgFragmentProgram, "normalizeCube2");
checkForCgError("getting normalizeCube2 parameter");
```

We initialize input parameter handles in the same manner as done for vertex parameter handles.

Setting OpenGL Texture Objects for Sampler Parameters

```
cgGLSetTextureParameter(myCgFragmentParam_normalMap,
  TO_NORMAL_MAP);
checkForCgError("setting normal map 2D texture");

cgGLSetTextureParameter(myCgFragmentParam_normalizeCube,
  TO_NORMALIZE_VECTOR_CUBE_MAP);
checkForCgError("setting 1st normalize vector cube map");

cgGLSetTextureParameter(myCgFragmentParam_normalizeCube2,
  TO_NORMALIZE_VECTOR_CUBE_MAP);
checkForCgError("setting 2nd normalize vector cube map");
```

Parameter handles for sampler parameters need to be associated with OpenGL texture objects. The first **`cgGLSetTextureParameter`** call associates the **`TO_NORMAL_MAP`** texture object with the **`myCgFragmentParam_normalMap`** parameter handle.

Notice how the **`TO_NORMALIZE_VECTOR_CUBE_MAP`** texture object is associated with the *two* distinct sampler parameters, **`normalizeCube`** and **`normalizeCube2`**. The reason this is done is to support older DirectX 8-class hardware such as the GeForce3 and GeForce4 Ti. These older DirectX 8-class GPUs must sample the texture associated with a given texture unit and that unit's corresponding texture coordinate set (and *only* that texture coordinate set). In order to support DirectX 8-class profiles (namely, **`fp20`**), the **`C8E4f_specSurf`** fragment program is written in such a way that the texture units associated with the two 3D vectors to be normalized (**`lightDirection`** and **`halfAngle`**) are each bound to the same "normalization vector" cube map. If there was no desire to support older DirectX 8-class hardware, fragment programs targeting the more general DirectX 9-class profiles (namely, **`arbfp1`** and **`fp30`**) could simply sample a single "normalization vector" texture unit.

Alternatively, the Cg fragment program could normalize the 3D lighting vectors with the **`normalize`** Cg standard library routine (see Exercise 5 at the end of this article), but for a lot of current hardware, a "normalization vector" cube map is faster and the extra precision for a mathematical normalize function is not crucial for lighting.

Start Event Processing

```
  glutMainLoop();
  return 0;  /* Avoid a compiler warning. */
}
```

GLUT, OpenGL, and Cg are all initialized now so we can start GLUT event processing. This routine never returns. When a redisplay of the GLUT window created earlier is needed, the **`display`** callback is called. When a key press occurs in the window, the **`keyboard`** callback is called.

Displaying the Window

Earlier in the code, we forward declared the **`display`** callback. Now it's time to discuss what the **`display`** routine does and how exactly we render our bump-mapped torus using the textures and Cg vertex and fragment programs we've loaded.

Rendering a 2D Mesh to Generate a Torus

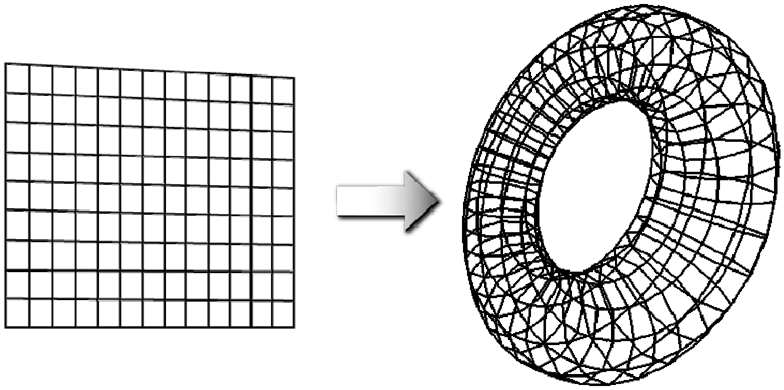
In the course of updating the window, the **`display`** callback invokes the **`drawFlatPatch`** subroutine. This subroutine renders a flat 2D mesh with immediate-mode OpenGL commands.

```
/* Draw a flat 2D patch that can be "rolled & bent" into a 3D torus by
   a vertex program. */
void
drawFlatPatch(float rows, float columns)
{
  const float m = 1.0f/columns;
  const float n = 1.0f/rows;
  int i, j;

  for (i=0; i<columns; i++) {
    glBegin(GL_QUAD_STRIP);
    for (j=0; j<=rows; j++) {
      glVertex2f(i*m, j*n);
      glVertex2f((i+1)*m, j*n);
    }
    glVertex2f(i*m, 0);
    glVertex2f((i+1)*m, 0);
    glEnd();
  }
}
```

The mesh consists of a number of adjacent quad strips. The **`C8E6v_torus`** vertex program will take these 2D vertex coordinates and use them as parametric coordinates for evaluating the position of vertices on a torus.

Nowadays it's much faster to use OpenGL vertex arrays, particularly with vertex buffer objects, to render geometry, but for this simple demo, immediate mode rendering is easier.



2D Grid Over (s,t) ∈ [0,1]

Tessellated Torus

Figure 8-7 from *The Cg Tutorial* is replicated to illustrate how a 2D mesh could be procedurally “rolled and bent” into a torus by a vertex program.

The Display Callback

```
static void display(void)
{
  const float outerRadius = 6, innerRadius = 2;
  const int sides = 20, rings = 40;
  const float eyeRadius = 18.0;
  const float eyeElevationRange = 8.0;
  float eyePosition[3];

  glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
```

The `display` callback has a number of constants that control the torus size and tessellation and how the torus is viewed.

```
  eyePosition[0] = eyeRadius * sin(myEyeAngle);
  eyePosition[1] = eyeElevationRange * sin(myEyeAngle);
  eyePosition[2] = eyeRadius * cos(myEyeAngle);

  glLoadIdentity();
  gluLookAt(
    eyePosition[0], eyePosition[1], eyePosition[2],
    0.0 ,0.0,  0.0,   /* XYZ view center */
    0.0, 1.0,  0.0);  /* Up is in positive Y direction */
```

The viewing transform is re-specified each frame. The eye position is a function of `myEyeAngle`. By animating this variable, the viewer rotates around the torus with a sinusoidally varying elevation. Because specular bump mapping is view-dependent, the specular lighting varies over the torus as the viewer rotates around.

Binding, Configuring, and Enabling the Vertex Program

```
cgGLBindProgram(myCgVertexProgram);
checkForCgError("binding vertex program");

cgGLSetStateMatrixParameter(myCgVertexParam_modelViewProj,
                            CG_GL_MODELVIEW_PROJECTION_MATRIX,
                            CG_GL_MATRIX_IDENTITY);
checkForCgError("setting modelview-projection matrix");
cgGLSetParameter3f(myCgVertexParam_lightPosition, -8, 0, 15);
checkForCgError("setting light position");
cgGLSetParameter3fv(myCgVertexParam_eyePosition, eyePosition);
checkForCgError("setting eye position");
cgGLSetParameter2f(myCgVertexParam_torusInfo, outerRadius, innerRadius);
checkForCgError("setting torus information");

cgGLEnableProfile(myCgVertexProfile);
checkForCgError("enabling vertex profile");
```

Prior to rendering the 2D mesh, we must bind to the vertex program, set the various input parameters used by the program with the parameter handles, and then enable the particular profile. Underneath the covers of these OpenGL-specific Cg routines, the necessary OpenGL commands are invoked to configure the vertex program with its intended parameter values.

Rather than specifying the parameter value explicitly as with the **`cgGLSetParameter`** routines, the **`cgGLSetStateMatrixParameter`** call binds the current composition of the modelview and projection matrices (specified earlier by **`gluLookAt`** and **`gluPerspective`** commands respectively) to the **`modelViewProj`** parameter.

One of the really nice things about the CgGL runtime is it saves you from having to know the details of what OpenGL routines are called to configure use of your Cg vertex and fragment programs. Indeed, the required OpenGL commands can very considerably between different profiles.

Binding, Configuring, and Enabling the Fragment Program

```
  cgGLBindProgram(myCgFragmentProgram);
  checkForCgError("binding fragment program");

  cgGLSetParameter4fv(myCgFragmentParam_ambient, myAmbient);
  checkForCgError("setting ambient");
  cgGLSetParameter4fv(myCgFragmentParam_LMd, myLMd);
  checkForCgError("setting diffuse material");
  cgGLSetParameter4fv(myCgFragmentParam_LMs, myLMs);
  checkForCgError("setting specular material");

  cgGLEnableTextureParameter(myCgFragmentParam_normalMap);
  checkForCgError("enable texture normal map");
  cgGLEnableTextureParameter(myCgFragmentParam_normalizeCube);
  checkForCgError("enable 1st normalize vector cube map");
  cgGLEnableTextureParameter(myCgFragmentParam_normalizeCube2);
  checkForCgError("enable 2nd normalize vector cube map");

  cgGLEnableProfile(myCgFragmentProfile);
  checkForCgError("enabling fragment profile");
```

The fragment program is bound, configured, and enabled in much the same manner with the additional task of enabling texture parameters with **`cgGLEnableTextureParameter`** to ensure the indicated texture objects are bound to the proper texture units.

Without you having to know the details, **`cgGLEnableTextureParameter`** calls **`glActiveTexture`** and **`glBindTexture`** to bind the correct texture object (specified earlier with **`cgGLSetTextureParameter`**) into the compiled fragment program's appropriate texture unit in the manner required for the given profile.

Render the 2D Mesh

```
  drawFlatPatch(sides, rings);
```

With the vertex and fragment program each configured properly, now render the flat 2D mesh that will be formed into a torus and illuminated with specular and diffuse bump mapping.

Disable the Profiles and Swap

```
  cgGLDisableProfile(myCgVertexProfile);
  checkForCgError("disabling vertex profile");

  cgGLDisableProfile(myCgFragmentProfile);
  checkForCgError("disabling fragment profile");

  glutSwapBuffers();
}
```

While not strictly necessary for this demo because just one object is rendered per frame, after rendering the 2D mesh, the profiles associated with the vertex program and fragment program are each disabled. This way you could perform conventional OpenGL rendering. After using the OpenGL-specific Cg runtime, be careful not to assume how OpenGL state such as what texture objects are bound to what texture units.

Keyboard Processing

Along with the **`display`** callback, we also forward declared and registered the **`keyboard`** callback. Now it's time to see how the demo responses to simple keyboard input.

Animating the Eye Position

```
static void advanceAnimation(void)
{
  myEyeAngle += 0.05f;
  if (myEyeAngle > 2*3.14159)
    myEyeAngle -= 2*3.14159;
  glutPostRedisplay();
}
```

In order to animate the changing eye position so the view varies, the **`advanceAnimation`** callback is registered as the GLUT idle function. The routine advances **`myEyeAngle`** and posts a request for GLUT to redraw the window with **`glutPostRedisplay`**. GLUT calls the idle function repeatedly when there are no other events to process.

The Keyboard Callback

```
static void keyboard(unsigned char c, int x, int y)
{
  static int animating = 0;

  switch (c) {
  case ' ':
    animating = !animating; /* Toggle */
    glutIdleFunc(animating ? advanceAnimation : NULL);
    break;
```

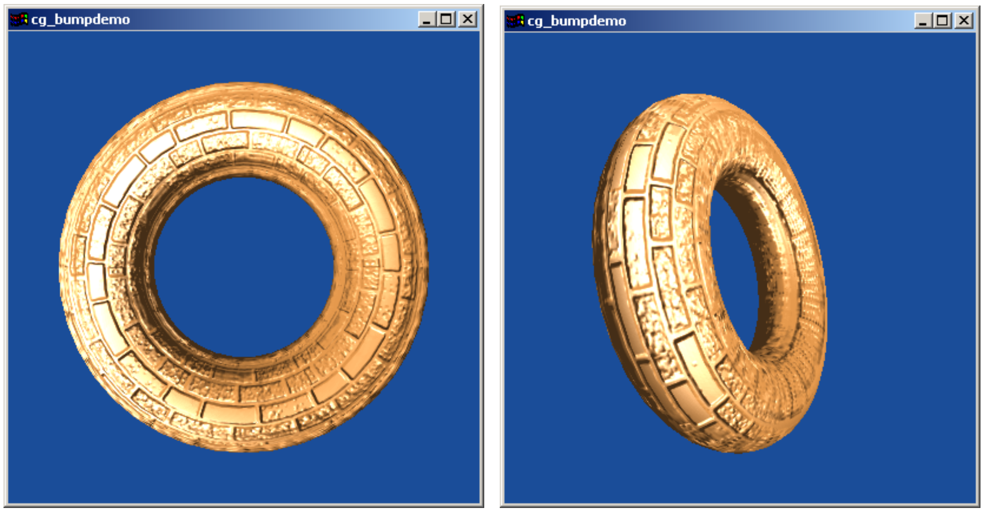
The space bar toggles animation of the scene by registering and de-registering the **`advanceAnimation`** routine as the idle function.

```
  case 27:  /* Esc key */
    cgDestroyProgram(myCgVertexProgram);
    cgDestroyProgram(myCgFragmentProgram);
    cgDestroyContext(myCgContext);
    exit(0);
    break;
  }
}
```

The Esc key exits the demo. While it is not necessary to do so, the calls to **`cgDestroyProgram`** and **`cgDestroyContext`** deallocate the Cg runtime objects, along with their associated OpenGL state.

The Demo in Action

The images below show the rendered bump-mapped torus initially (left) and while animating (right).



Conclusions

This tutorial presents a complete Cg bump mapping demo written in ANSI C and rendering with OpenGL, relying on two of the actual Cg vertex and fragment programs detailed in *The Cg Tutorial*. I hope this tutorial “fills in the gaps” for those intrepid *Cg Tutorial* readers now inspired to integrate Cg technology into their graphics application. The `cg_bumpdemo` demo works on ATI and NVIDIA GPUs (and GPUs from any other vendor that support the standard, multi-vendor vertex and fragment program extensions). The demo is cross-platform as well, supporting Windows, OS X, and Linux systems.

The time you invest integrating the Cg runtime to your graphics application is time well spent because of the productivity and cross-platform support you unleash by writing shaders in Cg rather than resorting to low-level 3D rendering commands or a high-level shading language tied to a particular 3D API. With Cg, you can write shaders that work with two implementations of the same basic language (Cg & HLSL), two 3D rendering programming interfaces (OpenGL & Direct3D), three operating systems (Windows, OS X, and Linux), and the two major GPU vendors (ATI & NVIDIA—and any other vendors supporting DirectX 9-level graphics functionality).

Finally, Cg has evolved considerably since Randy and I wrote *The Cg Tutorial*. Cg 1.2 introduced a “sub-shader” facility allowing you to write shaders in Cg in a more modular fashion. And be sure to explore Cg 1.4’s updated implementation of the CgFX meta-shader format (compatible with Microsoft’s DirectX 9 FX format) to encapsulate non-programmable state, semantics, hardware-dependent rendering techniques, and support for multiple passes.

Exercises

Just as *The Cg Tutorial* provides exercises at the end of each chapter, here are some exercises to help you expand on what you've learned.

Improving the Shading

1. Support two lights. You'll need a second light position uniform parameter and your updated vertex program must output a second tangent-space light position. Example 5-4 in *The Cg Tutorial* will give you some ideas for supporting multiple lights. However, Example 5-4 is for two *per-vertex* lights; for this exercise, you want two *per-fragment* lights combined with bump mapping. *Hint:* If you add multiple lights, you might want to adjust down the values of `ambient`, `LMd`, and `LMs` to avoid an "over bright" scene.
2. Support a *positional* light (the current light is directional). Add controls so you can interactively position the light in the "hole" of the torus. Section 5.5 of *The Cg Tutorial* briefly explains the distinction between directional and positional lights.
3. Add geometric self-shadowing to the fragment program.
    a. Clamp the specular to zero if the *z* component of the tangent-space light direction is non-positive to better simulate self-shadowing (this is a situation where the light is "below" the horizon of the torus surface). See section 8.5.3 of *The Cg Tutorial* for details about geometric self-shadowing.
    b. Further tweak the geometric self-shadowing. Instead of clamping, modulate with `saturate(8*lightDirection.z)` so specular highlights don't "wink off" when self-shadowing occurs but rather drop off. When the scene animates, which approach looks better?
4. Change the specular exponent computation to use the `pow` standard library function instead of successive multiplication (you'll find `pow` is only available on more recent DirectX 9-class profiles such as `arbfp1` and `fp30`, not `fp20`). Provide the specular exponent as a uniform parameter to the fragment program.
5. Instead of using normalization cube maps, use the `normalize` standard library routine? Does the lighting change much? Does the performance change?
6. Rather than compute the tangent-space half-angle vector at each vertex and interpolate the half-angle for each fragment, compute the view vector at each vertex; then compute the half-angle at each fragment (by normalizing the sum of the interpolated normalized light vector and the interpolated normalized view vector). Does the lighting change much? Does the performance change?
7. **Advanced:** Read section 8.4 of *The Cg Tutorial* and implement bump mapping on an arbitrary textured polygonal mesh. Implement this approach to bump map an arbitrary textured model.

8. **Advanced:** Read section 9.4 of *The Cg Tutorial* and combine bump mapping with shadow mapping.

Improving the Cg Runtime Usage

9. Provide command line options to specify what file names contain the vertex and fragment programs.
10. Provide better diagnostic messages when errors occur.
11. Use the Cg runtime to query the uniform parameter names and then prompt the user for values for the various parameters (rather than having the parameter names and values hard coded in the program itself).
12. Rather than using global variables for each vertex and fragment program object, support loading a set of vertex and fragment programs and allow the user to select the current vertex and current fragment program from an interactive menu.

Appendix A: C8E6v_torus.cg Vertex Program

```
void C8E6v_torus(float2 parametric : POSITION,

             out float4 position       : POSITION,
             out float2 oTexCoord      : TEXCOORD0,
             out float3 lightDirection : TEXCOORD1,
             out float3 halfAngle      : TEXCOORD2,

         uniform float3 lightPosition,  // Object-space
         uniform float3 eyePosition,    // Object-space
         uniform float4x4 modelViewProj,
         uniform float2 torusInfo)
{
  const float pi2 = 6.28318530;  // 2 times Pi
  // Stetch texture coordinates counterclockwise
  // over torus to repeat normal map in 6 by 2 pattern
  float M = torusInfo[0];
  float N = torusInfo[1];
  oTexCoord = parametric * float2(-6, 2);
  // Compute torus position from its parameteric equation
  float cosS, sinS;
  sincos(pi2 * parametric.x, sinS, cosS);
  float cosT, sinT;
  sincos(pi2 * parametric.y, sinT, cosT);
  float3 torusPosition = float3((M + N * cosT) * cosS,
                                (M + N * cosT) * sinS,
                                N * sinT);
  position = mul(modelViewProj, float4(torusPosition, 1));
  // Compute per-vertex rotation matrix
  float3 dPds = float3(-sinS*(M+N*cosT), cosS*(M+N*cosT), 0);
  float3 norm_dPds = normalize(dPds);
  float3 normal = float3(cosS * cosT, sinS * cosT, sinT);
  float3 dPdt = cross(normal, norm_dPds);
  float3x3 rotation = float3x3(norm_dPds,
                               dPdt,
                               normal);
  // Rotate object-space vectors to texture space
  float3 eyeDirection = eyePosition - torusPosition;
  lightDirection = lightPosition - torusPosition;
  lightDirection = mul(rotation, lightDirection);
  eyeDirection = mul(rotation, eyeDirection);
  halfAngle = normalize(normalize(lightDirection) +
                        normalize(eyeDirection));
}
```

Appendix B: C8E4f_specSurf.cg Fragment Program

```
float3 expand(float3 v) { return (v-0.5)*2; }

void C8E4f_specSurf(float2 normalMapTexCoord : TEXCOORD0,
                    float3 lightDirection    : TEXCOORD1,
                    float3 halfAngle         : TEXCOORD2,

               out float4 color : COLOR,

           uniform float  ambient,
           uniform float4 LMd, // Light-material diffuse
           uniform float4 LMs, // Light-material specular
           uniform sampler2D   normalMap,
           uniform samplerCUBE normalizeCube,
           uniform samplerCUBE normalizeCube2)
{
  // Fetch and expand range-compressed normal
  float3 normalTex = tex2D(normalMap, normalMapTexCoord).xyz;
  float3 normal = expand(normalTex);
  // Fetch and expand normalized light vector
  float3 normLightDirTex = texCUBE(normalizeCube,
                                   lightDirection).xyz;
  float3 normLightDir = expand(normLightDirTex);
  // Fetch and expand normalized half-angle vector
  float3 normHalfAngleTex = texCUBE(normalizeCube2,
                                    halfAngle).xyz;
  float3 normHalfAngle = expand(normHalfAngleTex);

  // Compute diffuse and specular lighting dot products
  float diffuse = saturate(dot(normal, normLightDir));
  float specular = saturate(dot(normal, normHalfAngle));
  // Successive multiplies to raise specular to 8th power
  float specular2 = specular*specular;
  float specular4 = specular2*specular2;
  float specular8 = specular4*specular4;

  color = LMd*(ambient+diffuse) + LMs*specular8;
}
```

Re-implementing the Follow-up Cg Runtime Tutorial with CgFX[*]

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This whitepaper continues a tutorial I wrote a year ago titled "A Follow-up Cg Runtime Tutorial for Readers of *The Cg Tutorial"* in which I presented a complete OpenGL demo written in ANSI C that renders a procedurally-generated bump-mapped torus using Cg programs discussed in *The Cg Tutorial*,[†] a book I co-wrote about Cg programming.

Now I present the same demo but re-implement it with CgFX, a shading effect system built around Cg. CgFX is a file format and an associated runtime API for describing a complete shading effect that includes Cg programs, how these Cg programs are combined into potentially multiple rendering passes, how the input parameters for these programs are computed, how other non-programmable GPU state should be configured, and finally annotations so an application can appropriately associate its application-state to the effect's input parameters and rendering passes.

CgFX allows us to package a complete shading effect as a single unit so it can more easily be tweaked and shared among multiple applications. Re-implementing the original demo in CgFX also results in less application code.

The original whitepaper's demo program is called `cg_bumpdemo` so the new CgFX-based demo is called `cgfx_bumpdemo`. Before walking you through the complete source code for `cgfx_bumpdemo`, I first explain the rationale for CgFX and how CgFX structures the specification of a shading effect.

The Why and What of CgFX

CgFX addresses the fact that Cg programs, even though written in an expressive high-level language, do not completely express what is required to use a particular Cg program properly for a given shading effect. For one thing, you often need both a vertex and fragment program to be used simultaneously. You also need to know how non-

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[†] *The Cg Tutorial* by Randima (Randy) Fernando and Mark J. Kilgard is published by Addison-Wesley (ISBN 0321194969, 336 pages). The book is now available in Japanese translation (ISBN4-939007-55-3).

programmable state such as blending or depth testing should be configured. The complete effect may even require multiple rendering passes, performed in a particular order. And because of the differences in graphics hardware you must support or varying requirements for rendering quality and performance, multiple implementations of a particular effect—termed *techniques* in CgFX—may be required. Finally the parameters of the effect may require meta-information about the parameters such as their valid range or how the parameter is computed from other parameters. The big advantage of CgFX is you combine together everything needed to render a shading effect in a single place.

If you simply use Cg programs to implement a given rendering effect, you wind up embedding "application/effect glue" knowledge about your rendering effect in your application code. This makes it difficult for a rendering effect to be authored in isolation from your particular application. Artists and programmers working with shading effects should be able to treat shading as a form of 3D "content" that can be created, tweaked, deployed, and reused in much the same ways texture images and geometric models for 3D games and applications are managed as art resources that are distinct from the applications that create and use them.

For example, you might author an awesome shading effect to create the appearance of volumetric fog (or human skin or glowing lava or whatever) in your prototype rendering system. Now your manager/publisher/client wants your effect in a different 3D engine yesterday. The question is: How can you successfully author a shading effect without tying it to a particular application? CgFX answers this question.

The goal of CgFX is to separate a particular rendering effect from the application—or even better—the multiple applications that can render or *apply* the effect.

An *effect*—in the CgFX use of the term—is a shading algorithm and everything needed to utilize it that can be authored independently from the 3D application that ultimately renders the effect. In short, an effect should be a form of content that can be authored, tweaked, deployed, and reused without having to change the applications that use the effect.

Platform-independence for Effects

To provide the broadest benefits, this decoupling should also provide platform-independence both for content creation and deployment of effects. This independence includes:

- 3D API independence (across mainstream OpenGL, OpenGL ES, Direct3D, or "direct to the hardware" APIs),
- Operating system independence (across Windows, Linux, OS X, Solaris, or embedded systems),
- Graphics hardware vendor independence (whether NVIDIA or ATI), and
- Graphics platform independence (across PC, console, handheld device, or embedded devices).

Because CgFX builds upon Cg that already supports all the above platform variations, CgFX provides a uniquely interoperable basis for encapsulating shading effects. Each CgFX file contains multiple Cg functions, type declarations, effect parameters, and techniques.

The Structure of a CgFX Effect

Every valid CgFX file has the same basic syntax and structure for specifying an effect. When parsed by the Cg compiler, a CgFX file is first preprocessed by a C-like preprocessor pass so you can use **`#define`**, **`#include`**, and **`#ifdef`** as you do when writing C or C++ code.

The CgFX file syntax for an effect is broken into two types of constructs:

1. Techniques, and
2. Cg code that is referenced by expressions found within the techniques.

The Cg code and techniques can be more or less arbitrarily interleaved as long as Cg functions, types, and variables are declared before being referenced.

The Cg code within a CgFX file may specify Cg functions, type definitions, and *effect parameters* (basically Cg variable definitions). Each technique defines the implementation of a particular version of the effect and typically does so by referencing Cg code from within Cg expressions found within the technique. A single effect file may specify multiple techniques for the same effect. One effect may be designed for the best quality on the latest-and-greatest GPU available while another effect may be intended for lowest-common denominator rendering capabilities.

Each technique specifies its optional name and contains a sequence of passes. Likewise each *pass* specifies its optional name and contains a sequence of state assignments. Each *state assignment* is a name/value pair that assigns the value of some expression (written using the ful expressiveness of the Cg programming language) to a named state.

A *state* in CgFX is something such as whether blending is enabled or what fragment program should be bound. The value of a state assignment's expression and the named state's type must match. Each state's name and type correspond to some pre-registered 3D API state or some user-specified kind of state. Expressions can reference Cg functions, type definitions, and parameters declared earlier in the file. Expressions for state assignments can also use Cg standard library routines just as expressions in Cg programs can.

Here is an example of one of the techniques from `cgfx_bumpdemo.cgfx` file:

```
technique bumpdemo_arb {
  pass {
    FragmentProgram = compile arbfp1
      C8E4f_specSurf(Ambient,
                     float4(DiffuseMaterial  * LightColor, 1),
                     float4(SpecularMaterial * LightColor, 1),
                     normalMap, normalizeCube, normalizeCube);
    VertexProgram = compile arbvp1
      C8E6v_torus(LightPosition, EyePosition, ModelViewProj,
                  float2(OuterRadius, InnerRadius));
  }
}
```

(The complete contents of `bumpdemo.cgfx` are found in Appendix A.)

This technique is rather simple since it only implements a single pass. Multi-pass techniques list more than one `pass` definition. This technique has two state assignments to bind a vertex and fragment program.

Program State Assignments

The `FragmentProgram` and `VertexProgram` state assignments are somewhat "special" because they each expect a value that is a valid compiled Cg program. The `compile` keyword is followed by a Cg profile name (`arbfp1` for the multi-vendor OpenGL `ARB_fragment_program` profile and `arbvp1` for the multi-vendor OpenGL `ARB_vertex_program` profile) followed by a Cg entry function declared earlier in the file. The function name is followed by an ordered parameter list; however only function parameters declared as `uniform` are listed in this parameter list. In other words, output parameters and varying input parameters such as the vertex position or texture coordinates are excluded. Each parameter in the list is a Cg expression that evaluates to a value for the respective uniform parameter of the entry function. Often the expression is either a constant or simply references some effect parameter, but the expression could be arbitrarily complex.

Take a look at this expression from the `FragmentProgram` state assignment above:

```
                     float4(DiffuseMaterial  * LightColor, 1)
```

Notice how this expression multiplies the 3-component `DiffuseMaterial` and `LightColor` parameters together and forces the 4th component to be one. It is the value resulting from the evaluation of this expression that provides the value of the second uniform parameter (`LMd`) for the `C8E4f_specSurf` fragment program.

When a state assignment is *set* in the course of applying a technique (the Cg runtime API calls to set the state assignments of a pass are discussed later), the Cg runtime iterates in order over each state assignment for the selected pass. The Cg runtime evaluates expressions using the current values of any referenced effect parameters to determine the value for each state assignment. Then the Cg runtime assigns the resulting values to its corresponding state.

How does the Cg runtime evaluate expressions? In the course of the Cg runtime creating the effect, the Cg compiler (which exists within the Cg runtime) parses the effect and builds (compiles) each expression into a data structure that can be evaluated with a virtual machine (which also exists within the Cg runtime). Typically these expressions are quite simple (often merely constants or direct references to effect parameters) so the expense to evaluate such expressions is nominal.

As a consequence of setting a state assignment, the Cg runtime (or possibly a custom user-registered state callback) issues the appropriate 3D API commands associated with each state. In the case of the **`FragmentProgram`** and **`VertexProgram`** state assignments shown above, this means binding to the proper compiled program object and setting that program's parameters to the respective value of each evaluated expression.

Once all the state assignments for a pass have been set, the application can render objects and the appropriate GPU processing occurs.

State Assignments for Other Non-programmable State

The state assignments for Cg programs are special because they involve the compilation of Cg programs. Other state assignments can control non-programmable 3D API state such as blending and are typically simpler to specify. For example, to make sure a pass enables *SrcAlpha*/*OneMinusSrcAlpha* blending, you could write this state assignment within a pass definition:

```
BlendEnable = true;
BlendFunc = int2(SrcAlpha, OneMinusSrcAlpha);
```

These state assignments for **`BlendEnable`** and **`BlendFunc`** are registered to set the respective state within the conventional 3D hardware rendering pipeline. For a state such as **`BlendFunc`** that is most conveniently specified with enumerated names, such names are pre-registered for the state values.

Complex effects often involve the combination of state assignments for programmable and non-programmable states. With the CgFX runtime you can even register custom states to extend CgFX to handle unanticipated or effect-specific states.

Annotations

Along with Cg code and techniques, CgFX files also can associate annotations with each technique, pass, program, or effect parameter. An *annotation* is a typed name/value pair that can be queried (inspected) by applications using the Cg runtime. The purpose of an annotation is to associate some meta-information with the annotated object that an application can use to apply the effect properly.

Here is an example:

```
float3 DiffuseMaterial<
  string type = "color";
  float3 minValue = float3(0,0,0);
  float3 maxValue = float3(1,1,1);
> = { 0.9, 0.6, 0.3 };
```

The angle brackets after the effect parameter name **`DiffuseMaterial`** delimit a sequence of annotations. In this example, three annotations are specified.

How annotations are used is entirely application dependent. The expectation is that effect authors and 3D application developers desiring to share effects would agree to an appropriate set of annotations. For example, the **`type`**, **`minValue`**, and **`maxValue`** annotations would allow an effect editor to display a color chooser widget with the appropriate numeric range for setting the **`DiffuseMaterial`** effect parameter.

CgFX Runtime API Support

As of Cg Toolkit version 1.4, the Cg runtime API includes support for loading and using CgFX files. When we discuss **`cgfx_bumpdemo.c`**, we will see portions of this API for CgFX in action. Support for CgFX is not a layer upon Cg but rather a first-class capability implemented within the Cg runtime.

A Complete CgFX Demo

What follows is the *complete* source code for a CgFX-based version of **`cg_bumpdemo`**. Hence this new demo is called **`cgfx_bumpdemo`**.

The demo's CgFX effect file, named **`bumpdemo.cgfx`**, contains two Cg programs taken directly from Chapter 8 (Bump Mapping) of *The Cg Tutorial*. While the Cg programs are included in the appendix the end of this article, please consult *The Cg Tutorial* for an explanation of the programs and the underlying bump mapping background and mathematics.

The demo renders with OpenGL and interfaces with the window system via the cross-platform OpenGL Utility Toolkit (GLUT).[†] To interface the application with the Cg programs, the demo calls the generic Cg and OpenGL-specific CgGL runtime routines.

OpenGL, GLUT, and the Cg and CgGL runtimes are supported on Windows, OS X, Linux, and Solaris so this demo source code compiles and runs on all these operating systems. The demo automatically selects the most appropriate profile for your hardware.

[†] Documentation, source code, and pre-compiled GLUT libraries are available from http://www.opengl.org/developers/documentation/glut.html

Cg supports multi-vendor OpenGL profiles (namely, `arbvp1` and `arbfp1`) so the demo works on GPUs from ATI, NVIDIA, or any other OpenGL implementation, such as Brian Paul's open source Mesa library, that exposes the multi-vendor `ARB_vertex_program` and `ARB_fragment_program` OpenGL extensions.

CgFX Demo Source Code Walkthrough

The `cgfx_bumpdemo` demo consists of the following four source files:

1. `cgfx_bumpdemo.c`—ANSI C source code for the CgFX-based demo.
2. `brick_image.h`—Header file containing RGB8 image data for a mipmapped 128x128 normal map for a brick pattern.
3. `nmap_image.h`—Header file containing RGB8 image data for a normalization vector cube map with 32x32 faces.
4. `cgfx_bumpdemo.cgfx`—CgFX effect file.

Later, we will go through `cgfx_bumpdemo.c` line-by-line.

Pre-defined Texture Data

To keep the demo self-contained and maintain the focus on how the Cg runtime loads and configures the CgFX effect and then renders with the effect, this demo uses static texture image data included in the two header files. These two image data header files are the same ones used in the prior `cg_bumpdemo` example.

The data in these header files are used to construct OpenGL texture objects for a brick pattern normal map 2D texture and a "vector normalization" cube map. These texture objects are sampled by the fragment program.

The data in the two headers files consists of hundreds of comma-separated numbers (I'll save you the tedium of publishing all the numbers in this article…). Rather than static data compiled into an executable, a typical application would read normal map textures from on-disk image files or convert a height-field image file to a normal map. Likewise, a "normalization vector" cube map is typically procedurally generated rather than loaded from static data.

The Effect File Contents

The heart of the demo's shading is encapsulated within the `bumpdemo.cgfx` effect file. The demo reads this effect file when the demo begins running. The demo uses the Cg runtime to create an effect from `bumpdemo.cgfx` and then selects a valid technique for rendering the demo's bump-mapped torus.

Cg Programs within the Effect File

The CgFX file begins with the Cg vertex and fragment programs needed by the effect. These functions are explained in Chapter 8 (Bump Mapping) of *The Cg Tutorial*.

Rather than rehash the background, theory, and operation of these Cg programs, you should consult Chapter 8 of *The Cg Tutorial*. Pages 200 to 204 explain the construction of the brick pattern normal map. Pages 206 to 208 explain the construction and application of a normalization cube map. Pages 208 to 211 explains specular bump mapping, including the `C8E4f_specSurf` fragment program. Pages 211 to 218 explain texture-space bump mapping. Pages 218 to 224 explain the construction of the per-vertex coordinate system needed for texture-space bump mapping for the special case of an object (the torus) that is generated from parametric equations by the `C8E6v_torus` vertex program.

Effect Parameters within the Effect File

After the Cg programs in `cgfx_bumpdemo.cgfx`, there are a set of effect parameters. These effect parameters drive the input parameters for the Cg programs.

Most of the effect parameters have reasonable default initializations and so can simply be left alone. These include the torus size parameters (`OuterRadius` and `InnerRadius`) and the light and material colors (`Ambient`, `DiffuseMaterial`, `SpecularMaterial`, and `LightColor`). Providing a default value for an effect parameter is simply a matter of assigning a value to the parameter. Example:

```
float OuterRadius = 6;
float InnerRadius = 2;
```

To help an application know which effect parameters contain colors and what the expected component range is for these parameters, the light and material color parameters include appropriate annotations. Example:

```
float Ambient<
  string type = "ambient";
  float minValue = 0.0;
  float maxValue = 1.0;
> = 0.3;
```

The `cgfx_bumpdemo` application does not actually use these annotation (it does not even query them), but these annotations could be used by other applications that seek to load the effect. Making use of effect-specific annotations can be very useful but is beyond the scope of this tutorial. Note that annotations can include strings.

Two other parameters (`normalMap` and `normalizeCube`) name sampler effect parameters. A *sampler* in Cg provides a means to sample a texture object (effectively, performing a texture lookup). Because the texture objects are created by the application, conventional initialization of sampler parameters does not make much sense. However you can instead specify some sampling state appropriate for textures using a special `sampler_state` keyword to assign a set of sampler states to a sampler effect parameter. For example, you can indicate the proper filtering and wrap modes as well as whether mipmaps should be automatically generated for the texture. Examples:

```
sampler2D normalMap = sampler_state {
  generateMipMap = true;
  minFilter = LinearMipMapLinear;
  magFilter = Linear;
};

samplerCUBE normalizeCube = sampler_state {
  minFilter = Linear;
  magFilter = Linear;
  wrapS = ClampToEdge;
  wrapT = ClampToEdge;
};
```

Other effect parameters (`ModelViewProj`, `LightPosition`, and `EyePosition`) control the scene's spatial arrangement. While the default initialization of these parameters can provide an initial spatial arrangement for the scene, we expect these effect parameters will be updated to animate the rendered scene. In this particular demo, we expect to rotate the viewer around the torus to observe how the lighting changes so every frame will update the eye position.

The Cg runtime allows us to query by name, by semantic, or iterate through all the effect parameters in an effect. Handles to each parameter can then be used to query and set the values of these effect parameters. This is identical to how the Cg runtime support for program parameters (rather than effect parameters) allows parameters for programs to be queried and set. However effect parameters are more powerful because a single effect parameter can drive program parameters for multiple different programs belonging to different passes of different techniques. Also because program parameters in a vertex or fragment program state assignment are specified as expressions, such expressions can combine multiple effect parameters to compute each program parameter for the vertex or fragment program.

As we will see, an effect can be parameterized with high-level effect parameters that drive program parameters automatically. For example, the `C8E4f_specSurf` fragment program expects its parameter named `LMd` to contain the light color and diffuse material color pre-multiplied together. Likewise its `LMs` parameter expects to contain the light color and specular material color pre-multiplied together. As we will see, effect parameters allow us to specify the light color, the diffuse material color, and specular material color independently and let the Cg runtime perform the necessary pre-multiplication.

Because effect parameters drive the values of program parameters through programmable expressions, effect parameters can be more abstract than program parameters without compromising the performance of vertex and fragment programs.

Techniques within the Effect File

Once some effect parameters and Cg parameters have been specified, we can specify a set of techniques that use those Cg programs and effect parameters.

We define four techniques for four different combinations of OpenGL profiles supported by Cg. This allows the demo to select the best available technique for the effect based on the GPU capabilities available when the demo is run. The techniques are:

1. **`bumpdemo_nv40`**—Targets the full fragment and vertex capabilities of NVIDIA's GeForce 6 and 7 Series of GPUs (designated by their architectural family code name "nv40"). This technique compiles the effect's Cg vertex and fragment programs for the **`vp40`** and **`fp40`** profiles respectively.
2. **`bumpdemo_arb`**—Targets the fragment and vertex capabilities of the **`ARB_vertex_program`** and **`ARB_fragment_program`** multi-vendor extensions established as OpenGL Architectural Review Board (the ARB) standards. This technique compiles the effect's Cg vertex and fragment programs for the **`arbvp1`** and **`arbfp1`** profiles respectively.
3. **`bumpdemo_nv30`**—Targets the fragment and vertex capabilities of NVIDIA's GeForce FX Series of GPUs (designated by their architectural family code name "nv30"). This technique compiles the effect's Cg vertex and fragment programs for the **`vp30`** and **`fp30`** profiles respectively.
4. **`bumpdemo_nv20`**— Targets the more limited fragment and vertex capabilities of NVIDIA's GeForce3 and GeForce 4 Ti GPUs (designated by their architectural family code name "nv20"). This technique compiles the effect's Cg vertex and fragment programs for the **`vp20`** and **`fp20`** profiles respectively.

All four techniques are identical with the exception of the vertex and fragment profiles they specify when compiling the **`VertexProgram`** and **`FragmentProgram`** state assignments. This allows each technique to be specialized to the capabilities of a specific GPU architecture for optimal performance.

They are all quite similar and the **`bumpdemo_arb`** technique has already been listed earlier so here is the **`bumpdemo_nv40`** technique:

```
technique bumpdemo_nv40 {
  pass {
    FragmentProgram = compile fp40
      C8E4f_specSurf(Ambient,
                     float4(DiffuseMaterial  * LightColor, 1),
                     float4(SpecularMaterial * LightColor, 1),
                     normalMap, normalizeCube, normalizeCube);
    VertexProgram = compile vp40
      C8E6v_torus(LightPosition, EyePosition, ModelViewProj,
                 float2(OuterRadius, InnerRadius));
  }
}
```

While these techniques are different only in their Cg profiles, a given technique for an effect could be implemented differently, often using entirely different Cg programs. For example, one technique might account for shadowing for more realism while another version of the same effect might skip shadows or compute intermediate values with more precision.

On to the C Code

Now that we understand the effect that `cgfx_bumpdemo` will use, it's time to dissect `cgfx_bumpdemo.c` line-by-line as promised (we'll skip comments in the source code if the comments are redundant with the discussion below).

Initial Declarations

```
#include <math.h>
#include <stdlib.h>
#include <stdio.h>
#include <GL/glut.h>
#include <Cg/cg.h>
#include <Cg/cgGL.h>
```

The first three includes are basic ANSI C standard library includes. We will be using `sin`, `cos`, `printf`, `exit`, and `NULL`. We rely on the GLUT header file to include the necessary OpenGL and OpenGL Utility Library (GLU) headers.

The `<Cg/cg.h>` header contains generic routines for loading and compiling Cg programs and CgFX effects but does not contain routines that call the 3D API to configure the Cg programs and CgFX effects for rendering. The generic Cg routines begin with a `cg` prefix; the generic Cg types begin with a `CG` prefix; and the generic Cg macros and enumerations begin with a `CG_` prefix.

The `<Cg/cgGL.h>` contains the OpenGL-specific routines for configuring Cg programs for rendering with OpenGL. The OpenGL-specific Cg routines begin with a `cgGL` prefix; the OpenGL-specific Cg types begin with a `CGGL` prefix; and the OpenGL-specific Cg macros and enumerations begin with a `CGGL_` prefix.

Technically, the `<Cg/cgGL.h>` header includes `<Cg/cg.h>` so we do not have to explicitly include `<Cg/cg.h>` but we include both to remind you that we will be calling both generic Cg routines and OpenGL-specific Cg routines.

Cg Runtime Variables

Next, we will list all global variables we plan to use. We use the `my` prefix to indicate global variables that we define (to make it crystal clear what names we are defining rather than those names defined by header files). When we declare a variable of a type defined by the Cg runtime, we use the `myCg` prefix to remind you that the variable is for use with the Cg runtime.

```
CGcontext   myCgContext;
CGeffect    myCgEffect;
CGtechnique myCgTechnique;
CGparameter myCgEyePositionParam,
            myCgModelViewProjParam;
```

These are the global Cg runtime variables the demo initializes and uses. We need a single Cg compilation context (**`myCgContext`**). Think of your Cg compilation context as the "container" for all the Cg handles you manipulate. Typically your program requires just one Cg compilation context.

We need one Cg effect (**`myCgEffect`**) for when we load **`bumpdemo.cgfx`**.

We need one Cg technique (**`myCgTechnique`**) for the particular technique we will use to render the torus. While there are four possible techniques, we will select the first technique valid for the GPU upon which the demo is actually running.

We need handles for the two effect parameters that we plan to set as the demo animates. We do not plan to change the default initialization of most of the effect parameters so we need not keep effect parameter handles for these parameters.

In a real program, you'll probably have more Cg effects, techniques, and effect parameters than shown in this simple example. You may have hundreds depending on how complicated the shading is in your application. Keep in mind that this demo is trying to be very simple.

Demo Initialization

```
static void initCgFX();
static void initOpenGL();
static void display(void);
static void keyboard(unsigned char c, int x, int y);
```

The demo first declares various routines, described later, used by the demo's **`main`** routine.

```
int main(int argc, char **argv)
{
  glutInitDisplayMode(GLUT_RGB | GLUT_DOUBLE | GLUT_DEPTH);
  glutInitWindowSize(400, 400);
  glutInit(&argc, argv);
  glutCreateWindow("cgfx_bumpdemo");
```

The **`main`** routine creates a GLUT window with an associated OpenGL rendering context.

```
  initCgFX();
  initOpenGL();
```

Then CgFX objects are initialized along with OpenGL rendering state.

```
  glutDisplayFunc(display);
  glutKeyboardFunc(keyboard);
  glutMainLoop();
  return 0;
}
```

The demo registers callbacks for displaying the window, resizing the window, and accepting keyboard input. Finally GLUT event processing begins.

Error Reporting Helper Routine

Cg initialization depends on a helper routine for reporting Cg-related errors:

```
static void checkForCgError(const char *situation)
{
  CGerror error;
  const char *string = cgGetLastErrorString(&error);

  if (error != CG_NO_ERROR) {
    printf("cgfx_bumpdemo: %s: %s\n", situation, string);
    if (error == CG_COMPILER_ERROR) {
      printf("%s\n", cgGetLastListing(myCgContext));
    }
    exit(1);
  }
}
```

Cg runtime routines report errors by setting a global error value. Calling the `cgGetLastErrorString` routine both returns a human-readable string describing the last generated Cg error and writes an error code of type `CGerror`. `CG_NO_ERROR` (defined to be zero) means there was no error. As a side-effect, `cgGetLastErrorString` also resets the global error value to `CG_NO_ERROR`. The Cg runtime also includes the simpler function `cgGetError` that just returns and then resets the global error code if you just want the error code and don't need a human-readable string too.

The `checkForCgError` routine is used to ensure proper error checking within the demo. If an error has occurred, the routine prints an error message including the `situation` string and translated Cg error value string, and then exits the demo.

When the error returned is `CG_COMPILER_ERROR` that means there are compiler error messages too. So `checkForCgError` then calls `cgGetLastListing` to get a listing of the compiler error messages and prints these out too. For example, if your CgFX effect file had a syntax error, you'd see the compiler's error messages including the line numbers where the compiler identified problems.

While "just exiting" is fine for a demo, real applications will want to properly handle any errors generated. In general, you don't have to be so paranoid as to call `cgGetLastErrorString` after every Cg runtime routine. Check the runtime API documentation for each routine for the reasons it can fail; when in doubt, check for failures.

Cg Initialization

```
static void initCgFX(void)
{
  myCgContext = cgCreateContext();
  cgGLRegisterStates(myCgContext);
  cgGLSetManageTextureParameters(myCgContext, CG_TRUE);
  checkForCgError("establishing Cg context");
```

First we create a Cg context, register the standard states (if you fail to do this, your Cg context will lack the standard states needed for processing standard 3D API state assignments—alternatively you could load your own implementations of the standard CgFX states), and request that the Cg runtime manage texture binds (saving your application the trouble when applying techniques).

```
  myCgEffect = cgCreateEffectFromFile(myCgContext, "bumpdemo.cgfx", NULL);
  checkForCgError("creating bumpdemo.cgfx effect");
```

Now we read the `bumpdemo.cgfx` effect file to create an effect.

```
  myCgTechnique = cgGetFirstTechnique(myCgEffect);
  while (myCgTechnique && cgValidateTechnique(myCgTechnique) == CG_FALSE) {
    fprintf(stderr,
      "cgfx_bumpdemo: Technique %s did not validate.  Skipping.\n",
      cgGetTechniqueName(myCgTechnique));
    myCgTechnique = cgGetNextTechnique(myCgTechnique);
  }
  if (myCgTechnique) {
    fprintf(stderr, "cgfx_bumpdemo: Use technique %s.\n",
      cgGetTechniqueName(myCgTechnique));
  } else {
    fprintf(stderr, "cgfx_bumpdemo: No valid technique\n");
    exit(1);
  }
```

We iterate in order through the techniques defined by the effect. We attempt to validate each technique. This is because the techniques are listed in the effect file in roughly the order of most-optimal to least-optimal. As soon as we find a technique that is valid for our GPU, we choose that technique and go on. If we find no valid technique, our GPU is not capable of rendering the effect so we exit with an error.

```
  myCgModelViewProjParam =
    cgGetEffectParameterBySemantic(myCgEffect, "ModelViewProjection");
  if (!myCgModelViewProjParam) {
    fprintf(stderr,
      "cgfx_bumpdemo: no parameter with ModelViewProjection semantic\n");
    exit(1);
  }
  myCgEyePositionParam =
    cgGetNamedEffectParameter(myCgEffect, "EyePosition");
  if (!myCgEyePositionParam) {
    fprintf(stderr, "cgfx_bumpdemo: no parameter named EyePosition\n");
    exit(1);
  }
}
```

As discussed earlier, most of the effect parameters have appropriate defaults. However if we want to set effect parameters to other values, we need to query a handle for such effect parameters. In this case, we want to animate the eye position and track OpenGL's modelview and projection matrices.

We can query effect parameters by iterating through the entire list (with **`cgGetFirstEffectParameter`** and **`cgGetNextParameter`**) or query the effect parameters by either name or semantic as shown above. Once we have the handle to an effect parameter we can query its name, type, value, semantic, and other information. We can also set its value and other properties.

A more sophisticated demo would iterate over and query all the effect parameters and inspect their annotations to determine how to interface the application's data to the effect. This allows such demos to operate with a much boarder range of effects. This demo is intentionally simplistic so it just queries by name the parameters the demo expects.

Texture Data

Before explaining how we initialize OpenGL, for completeness we discuss how the necessary textures are loaded. This code exactly matches the **`cg_bumpdemo`** source code.

```
/* OpenGL texture object (TO) handles. */
enum {
  TO_NORMALIZE_VECTOR_CUBE_MAP = 1,
  TO_NORMAL_MAP = 2,
};
```

The **`TO_`** prefixed enumerants provide numbers for use as OpenGL texture object names.

```
static const GLubyte
myBrickNormalMapImage[3*(128*128+64*64+32*32+16*16+8*8+4*4+2*2+1*1)] = {
/* RGB8 image data for mipmapped 128x128 normal map for a brick pattern */
#include "brick_image.h"
};

static const GLubyte
myNormalizeVectorCubeMapImage[6*3*32*32] = {
/* RGB8 image data for normalization vector cube map with 32x32 faces */
#include "normcm_image.h"
};
```

These static, constant arrays include the header files containing the data for the normal map's brick pattern and the "normalization vector" cube map. Each texel is 3 unsigned bytes (one for red, green, and blue). While each byte of the texel format is unsigned, normal map components, as well as the vector result of normalizing an arbitrary direction vector, are logically signed values within the [-1,1] range. To accommodate signed values with OpenGL's conventional `GL_RGB8` unsigned texture format, the unsigned [0,1] range is expanded in the fragment program to a signed [-1,1] range. This is the reason for the `expand` helper function called by the `C8E4f_specSurf` fragment program (see Appendix A).

The normal map has mipmaps so there is data for the 128x128 level, and then, each of the successively downsampled mipmap levels. However this version of the demo asks the driver to generate the mipmaps for the normal map instead by using a sampler state assignment to request mipmap generation.

The "normalization vector" cube map has six 32x32 faces without mipmaps.

Initializing Sampler Effect Parameters

To fully initialize the OpenGL state required, we need to associate the OpenGL texture objects for the normal map and normalization cube map textures with their respective sampler effect parameters.

```
static void useSamplerParameter(CGeffect effect,
                                 const char *paramName,
                                 GLuint texobj)
{
  CGparameter param;

  param = cgGetNamedEffectParameter(effect, paramName);
  if (!param) {
    fprintf(stderr, "cgfx_bumpdemo: expected effect parameter named %s\n",
      paramName);
    exit(1);
  }
  cgGLSetTextureParameter(param, texobj);
  cgSetSamplerState(param);
}
```

We query the named effect parameter and then use `cgGLSetTextureParameter` to set an OpenGL texture object for the sampler. Next we use `cgSetSamplerState` to make the appropriate OpenGL calls to set the `sampler_state` state settings for the sampler effect parameter. This ensures each sampler's texture object is configured with the effect's intended filtering and wrap modes set and so mipmap generation occurs if requested.

OpenGL Rendering State Initialization

```
static void initOpenGL(void)
{
  const GLubyte *image;
  unsigned int face;

  glPixelStorei(GL_UNPACK_ALIGNMENT, 1); /* Tightly packed texture data. */
```

By default, OpenGL's assumes each image scanline is aligned to begin on 4 byte boundaries. However, RGB8 data (3 bytes per pixel) is usually tightly packed to a 1 byte alignment is appropriate. That's indeed the case for the RGB8 pixels in our static arrays used to initialize our textures. If you didn't know about this OpenGL pitfall before, you do now.[‡]

```
/* OpenGL tokens for cube maps missing from Windows version of <GL/gl.h> */
#define GL_TEXTURE_CUBE_MAP                    0x8513
#define GL_TEXTURE_CUBE_MAP_POSITIVE_X         0x8515
  glBindTexture(GL_TEXTURE_CUBE_MAP, TO_NORMALIZE_VECTOR_CUBE_MAP);
  useSamplerParameter(myCgEffect, "normalizeCube",
                      TO_NORMALIZE_VECTOR_CUBE_MAP);
  /* Load each 32x32 face (without mipmaps) of range-compressed "normalize
     vector" cube map. */
  for (face = 0, image = myNormalizeVectorCubeMapImage;
       face < 6;
       face++, image += 3*32*32) {
    glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_X + face, 0,
      GL_RGB8, 32, 32, 0, GL_RGB, GL_UNSIGNED_BYTE, image);
  }
```

First we bind the texture object for the "normalization vector" cube map[‡] intended to quickly normalize the 3D lighting vectors that are passed as texture coordinates. Calling

---

[‡] Being aware of pitfalls such as this one can save you a lot of time debugging. This and other OpenGL pitfalls are enumerated in my article "Avoiding 19 Common OpenGL Pitfalls" found here http://developer.nvidia.com/object/Avoiding_Common_ogl_Pitfalls.html An earlier HTML version of the article (with just 16 pitfalls) is found here http://www.opengl.org/developers/code/features/KilgardTechniques/oglpitfall/oglpitfall.html

[‡] Using a "normalization vector" cube map allows our demo to work on older DirectX 8-class GPUs that lacked the shading generality to normalize vectors mathematically. Ultimately as more capable GPUs become ubiquitous, use of normalization cube maps is sure to disappear in favor of normalizing a vector mathematically. A technique using a different Cg program could use Cg's `normalize` standard library routine instead.

useSamplerParameter binds this effect's sampler to the just created normalization cube map and sets the sampler state as requested by the effect. The cube map texture has six faces but there is no need for mipmaps. Each face is packed into the **myNormalizeVectorCubeMapImage** array right after the prior face with the faces ordered in the order of the sequential texture cube map face OpenGL enumerants.

```
  glBindTexture(GL_TEXTURE_2D, TO_NORMAL_MAP);
  useSamplerParameter(myCgEffect, "normalMap",
                      TO_NORMAL_MAP);
  glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB8, 128, 128, 0,
    GL_RGB, GL_UNSIGNED_BYTE, myBrickNormalMapImage);
```

Next we bind to the texture object for our brick pattern normal map 2D texture, call **useSamplerParameter** to binds this effect's sampler to the just created normal map and set the sampler state as requested by the effect, and then load the base level of the normal map (from which mipmaps will be automatically generated because mipmap generation is specified in the effect parameter's **sampler_state** initialization).

```
  glEnable(GL_DEPTH_TEST);
  glMatrixMode(GL_PROJECTION);
  glLoadIdentity();
  gluPerspective(
    60.0,   /* Field of view in degree */
    1.0,    /* Aspect ratio */
    0.1,    /* Z near */
    100.0); /* Z far */
  glMatrixMode(GL_MODELVIEW);
  glClearColor(0.1, 0.3, 0.6, 0.0);  /* Blue background */
}
```

Finally we enable depth testing, establish a perspective projection transform, and set the background color to blue. Alternatively we could enable the depth test in a state assignment within each technique's pass but this would set the depth test every time we apply the technique. It is easier to simply leave the depth test always enabled since we never need it disabled.

Displaying the Window

Earlier in the code, we forward declared the **display** callback. Now is the time to discuss what the **display** routine does and how exactly we render our bump-mapped torus using the textures and Cg vertex and fragment programs we've loaded.

Rendering a 2D Mesh to Generate a Torus

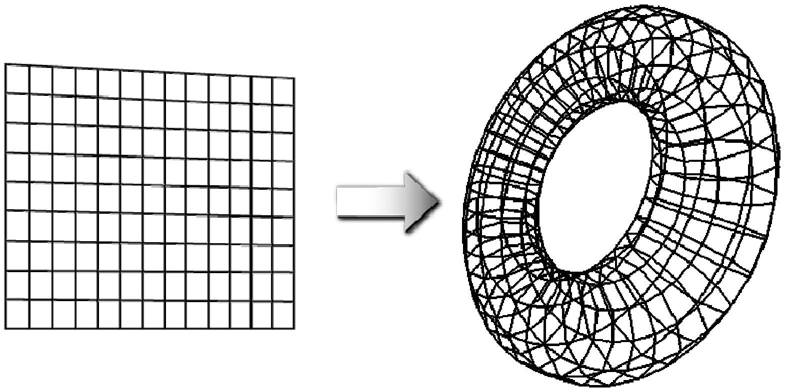
In the course of updating the window, the **display** callback invokes the **drawFlatPatch** subroutine. This subroutine renders a flat 2D mesh with immediate-mode OpenGL commands. This routine is unchanged from the **cg_bumpdemo** version of this demo.

```
/* Draw a flat 2D patch that can be "rolled & bent" into a 3D torus by
   a vertex program. */
void
drawFlatPatch(float rows, float columns)
{
  const float m = 1.0f/columns;
  const float n = 1.0f/rows;
  int i, j;

  for (i=0; i<columns; i++) {
    glBegin(GL_QUAD_STRIP);
    for (j=0; j<=rows; j++) {
      glVertex2f(i*m, j*n);
      glVertex2f((i+1)*m, j*n);
    }
    glVertex2f(i*m, 0);
    glVertex2f((i+1)*m, 0);
    glEnd();
  }
}
```

The mesh consists of a number of adjacent quad strips. The `C8E6v_torus` vertex program will take these 2D vertex coordinates and use them as parametric coordinates for evaluating the position of vertices on a torus.

Nowadays it's much faster to use OpenGL vertex arrays, particularly with vertex buffer objects, to render geometry, but for this simple demo, immediate mode rendering is easier.



2D Grid Over (s,t) ∈ [0,1]

Tessellated Torus

Figure 8-7 from *The Cg Tutorial* is replicated to illustrate how a 2D mesh could be procedurally "rolled and bent" into a torus by a vertex program.

The Display Callback

```
/* Initial scene state */
static float myEyeAngle = 0;
```

The viewer rotates around the torus and bobs up and down based on **`myEyeAngle`** that the demo animates.

```
static void display(void)
{
  const int sides = 20, rings = 40;
  const float eyeRadius = 18.0,
              eyeElevationRange = 8.0;
  float eyePosition[3];
```

The **`display`** callback has a number of constants that control the torus size and tessellation and how the torus is viewed.

```
  CGpass pass;
```

In the course of applying our chosen technique, we need a handle to a CgFX pass.

```
  glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

  eyePosition[0] = eyeRadius * sin(myEyeAngle);
  eyePosition[1] = eyeElevationRange * sin(myEyeAngle);
  eyePosition[2] = eyeRadius * cos(myEyeAngle);

  glLoadIdentity();
  gluLookAt(
    eyePosition[0], eyePosition[1], eyePosition[2],
    0.0 ,0.0,  0.0,   /* XYZ view center */
    0.0, 1.0,  0.0);  /* Up is in positive Y direction */
```

The viewing transform is re-specified each frame. The eye position is a function of **`myEyeAngle`**. By animating this variable, the viewer rotates around the torus with a sinusoidally varying elevation. Because specular bump mapping is view-dependent, the specular lighting varies over the torus as the viewer rotates around.

```
  cgGLSetStateMatrixParameter(myCgModelViewProjParam,
    CG_GL_MODELVIEW_PROJECTION_MATRIX,
    CG_GL_MATRIX_IDENTITY);
  cgSetParameter3fv(myCgEyePositionParam, eyePosition);
```

We set the effect parameter for the modelview-projection matrix to the current OpenGL modelview-projection matrix (even though in this demo we aren't actually changing it—but we could move and rotate the torus if we did).

```
  pass = cgGetFirstPass(myCgTechnique);
  while (pass) {
    cgSetPassState(pass);
```

This begins the "guts" of the rendering where we apply our chosen technique. All our techniques involve only a single pass, but the code is written so it could iterate through a sequence of passes if our technique did provide multiple passes.

We get the first pass for our chosen technique with **`cgGetFirstPass`**. Then **`cgSetPassState`** sets all the state assignments for the pass. This includes evaluating as necessary any state assignment expressions to determine their updated values. The appropriate OpenGL API commands are issued to bind to the pass's vertex and fragment program (as established when we called **`cgGLRegisterStates`** from **`main`**).

```
    drawFlatPatch(sides, rings);
```

Then we render the flat patch with **`drawFlatPatch`** which renders the bump-mapped torus using the effect loaded from **`bumpdemo.cgfx`**.

```
    cgResetPassState(pass);
```

We clean up any OpenGL state modified by **`cgSetPassState`** by calling **`cgResetPassState`**. In this case, the state is restored to OpenGL's initial state. This helps keep our state assignments from unintentionally affecting subsequent rendering.

```
    pass = cgGetNextPass(pass);
  }
```

We request the next pass in the technique and repeat until we run out of passes. All four techniques in our effect each just have a single pass so this is not really necessary (but would be if multi-pass techniques were involved).

```
  glutSwapBuffers();
}
```

We complete the rendering by performing a buffer swap to display the results.

Keyboard Processing

Along with the **`display`** callback, we also forward declared and registered the **`keyboard`** callback. Now it's time to see how the demo responses to simple keyboard input. This code is unchanged from the original **`cg_bumpdemo`** source code.

Animating the Eye Position

```
static void advanceAnimation(void)
{
  myEyeAngle += 0.05f;
  if (myEyeAngle > 2*3.14159)
    myEyeAngle -= 2*3.14159;
  glutPostRedisplay();
}
```

In order to animate the changing eye position so the view varies, the **`advanceAnimation`** callback is registered as the GLUT idle function. The routine advances **`myEyeAngle`** and posts a request for GLUT to redraw the window with **`glutPostRedisplay`**. GLUT calls the idle function repeatedly when there are no other events to process.

The Keyboard Callback

```
static void keyboard(unsigned char c, int x, int y)
{
  static int animating = 0;

  switch (c) {
  case ' ':
    animating = !animating; /* Toggle */
    glutIdleFunc(animating ? advanceAnimation : NULL);
    break;
```

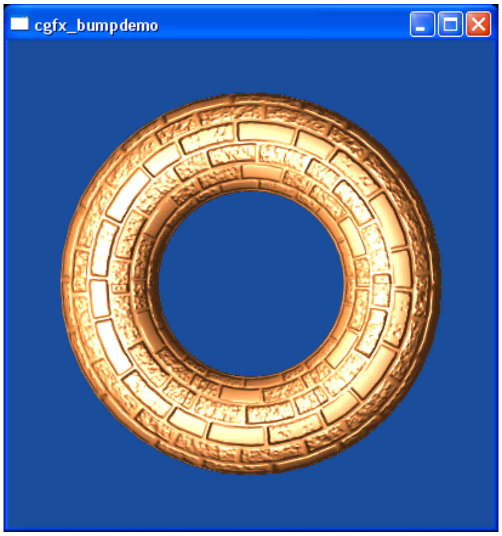
The space bar toggles animation of the scene by registering and de-registering the **`advanceAnimation`** routine as the idle function.

```
  case 27:  /* Esc key */
    cgDestroyEffect(myCgEffect);
    cgDestroyContext(myCgContext);
    exit(0);
    break;
  }
}
```

The Esc key exits the demo. While it is not necessary to do so, the calls to **`cgDestroyEffect`** and **`cgDestroyContext`** deallocate the Cg runtime objects, along with their associated OpenGL state.

The Demo in Action

The images below show the rendered bump-mapped torus initially (left) and while animating (right).



Conclusions

Using CgFX functionality, I have rewritten the `cg_bumpdemo` demo with considerably fewer lines of source code. More importantly, the shading effect is encapsulated in a single CgFX file.

You can use the CgFX shading system to better isolate shading effects from the applications that apply those effects. The concepts of techniques, passes, and state assignments provide a clean framework to structure your effects for maximal platform-independence. Annotations allow you to keep meta-information about effect parameters and other effect objects within the effect file.

I encourage your to explore CgFX and particularly NVIDIA's FX Composer[§] integrated development environment for authoring effect files.

[§] Download it today from http://developer.nvidia.com/object/fx_composer_home.html

Appendix A: bumpdemo.cgfx Effect File

Cg Vertex Program

```
void C8E6v_torus(float2 parametric : POSITION,

             out float4 position       : POSITION,
             out float2 oTexCoord      : TEXCOORD0,
             out float3 lightDirection : TEXCOORD1,
             out float3 halfAngle      : TEXCOORD2,

         uniform float3 lightPosition,  // Object-space
         uniform float3 eyePosition,    // Object-space
         uniform float4x4 modelViewProj,
         uniform float2 torusInfo)
{
  const float pi2 = 6.28318530;  // 2 times Pi
  // Stetch texture coordinates counterclockwise
  // over torus to repeat normal map in 6 by 2 pattern
  float M = torusInfo[0];
  float N = torusInfo[1];
  oTexCoord = parametric * float2(-6, 2);
  // Compute torus position from its parameteric equation
  float cosS, sinS;
  sincos(pi2 * parametric.x, sinS, cosS);
  float cosT, sinT;
  sincos(pi2 * parametric.y, sinT, cosT);
  float3 torusPosition = float3((M + N * cosT) * cosS,
                                (M + N * cosT) * sinS,
                                N * sinT);
  position = mul(modelViewProj, float4(torusPosition, 1));
  // Compute per-vertex rotation matrix
  float3 dPds = float3(-sinS*(M+N*cosT), cosS*(M+N*cosT), 0);
  float3 norm_dPds = normalize(dPds);
  float3 normal = float3(cosS * cosT, sinS * cosT, sinT);
  float3 dPdt = cross(normal, norm_dPds);
  float3x3 rotation = float3x3(norm_dPds,
                               dPdt,
                               normal);
  // Rotate object-space vectors to texture space
  float3 eyeDirection = eyePosition - torusPosition;
  lightDirection = lightPosition - torusPosition;
  lightDirection = mul(rotation, lightDirection);
  eyeDirection = mul(rotation, eyeDirection);
  halfAngle = normalize(normalize(lightDirection) +
                        normalize(eyeDirection));
}
```

Cg Fragment Program

```
float3 expand(float3 v) { return (v-0.5)*2; }

void C8E4f_specSurf(float2 normalMapTexCoord : TEXCOORD0,
                    float3 lightDirection    : TEXCOORD1,
                    float3 halfAngle         : TEXCOORD2,

               out float4 color : COLOR,

           uniform float  ambient,
           uniform float4 LMd, // Light-material diffuse
           uniform float4 LMs, // Light-material specular
           uniform sampler2D   normalMap,
           uniform samplerCUBE normalizeCube,
           uniform samplerCUBE normalizeCube2)
{
  // Fetch and expand range-compressed normal
  float3 normalTex = tex2D(normalMap, normalMapTexCoord).xyz;
  float3 normal = expand(normalTex);
  // Fetch and expand normalized light vector
  float3 normLightDirTex = texCUBE(normalizeCube,
                                   lightDirection).xyz;
  float3 normLightDir = expand(normLightDirTex);
  // Fetch and expand normalized half-angle vector
  float3 normHalfAngleTex = texCUBE(normalizeCube2,
                                    halfAngle).xyz;
  float3 normHalfAngle = expand(normHalfAngleTex);

  // Compute diffuse and specular lighting dot products
  float diffuse = saturate(dot(normal, normLightDir));
  float specular = saturate(dot(normal, normHalfAngle));
  // Successive multiplies to raise specular to 8th power
  float specular2 = specular*specular;
  float specular4 = specular2*specular2;
  float specular8 = specular4*specular4;

  color = LMd*(ambient+diffuse) + LMs*specular8;
}
```

Effect Parameters

```
float4x4 ModelViewProj : ModelViewProjection;
float OuterRadius = 6;
float InnerRadius = 2;
float3 LightPosition = { -8, 0, 15 };
float3 EyePosition = { 0, 0, 18 };

float Ambient<
  string type = "ambient";
  float minValue = 0.0;
  float maxValue = 1.0;
> = 0.3;

float3 DiffuseMaterial<
  string type = "color";
  float3 minValue = float3(0,0,0);
  float3 maxValue = float3(1,1,1);
> = { 0.9, 0.6, 0.3 };

float3 SpecularMaterial<
  string type = "color";
  float3 minValue = float3(0,0,0);
  float3 maxValue = float3(1,1,1);
> = { 1, 1, 1 };

float3 LightColor<
  string type = "color";
  float3 minValue = float3(0,0,0);
  float3 maxValue = float3(1,1,1);
> = { 1.0, 0.9, 0.9 };

sampler2D normalMap = sampler_state {
  generateMipMap = true;
  minFilter = LinearMipMapLinear;
  magFilter = Linear;
};

samplerCUBE normalizeCube = sampler_state {
  minFilter = Linear;
  magFilter = Linear;
  wrapS = ClampToEdge;
  wrapT = ClampToEdge;
};
```

Techniques

```
// Because cgfx_bumpdemo.c picks the first valid technique,
// list techniques in relative order of preference...

technique bumpdemo_nv40 {
  pass {
    FragmentProgram = compile fp40
      C8E4f_specSurf(Ambient,
                     float4(DiffuseMaterial  * LightColor, 1),
                     float4(SpecularMaterial * LightColor, 1),
                     normalMap, normalizeCube, normalizeCube);
    VertexProgram = compile vp40
      C8E6v_torus(LightPosition, EyePosition, ModelViewProj,
                  float2(OuterRadius, InnerRadius));
  }
}

technique bumpdemo_nv30 {
  pass {
    FragmentProgram = compile fp30
      C8E4f_specSurf(Ambient,
                     float4(DiffuseMaterial  * LightColor, 1),
                     float4(SpecularMaterial * LightColor, 1),
                     normalMap, normalizeCube, normalizeCube);
    VertexProgram = compile vp30
      C8E6v_torus(LightPosition, EyePosition, ModelViewProj,
                  float2(OuterRadius, InnerRadius));
  }
}

technique bumpdemo_arb {
  pass {
    FragmentProgram = compile arbfp1
      C8E4f_specSurf(Ambient,
                     float4(DiffuseMaterial  * LightColor, 1),
                     float4(SpecularMaterial * LightColor, 1),
                     normalMap, normalizeCube, normalizeCube);
    VertexProgram = compile arbvp1
      C8E6v_torus(LightPosition, EyePosition, ModelViewProj,
                  float2(OuterRadius, InnerRadius));
  }
}

technique bumpdemo_nv20 {
  pass {
    FragmentProgram = compile fp20
      C8E4f_specSurf(Ambient,
                     float4(DiffuseMaterial  * LightColor, 1),
                     float4(SpecularMaterial * LightColor, 1),
                     normalMap, normalizeCube, normalizeCube);
    VertexProgram = compile vp20
      C8E6v_torus(LightPosition, EyePosition, ModelViewProj,
                  float2(OuterRadius, InnerRadius));
  }
}
```

Comparison Tables for HLSL, OpenGL Shading Language, and Cg

April 2006

	DirectX 9 HLSL	**OpenGL Shading Language**	**Cg Toolkit**
Availability			
Available today	Yes	Yes	Yes
Installation/upgrade requirements	Part of DirectX 9; comes with XP or a free Windows updated	May need driver update from hardware vendor for ARB extensions or OpenGL 2.0	User level libraries so no driver upgrade typically required
Time of first release	March 2003, DirectX 9 ship	June 2003, ARB standards approved; implementations in late 2003	December 2002, 1.0 release
Current version	DirectX 9.0c	1.10	Cg 1.5
Standard maker	Microsoft	OpenGL Architectural Review Board	NVIDIA
Implementer	Microsoft	Each OpenGL driver vendor	NVIDIA
3D Graphics API Support			
OpenGL	No	Yes	Yes
Direct3D	Yes	No	Yes
One shader can compile for either API	No	No	Yes

	DirectX 9 HLSL	**OpenGL Shading Language**	**Cg Toolkit**
OpenGL Specifics			
OpenGL 1.*x* support	n/a	Needs ARB GLSL extensions	Needs ARB or NV low-level assembly extensions
Multi-vendor ARB_vertex_program support	n/a	No	Yes
Multi-vendor ARB_fragment_program support	n/a	No	Yes
NVIDIA OpenGL extension support	n/a	No	Yes, profiles for fp20, vp20, fp30, vp30, fp40, vp40, glslv and glslf
Relationship to OpenGL standard	n/a	Part of core OpenGL 2.0 standard	Layered upon ARB-approved assembly extensions
Access to OpenGL state settings	n/a	Yes	Yes
Open Source OpenGL rendering support (via Mesa)	n/a	No Mesa support yet	Yes, no changes required
Language tied to OpenGL	n/a	Yes	No, API-independent
Targets GLSL as profiles	n/a	n/a	Yes, with 1.5
Direct3D Specifics			
DirectX 8 support	Requires DirectX 9 upgrade but supports DirectX 8-class hardware profiles	n/a	Yes
DirectX 9 support	Yes	n/a	Yes
GPU Hardware Support			
NVIDIA DirectX 9-class GPUs	Yes	Yes	Yes
ATI DirectX 9-class GPUs	Yes	Yes	Yes
3Dlabs DirectX 9-class GPUs	Yes	Yes	Yes
DirectX 8-class GPUs	Yes, with ps1.x and vs1.1 profiles	No	Yes, fp20 and vp20 profiles
PlayStation 3	No	No	Yes
Xbox 360	Yes	No	No

	DirectX 9 HLSL	**OpenGL Shading Language**	**Cg Toolkit**
Graphics Hardware Feature Support			
Vertex textures	Yes, if hardware supports vs3.0 profile	Yes, if hardware supports	Yes, if hardware supports vp40, glslv, or vs_3_0 profiles
Dynamic vertex branching	Yes, if hardware supports vs2.0 profile	Yes, if hardware supports	Yes, if hardware supports vp30, vp40, glslv, or vs_3_0 profiles
Dynamic fragment branching	Yes, if hardware supports ps3.0 profile	Yes, if hardware supports	Yes, if hardware supports fp40, glslf, ps_3_0 profiles
Fragment depth output	Yes	Yes	Yes
Multiple render targets (MRT)	Yes, if hardware supports	Yes, if hardware supports	Yes, if hardware supports MRT and fp40, glslf, or ps_3_0 profiles
1D, 2D, 3D, and cube map texture support	Yes	Yes	Yes
Shadow mapping	Yes	Yes, but needs special shadow texture fetch routines to be well-defined	Yes
Point size output	Yes	Yes	Yes
Clipping support	Output clip coordinate(s)	Output clip position	Output clip coordinate(s)
Texture rectangles	No	Yes, when ARB_texture_rectangle is supported	Yes, when ARB_texture_rectangle is supported
Access to fragment derivatives	Yes, when supported by the fragment profile	Yes	Yes, when supported by the fragment profile
Front and back vertex color outputs for two-sided lighting	No	Yes	Yes, for OpenGL
Front facing fragment shader input	Yes	Yes	Yes, for fp40, glslv, and ps_3_0 profiles
Window position fragment shader input	Yes, for ps2 and ps3 profiles	Yes	Yes, for all but fp20 profile

	DirectX 9 HLSL	**OpenGL Shading Language**	**Cg Toolkit**
Language Details			
C-like languages	Yes	Yes	Yes
Language compatibility with Microsoft's DirectX 9 HLSL	Yes	No	Yes
Vertex and fragment shaders written as separate programs	Yes	Yes	Yes
C operators with C precedence	Yes	Yes	Yes
C control flow (if, else, for, do while)	Yes	Yes	Yes
Vector data types	Yes	Yes	Yes
Fixed-point data type	No	No. has fixed reserved word	Yes, fixed
Matrix arrangement	Column major by default	Column major	Row major by default
Non-square matrices	Yes	No	Yes
Data type constructors	Yes	Yes	Yes
Structures and arrays	Yes	Yes	Yes
Function overloading	Yes	Yes	Yes
Function parameter qualifiers: in, out, and inout	Yes	Yes	Yes
Type qualifiers: uniform, const	Yes	Yes	Yes
Shader outputs readable	Yes	No	Yes
Texture samplers	Yes	Yes	Yes
Keyword discard to discard a fragment	Yes	Yes	Yes
C and C++ style comments	Yes	Yes	Yes
C preprocessor support	Yes	Yes	Yes
Vector write masking	Yes	No	Yes
Vector component and matrix swizzling	Yes	No	Yes
Vector ?: operator	Yes	No, Boolean only	Yes
Vector comparison operators	Yes	No, must use lessThan, etc. standard library routines	Yes
Semantic qualifiers	Yes	No	Yes
Array dimensionality	Multi-dimensional	1D only	Multi-dimensional
Un-sized arrays (dynamic sizing)	No	No	Yes

	DirectX 9 HLSL	OpenGL Shading Language	Cg Toolkit
Shader Linking Support			
Sub-shader support via interface mechanism	No	No, but keyword reserved	Yes, in Cg 1.4
Separate compilation and linking	D3DX utility library: Fragment Linker	Yes	No, but interfaces provide a structured form of program reconfiguration
Cross domain linking by varying name	No	Yes	Yes, in 1.5
Standard Library			
Standard function library	Yes	Yes	Yes
Standard function library compatibility with Microsoft's DirectX 9 HLSL	Yes	No	Yes
Operating System Support			
Windows support (98/2000/XP)	Yes	Yes	Yes
Legacy Windows 95 support	No	Yes	Yes
Legacy Windows NT 4.0 support	No	Yes	Yes
Linux	No	Yes	Yes
Mac OS X	No	Yes	Yes (since 1.2)
Solaris	No	No	Yes (since 1.5)

	DirectX 9 HLSL	**OpenGL Shading Language**	**Cg Toolkit**
Shader Meta File Format Support			
Standard shader meta file format	Yes (FX)	No	Yes (CgFX)
Shader meta file format compatible with DirectX 9 Effects format	Yes	n/a	Yes
Specification of multiple techniques for an effect	Yes	n/a	Yes
Virtual machine for CPU shader execution	Yes	No	Yes
Annotations	Yes	n/a	Yes
State assignments	Yes	n/a	Yes
Run-time API	Yes	n/a	Yes
Direct3D loader	Yes	n/a	Yes
OpenGL loader	n/a	n/a	Yes
User-defined state assignments	No	n/a	Yes
Free shader meta file viewer available	FX Composer	n/a	FX Composer
Collada integration	No	Proposed	Yes
Debugging			
Interactive shader debugger	Visual Studio .NET Shader Debugger	No	No
Documentation			
Specification or definitive documentation	MSDN Direct3D 9 documentation	*The OpenGL Shading Language* specification	*The Cg Language Specification*
Tutorial book	Various books	*OpenGL Shading Language* (Rost)	*The Cg Tutorial* (Fernando & Kilgard)
User's manual	MSDN Direct3D 9 documentation	No	*Cg User's Manual*
Japanese documentation available	Yes	No	Yes

	DirectX 9 HLSL	OpenGL Shading Language	Cg Toolkit
Example Code			
Sources of example code	Microsoft DirectX 9 SDK examples	ATI, 3Dlabs, NVIDIA SDK examples	Cg Tutorial examples, NVIDIA SDK examples
Miscellaneous			
Standalone command line compiler	Yes (fxc)	No	Yes (cgc)
Generates human-readable intermediate assembly code	Yes	No	Yes
Supports ILM's OpenEXR half-precision data type	Yes	Reserved word for half; NVIDIA supports it	Yes
Open source language parser available	No	Yes	Yes
Compiler tied into graphics driver	No	Yes, compiled result depends on end-user hardware and driver version	No
Multi-vendor extension mechanism	No	Yes	No
No-fee redistributable library	Yes, Windows only	n/a	Yes, all platforms
What its name stands for	High Level Shader Language	OpenGL Shading Language	C for Graphics

n/a = Not available *or* not applicable.

Based on available knowledge circa April 2006.

The GeForce 6 Series GPU Architecture

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Notice: This article is reprinted with permission from Chapter 30 of *GPU Gems 2: Programming Techniques for High-Performance Graphics and General-Purpose Computation* (ISBN: 0321335597, edited by Matt Pharr). References to other chapters within the text refer to chapters within the book, not these notes.

The previous chapter [of *GPU Gems 2*] described how GPU architecture has changed as a result of computational and communications trends in microprocessing. This chapter describes the architecture of the GeForce 6 Series GPUs from NVIDIA, which owe their formidable computational power to their ability to take advantage of these trends. Most notably, we focus on the GeForce 6800 (NVIDIA's flagship GPU at the time of writing, shown in Figure 30-1), which delivers hundreds of gigaflops of single-precision floating-point computation, as compared to approximately 12 gigaflops for high-end CPUs. We start with a general overview of where the GPU fits into the overall computer system, and then we describe the architecture along with details of specific features and performance characteristics.

Figure 30-1. The GeForce 6800 Microprocessor

30.1 How the GPU Fits into the Overall Computer System

The CPU in a modern computer system communicates with the GPU through a graphics connector such as a PCI Express or AGP slot on the motherboard. Because the graphics connector is responsible for transferring all command, texture, and vertex data from the CPU to the GPU, the bus technology has evolved alongside GPUs over the past few years. The original AGP slot ran at 66 MHz and was 32 bits wide, giving a transfer rate of 264 MB/sec. AGP 2×, 4×, and 8× followed, each doubling the available bandwidth, until finally the PCI Express standard was introduced in 2004, with a maximum theoretical bandwidth of 4 GB/sec available to and from the GPU. (Your mileage may vary; currently available motherboard chipsets fall somewhat below this limit—around 3.2 GB/sec or less.)

It is important to note the vast differences between the GPU's memory interface bandwidth and bandwidth in other parts of the system, as shown in Table 30-1.

Table 30-1. Available memory bandwidth in different parts of the computer system

Component	**Bandwidth**
GPU Memory Interface	35 GB/sec
PCI Express Bus (×16)	8 GB/sec
CPU Memory Interface (800 MHz Front-Side Bus)	6.4 GB/sec

Table 30-1 reiterates some of the points made in the preceding chapter: there is a vast amount of bandwidth available internally on the GPU. Algorithms that map to the GPU can therefore take advantage of this bandwidth to achieve dramatic performance improvements.

30.2 Overall System Architecture

The next two subsections go into detail about the architecture of the GeForce 6 Series GPUs. Section 30.2.1 describes the architecture in terms of its graphics capabilities. Section 30.2.2 describes the architecture with respect to the general computational capabilities that it provides. See Figure 30-2 for an illustration of the system architecture.

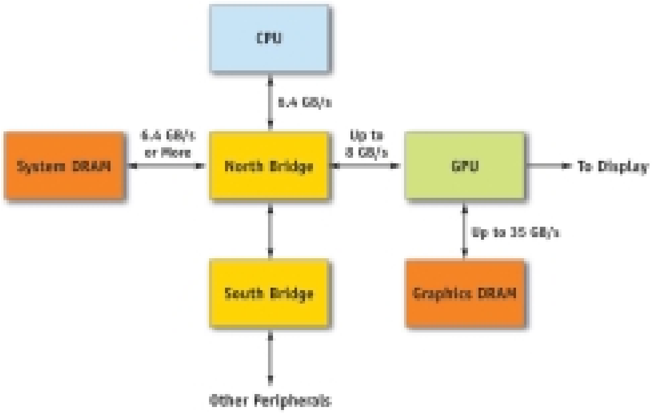

Figure 30-2. The Overall System Architecture of a PC

30.2.1 Functional Block Diagram for Graphics Operations

Figure 30-3 illustrates the major blocks in the GeForce 6 Series architecture. In this section, we take a trip through the graphics pipeline, starting with input arriving from the CPU and finishing with pixels being drawn to the frame buffer.

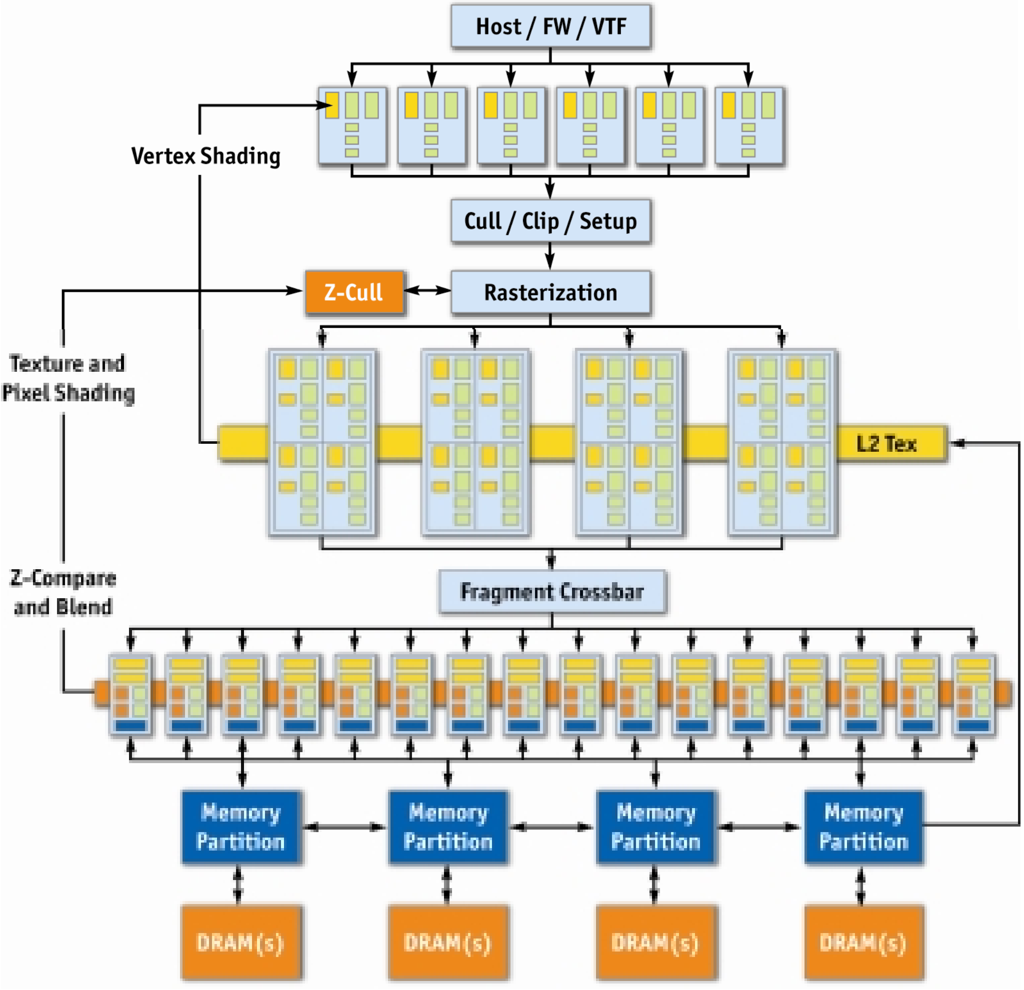

Figure 30-3. A Block Diagram of the GeForce 6 Series Architecture

First, commands, textures, and vertex data are received from the host CPU through shared buffers in system memory or local frame-buffer memory. A command stream is written by the CPU, which initializes and modifies state, sends rendering commands, and references the texture and vertex data. Commands are parsed, and a vertex fetch unit is used to read the vertices referenced by the rendering commands. The commands, vertices, and state changes flow downstream, where they are used by subsequent pipeline stages.

The vertex shading units, shown in Figure 30-4, allow for a program to be applied to each vertex in the object, performing transformations, skinning, and any other per-vertex operation the user specifies. For the first time, the GeForce 6 Series allows for vertex programs to fetch texture data. All operations are done in 32-bit floating-point (fp32) precision per component. The GeForce 6

Series architecture supports scalable vertex-processing horsepower, allowing the same architecture to service multiple price/performance points.

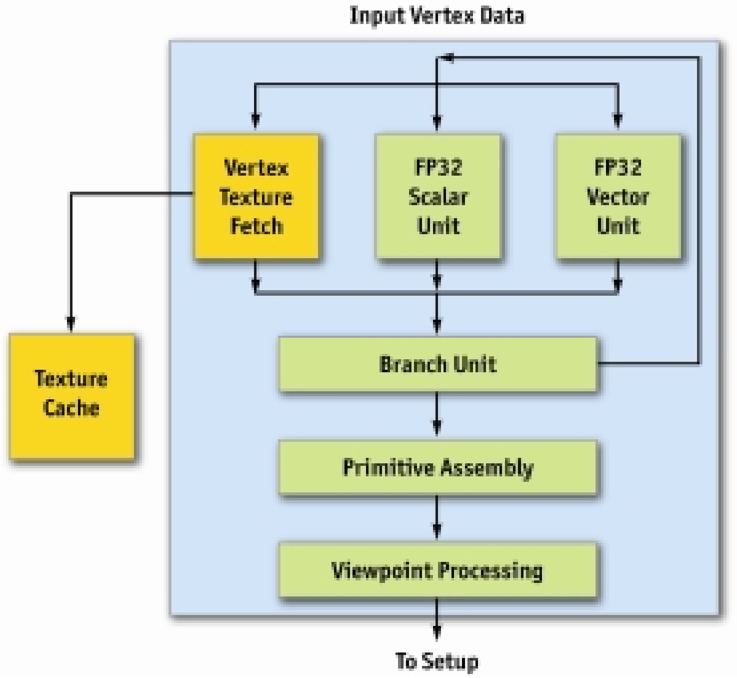

Figure 30-4. The GeForce 6 Series Vertex Processor

Because the vertex shader permits texture accesses, the vertex engines are connected to the texture cache, which is shared with the pixel shaders. In addition, there is a vertex cache that stores vertex data both before and after the vertex shader, reducing fetch and computation requirements. This means that if a vertex index occurs twice in a draw call (for example, in a triangle strip), the entire vertex program doesn't have to be rerun for the second instance of the vertex—the cached result is used instead.

Vertices are then grouped into primitives, which are points, lines, or triangles. The Cull/Clip/Setup blocks perform per-primitive operations, removing primitives that aren't visible at all, clipping primitives that intersect the view frustum, and performing edge and plane equation setup on the data in preparation for rasterization.

The rasterization block calculates which pixels (or samples, if multisampling is enabled) are covered by each primitive, and it uses the z-cull block to quickly discard pixels (or samples) that are occluded by objects with a nearer depth value.

Figure 30-5 illustrates the pixel shader and texel pipeline. The texture and pixel shading units operate in concert to apply a shader program to each pixel independently. The GeForce 6 Series architecture supports a scalable amount of pixel-processing horsepower. Another popular way to say this is that the GeForce 6 Series architecture can have a varying number of *pixel pipelines*. Similar to the vertex shader, texture data is cached on-chip to reduce bandwidth requirements and improve performance.

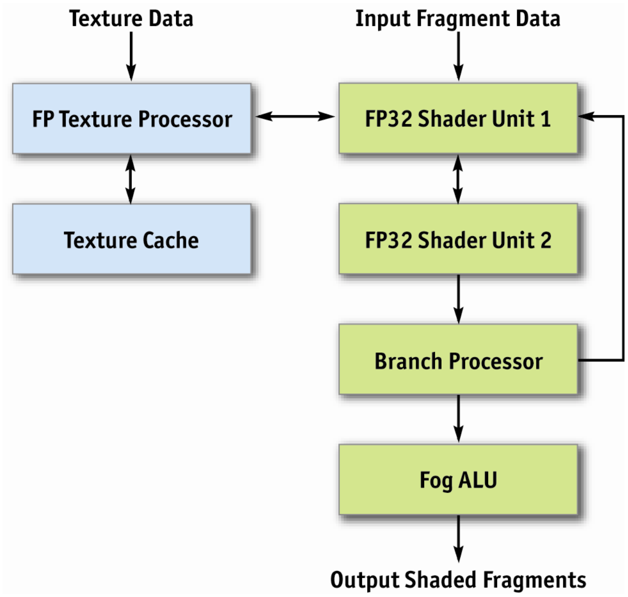

Figure 30-5. The GeForce 6 Series Pixel Shader and Texel Pipeline

The texture and pixel shading unit operates on squares of four pixels (called *quads*) at a time, allowing for direct computation of derivatives for calculating texture level of detail. Furthermore, the pixel shader works on groups of hundreds of pixels at a time in single-instruction, multiple-data (SIMD) fashion (with each pixel shader engine working on one pixel concurrently), hiding the latency of texture fetch from the computational performance of the pixel shader.

The pixel shader uses the texture unit to fetch data from memory, optionally filtering the data before returning it to the pixel shader. The texture unit supports many source data formats (see Section 30.3.3, “Supported Data Storage Formats”). Data can be filtered using bilinear, tri-linear, or anisotropic filtering. All data is returned to the pixel shader in fp32 or fp16 format. A texture can be viewed as a 2D or 3D array of data that can be read by the texture unit at arbitrary locations and filtered to reconstruct a continuous function. The GeForce 6 Series supports filtering of fp16 textures in hardware.

The pixel shader has two fp32 shader units per pipeline, and pixels are routed through both shader units and the branch processor before re-circulating through the entire pipeline to execute the next series of instructions. This rerouting happens once for each core clock cycle. Furthermore, fp32 shader unit 1 can be used for perspective correction of texture coordinates when needed (by dividing by *w*), or for general-purpose multiply operations. In general, it is possible to perform eight or more math operations in the pixel shader during each clock cycle, or four math operations if a texture fetch occurs in the first shader unit.

On the final pass through the pixel shader pipeline, the fog unit can be used to blend fog in fixed-point precision with no performance penalty. Fog blending happens often in conventional graphics applications and uses the following function:

```
out = FogColor * fogFraction + SrcColor * (1 - fogFraction)
```

This function can be made fast and small in fixed-precision math, but in general IEEE floating point, it requires two full multiply-adds to do effectively. Because fixed point is efficient and sufficient for fog, it exists in a separate small unit at the end of the shader. This is a good example of the trade-offs in providing flexible programmable hardware while still offering maximum performance for legacy applications.

Pixels leave the pixel shading unit in the order that they are rasterized and are sent to the z-compare and blend units, which perform depth testing (z comparison and update), stencil operations, alpha blending, and the final color write to the target surface (an off-screen render target or the frame buffer).

The memory system is partitioned into up to four independent memory partitions, each with its own dynamic random-access memories (DRAMs). GPUs use standard DRAM modules rather than custom RAM technologies to take advantage of market economies and thereby reduce cost. Having smaller, independent memory partitions allows the memory subsystem to operate efficiently regardless of whether large or small blocks of data are transferred. All rendered surfaces are stored in the DRAMs, while textures and input data can be stored in the DRAMs or in system memory. The four independent memory partitions give the GPU a wide (256 bits), flexible memory subsystem, allowing for streaming of relatively small (32-byte) memory accesses at near the 35 GB/sec physical limit.

30.2.2 Functional Block Diagram for Non-Graphics Operations

As graphics hardware becomes more and more programmable, applications unrelated to the standard polygon pipeline (as described in the preceding section) are starting to present themselves as candidates for execution on GPUs.

Figure 30-6 shows a simplified view of the GeForce 6 Series architecture, when used as a graphics pipeline. It contains a programmable vertex engine, a programmable pixel engine, a texture load/filter engine, and a depth-compare/blending data write engine.

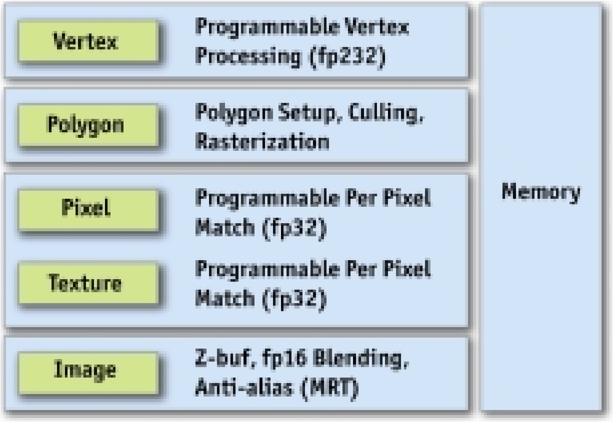

Figure 30-6. The GeForce 6 Series Architecture Viewed as a Graphics Pipeline

In this alternative view, a GPU can be seen as a large amount of programmable floating-point horsepower and memory bandwidth that can be exploited for compute-intensive applications completely unrelated to computer graphics.

Figure 30-7 shows another way to view the GeForce 6 Series architecture. When used for non-graphics applications, it can be viewed as two programmable blocks that run serially: the vertex shader and the pixel shader, both with support for fp32 operands and intermediate values. Both use the texture unit as a random-access data fetch unit and access data at a phenomenal 35 GB/sec (550 MHz memory clock × 256 bits per clock cycle). In addition, both the vertex and the pixel shader are highly computationally capable. (Performance details follow in Section 30.4.)

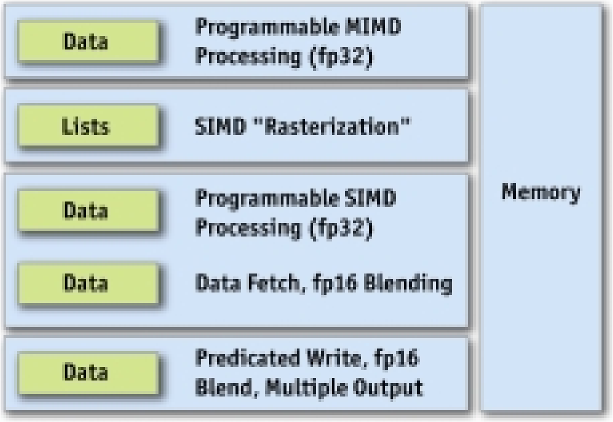

Figure 30-7. The GeForce 6 Series Architecture for Non-Graphics Applications

The vertex shader stores its data by passing it directly to the pixel shader, or by using the SIMD rasterizer to expand the data into interpolated values. At this point, each triangle (or point) from the vertex shader has become one or more *fragments*. Think of a fragment as a "candidate pixel": that is, it will pass through the pixel shader and several tests, and if it gets through all of them, it will end up carrying depth and color information to a pixel on the frame buffer (or render target).

Before a pixel reaches the pixel shader, the z-cull unit compares the pixel's depth with the values that already exist in the depth buffer. If the pixel's depth is greater, the pixel will not be visible, and there is no point shading that pixel, so the pixel shader isn't even executed. (This optimization happens only if it's clear that the pixel shader isn't going to modify the fragment's depth.) Thinking in a general-purpose sense, this *early culling* feature makes it possible to quickly decide to skip work on specific fragments based on a scalar test. Chapter 34 of this book, "GPU Flow Control Idioms," explains how to take advantage of this feature to efficiently predicate work for general-purpose computations.

After the pixel shader runs on a potential pixel (still a "fragment" because it has not yet reached the frame buffer), the fragment must pass a number of tests in order to move farther down the pipeline. (There may also be more than one fragment that comes out of the pixel shader if multiple render targets (MRTs) are being used. Up to four MRTs can be used to write out large amounts of data—up to 16 scalar floating-point values at a time, for example—plus depth.)

First, the scissor test rejects the fragment if it lies outside a specified subrectangle of the frame buffer. Although the popular graphics APIs define scissoring at this location in the pipeline, it is more efficient to perform the scissor test in the rasterizer. The *x* and *y* scissoring actually happen in the rasterizer, before pixel shading, and *z* scissoring happens during z-cull. This avoids all pixel shader work on scissored (rejected) pixels. Scissoring is rarely useful for general-purpose computation because general-purpose programmers typically draw rectangles to perform computations in the first place.

Next, the fragment's depth is compared with the depth in the frame buffer. If the depth test passes, the depth value in the frame buffer can optionally be replaced, and the fragment moves on in the pipeline.

After this, the fragment can optionally test and modify what is known as the stencil buffer, which stores an integer value per pixel. The stencil buffer was originally intended to allow programmers to mask off certain pixels (for example, to restrict drawing to a cockpit's windshield), but it has found other uses as a way to count values by incrementing or decrementing the existing value. This is used in stencil shadow volumes, for example.

If the fragment passes the depth and stencil tests, it can then optionally modify the contents of the frame buffer by using the blend function. A blend function can be described as

```
out = src * srcOp + dst * dstOp
```

where `source` is the fragment color flowing down the pipeline, `dst` is the color value in the frame buffer, and the `srcOp` and `dstOp` can be specified to be constants, source color components, or destination color components. Full blend functionality is supported for all pixel formats up to fp16×4. However, fp32 frame buffers don't support blending—only updating the buffer is allowed.

Finally, a feature called *occlusion query* makes it possible to quickly determine if any of the fragments that would be rendered in a particular computation would cause results to be written to the frame buffer. (Recall that fragments that do not pass the z-test don't have any effect on the values in the frame buffer.) Traditionally, the occlusion query test is used to allow graphics applications to avoid making draw calls for occluded objects, but it is very useful for GPGPU applications as well. For instance, if the depth test is used to tell which outputs need to be updated in a sparse array, updating depth can be used to tell when a given output has converged and no further work is needed. In this case, occlusion query can be used to tell when all output calculations are done. See Chapter 34 of this book, "GPU Flow Control Idioms," for further information about this idea.

30.3 GPU Features

This section covers both the fixed-function features and Shader Model 3.0 support (described in detail later) in GeForce 6 Series GPUs. As we describe the various pieces, we focus on the many new features that are meant to make applications shine (in terms of both visual quality and performance) on the GeForce 6 Series GPUs.

30.3.1 Fixed-Function Features

Geometry Instancing

With Shader Model 3.0, the capability for sending multiple batches of geometry with one Direct3D call has been added, greatly reducing driver overhead in these cases. The hardware feature that enables instancing is *vertex stream frequency*—the ability to read vertex attributes at a frequency less than once every output vertex, or to loop over a subset of vertices multiple times. Instancing is most useful when the same object is drawn multiple times with different positions and textures, for example, when rendering an army of soldiers or a field of grass.

Early Culling/Clipping

GeForce 6 Series GPUs are able to cull non-visible primitives before shading at a higher rate and clip partially visible primitives at full speed. Previous NVIDIA products would cull non-visible primitives at primitive-setup rates, and clip partially visible primitives at full speed.

Rasterization

Like previous NVIDIA products, GeForce 6 Series GPUs are capable of rendering the following objects:

- Point sprites
- Aliased and antialiased lines
- Aliased and antialiased triangles

Multisample antialiasing is also supported, allowing accurate antialiased polygon rendering. Multisample antialiasing supports all rasterization primitives. Multisampling is supported in previous NVIDIA products, though the 4× multisample pattern was improved for GeForce 6 Series GPUs.

Z-Cull

NVIDIA GPUs since GeForce3 have technology, called *z-cull*, that allows hidden surface removal at speeds much faster than conventional rendering. The GeForce 6 Series z-cull unit is the third generation of this technology, which has increased efficiency for a wider range of cases. Also, in cases where stencil is not being updated, early stencil reject can be employed to remove rendering early when stencil test (based on equals comparison) fails.

Occlusion Query

Occlusion query is the ability to collect statistics on how many fragments passed or failed the depth test and to report the result back to the host CPU. Occlusion query can be used either while rendering objects or with color and z-write masks turned off, returning depth test status for the objects that would have been rendered, without destroying the contents of the frame buffer. This feature has been available since the GeForce3 was introduced.

Texturing

Like previous GPUs, GeForce 6 Series GPUs support bilinear, tri-linear, and anisotropic filtering on 2D and cube-map textures of various formats. Three-dimensional textures support bilinear, tri-linear, and quad-linear filtering, with and without mipmapping. New texturing features on GeForce 6 Series GPUs are these:

- Support for all texture types (2D, cube map, 3D) with fp16×2, fp16×4, fp32×1, fp32×2, and fp32×4 formats
- Support for all filtering modes on fp16×2 and fp16×4 texture formats
- Extended support for non-power-of-two textures to match support for power-of-two textures, specifically:
    - Mipmapping
    - Wrapping and clamping
    - Cube map and 3D texture support

Shadow Buffer Support

NVIDIA graphics supports shadow buffering directly. The application first renders the scene from the light source into a separate z-buffer. Then during the lighting phase, it fetches the shadow buffer as a projective texture and performs z-compares of the shadow buffer data against an iterated value corresponding to the distance from the light. If the texel passes the test, it's in light; if not, it's in shadow. NVIDIA GPUs have dedicated transistors to perform four z-compares per pixel (on four neighboring z-values) per clock, and to perform bilinear filtering of the pass/fail data. This more advanced variation of percentage-closer filtering saves many shader instructions compared to GPUs that don't have direct shadow buffer support.

High-Dynamic-Range Blending Using fp16 Surfaces, Texture Filtering, and Blending

GeForce 6 Series GPUs allow for fp16×4 (four components, each represented by a 16-bit float) filtered textures in the pixel shaders; they also allow performing all alpha-blending operations on fp16×4 filtered surfaces. This permits intermediate rendered buffers at a much higher precision and range, enabling high-dynamic-range rendering, motion blur, and many other effects. In addition, it is possible to specify a separate blending function for color and alpha values. (The lowest-end member of the GeForce 6 Series family, the GeForce 6200 TC, does not support floating-point blending or floating-point texture filtering because of its lower memory bandwidth, as well as to save area on the chip.)

30.3.2 Shader Model 3.0 Programming Model

Along with the fixed-function features listed previously, the capabilities of the vertex and the pixel shader have been enhanced in GeForce 6 Series GPUs. With Shader Model 3.0, the programming models for vertex and pixel shaders are converging: both support fp32 precision, texture lookups, and the same instruction set. Specifically, here are the new features that have been added.

Vertex Shader

- **Increased instruction count.** The total instruction count is now 512 static instructions and 65,536 dynamic instructions. The static instruction count represents the number of instructions in a program as it is compiled. The dynamic instruction count represents the number of instructions actually executed. In practice, the dynamic count can be vastly higher than the static count due to looping and subroutine calls.
- **More temporary registers.** Up to 32 four-wide temporary registers can be used in a vertex shader program.
- **Support for instancing.** This enhancement was described earlier.
- **Dynamic flow control.** Branching and looping are now part of the shader model. On the GeForce 6 Series vertex engine, branching and looping have minimal overhead of just two cycles. Also, each vertex can take its own branches without being grouped in the way pixel shader branches are. So as branches diverge, the GeForce 6 Series vertex shader still operates efficiently.
- **Vertex texturing.** Textures can now be fetched in a vertex program, although only nearest-neighbor filtering is supported in hardware. More advanced filters can of course be implemented in the vertex program. Up to four unique textures can be accessed in a vertex program, although each texture can be accessed multiple times. Vertex textures generate latency for fetching data, unlike true constant reads. Therefore, the best way to use vertex textures is to do a texture fetch and follow it with many arithmetic operations to hide the latency before using the result of the texture fetch.

Each vertex engine is capable of simultaneously performing a four-wide SIMD `MAD` (multiply-add) instruction and a scalar special function per clock cycle. Special function instructions include:

- Exponential functions: `EXP`, `EXPP`, `LIT`, `LOG`, `LOGP`
- Reciprocal instructions: `RCP`, `RSQ`
- Trigonometric functions: `SIN`, `COS`

Pixel Shader

- **Increased instruction count.** The total instruction count is now 65,535 static instructions and 65,535 dynamic instructions. There are limitations on how long the operating system will wait while the shader finishes working, so a long shader program working on a full screen of pixels may time-out. This makes it important to carefully consider the shader length and number of pixels rendered in one draw call. In practice, the number of instructions exposed by the driver tends to be smaller, because the number of instructions can expand as code is translated from Direct3D pixel shaders or OpenGL fragment programs to native hardware instructions.
- **Multiple render targets.** The pixel shader can output to up to four separate color buffers, along with a depth value. All four separate color buffers must be the same format and size. MRTs can be particularly useful when operating on scalar data, because up to 16 scalar values can be written out in a single pass by the pixel shader. Sample uses of MRTs include particle physics, where positions and velocities are computed simultaneously, and similar GPGPU algorithms. Deferred shading is another technique that computes and stores multiple four-component floating-point values simultaneously: it computes all material properties and stores them in separate textures. So, for example, the surface normal and the diffuse and specular material properties could be written to textures, and the textures could all be used in subsequent passes when lighting the scene with multiple lights. This is illustrated in Figure 30-8.

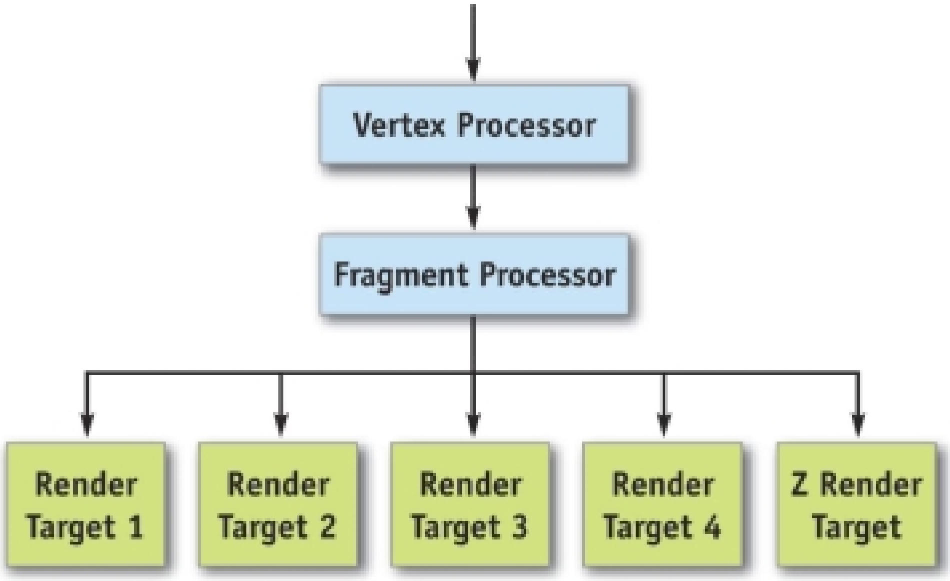

Figure 30-8. Using MRTs for Deferred Shading

- **Dynamic flow control (branching).** Shader Model 3.0 supports conditional branching and looping, allowing for more flexible shader programs.
- **Indexing of attributes.** With Shader Model 3.0, an index register can be used to select which attributes to process, allowing for loops to perform the same operation on many different inputs.
- **Up to ten full-function attributes.** Shader Model 3.0 supports ten full-function attributes/texture coordinates, instead of Shader Model 2.0's eight full-function attributes plus specular color and diffuse color. All ten Shader Model 3.0 attributes are interpolated at full fp32 precision, whereas Shader Model 2.0's diffuse and specular color were interpolated at only 8-bit integer precision.
- **Centroid sampling.** Shader Model 3.0 allows a per-attribute selection of center sampling, or *centroid sampling*. Centroid sampling returns a value inside the covered portion of the fragment, instead of at the center, and when used with multisampling, it can remove some artifacts associated with sampling outside the polygon (for example, when calculating diffuse or specular color using texture coordinates, or when using texture atlases).
- **Support for fp32 and fp16 internal precision.** Pixel shaders can support full fp32-precision computations and intermediate storage or partial-precision fp16 computations and intermediate storage.
- **3:1 and 2:2 co-issue.** Each four-component-wide vector unit is capable of executing two independent instructions in parallel, as shown in Figure 30-9: either one three-wide operation on RGB and a separate operation on alpha, or one two-wide operation on red-green and a separate two-wide operation on blue-alpha. This gives the compiler more opportunity to pack scalar computations into vectors, thereby doing more work in a shorter time.

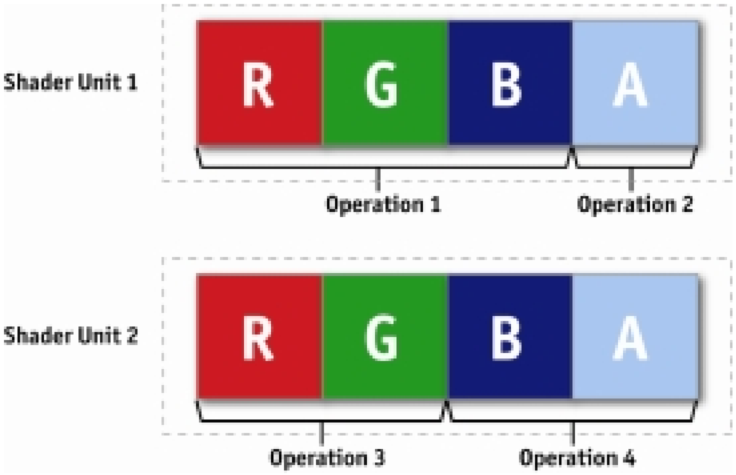

Figure 30-9. How Co-issue Works

- **Dual issue.** Dual issue is similar to co-issue, except that the two independent instructions can be executed on different parts of the shader pipeline. This makes the pipeline easier to schedule and, therefore, more efficient. See Figure 30-10.

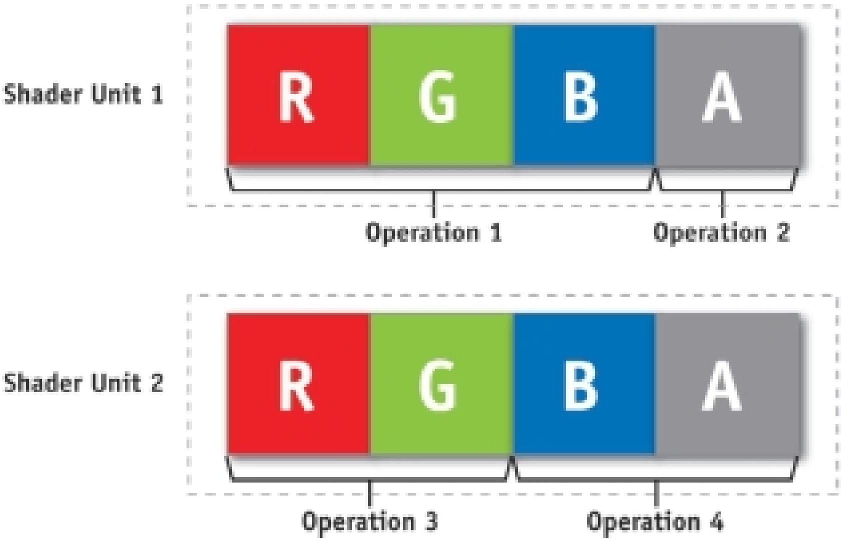

Figure 30-10. How Dual Issue Works

Shader Performance

The GeForce 6 Series shader architecture has the following performance characteristics:

- Each shader pipeline is capable of performing a four-wide, co-issue-able multiply-add (`MAD`) or four-term dot product (`DP4`), plus a four-wide, co-issue-able and dual-issue-able multiply instruction per clock in series, as shown in Figure 30-11. In addition, a multifunction unit that performs complex operations can replace the alpha channel `MAD` operation. Operations are performed at full speed on both fp32 and fp16 data, although store and bandwidth limitations can favor fp16 performance sometimes. In practice, it is sometimes possible to execute eight math operations as well as a texture lookup in a single cycle.

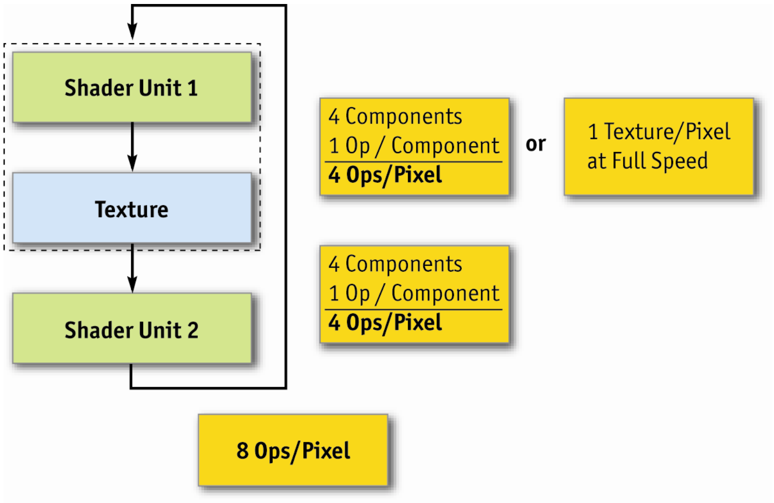

Figure 30-11. Shader Units and Capabilities

- Dedicated fp16 normalization hardware exists, making it possible to normalize a vector at fp16 precision in parallel with the multiplies and `MAD`s just described.

- Independent reciprocal operation can be performed in parallel with the multiply, `MAD`, and fp16 normalization described previously.
- Because the GeForce 6800 has 16 shader pipelines, the overall available performance of the system is given by these values multiplied by 16 and then by the clock rate.
- There is some overhead to flow-control operations, as defined in Table 30-2.

Table 30-2. Overhead incurred when executing flow-control operations in fragment programs.

Instruction	Cost (Cycles)
`If/endif`	4
`If/else/endif`	6
`Call`	2
`Ret`	2
`Loop/endloop`	4

Furthermore, pixel shader branching is affected by the level of divergence of the branches. Because the pixel shader operates on hundreds of pixels per instruction, if a branch is taken by some pixels and not others, all pixels execute both branches, but only writing to the registers on the branches each pixel is supposed to take. For low-frequency and mid-frequency branch changes, this effect is hidden, although it can become a limiter as the branch frequency increases.

30.3.3 Supported Data Storage Formats

Table 30-3 summarizes the data formats supported by the graphics pipeline.

Table 30-3. Data storage formats supported by the GeForce 6 series of GPUs.

Format	Description of Data in Memory	Vertex Texture Support	Pixel Texture Support	Render Target Support
B8	One 8-bit fixed-point number	No	Yes	Yes
A1R5G5B5	A 1-bit value and three 5-bit unsigned fixed-point numbers	No	Yes	Yes
A4R4G4B4	Four 4-bit unsigned fixed-point numbers	No	Yes	No
R5G6B5	5-bit, 6-bit, and 5-bit fixed-point numbers	No	Yes	Yes
A8R8G8B8	Four 8-bit fixed-point numbers	No	Yes	Yes
DXT1	Compressed 4×4 pixels into 8 bytes	No	Yes	No
DXT2,3,4,5	Compressed 4×4 pixels into 16 bytes	No	Yes	No
G8B8	Two 8-bit fixed-point numbers	No	Yes	Yes
B8R8_G8R8	Compressed as YVYU; two pixels in 32 bits	No	Yes	No
R8B8_R8G8	Compressed as VYUY; two pixels in 32 bits	No	Yes	No
R6G5B5	6-bit, 5-bit, and 5-bit unsigned fixed-point numbers	No	Yes	No
DEPTH24_D8	A 24-bit unsigned fixed-point number and 8 bits of garbage	No	Yes	Yes
DEPTH24_D8 FLOAT	A 24-bit unsigned float and 8 bits of garbage	No	Yes	Yes
DEPTH16	A 16-bit unsigned fixed-point number	No	Yes	Yes
DEPTH16_FLOAT	A 16-bit unsigned float	No	Yes	Yes
X16	A 16-bit fixed-point number	No	Yes	No
Y16_X16	Two 16-bit fixed-point numbers	No	Yes	No
R5G5B5A1	Three unsigned 5-bit fixed-point numbers and a 1-bit value	No	Yes	Yes
HILO8	Two unsigned 16-bit values compressed into two 8-bit values	No	Yes	No
HILO_S8	Two signed 16-bit values compressed into two 8-bit values	No	Yes	No
W16_Z16_Y16_X16 FLOAT	Four fp16 values	No	Yes	Yes
W32_Z32_Y32_X32 FLOAT	Four fp32 values	Yes, unfiltered	Yes, unfiltered	Yes
X32_FLOAT	One 32-bit floating-point number	Yes, unfiltered	Yes, unfiltered	Yes
D1R5G5B5	1 bit of garbage and three unsigned 5-bit fixed-point numbers	No	Yes	Yes
D8R8G8B8	8 bits of garbage and three unsigned 8-bit fixed-point numbers	No	Yes	Yes
Y16_X16 FLOAT	Two 16-bit floating-point numbers	No	Yes	No

30.4 Performance

The GeForce 6800 Ultra is the flagship product of the GeForce 6 Series family at the time of writing. Its performance is summarized as follows.

- 425 MHz internal graphics clock
- 550 MHz memory clock
- 600 million vertices/second
- 6.4 billion texels/second
- 12.8 billion pixels/second, rendering z/stencil-only (useful for shadow volumes and shadow buffers)
- 6 four-wide fp32 vector `MAD`s per clock cycle in the vertex shader, plus one scalar multifunction operation (a complex math operation, such as a sine or reciprocal square root)
- 16 four-wide fp32 vector `MAD`s per clock cycle in the pixel shader, plus 16 four-wide fp32 multiplies per clock cycle
- 64 pixels per clock cycle early z-cull (reject rate)

As you can see, there's plenty of programmable floating-point horsepower in the pixel and vertex shaders that can be exploited for computationally demanding problems.

30.5 Achieving Optimal Performance

While graphics hardware is becoming more and more programmable, there are still some tricks to ensuring that you exploit the hardware fully to get the most performance. This section lists some common techniques that you may find helpful. A more detailed discussion of performance advice is available in the *NVIDIA GPU Programming Guide*, which is freely available in several languages from the NVIDIA Developer Web Site (http://developer.nvidia.com/object/gpu_programming_guide.html).

30.5.1 Use Z-Culling Aggressively

Z-cull avoids work that won't contribute to the final result. It's better to determine early that a computation doesn't matter and save doing the work. In graphics, this can be done by rendering the z-values for all objects first, before shading. For general-purpose computation, the z-cull unit can be used to select which parts of the computation are still active, culling computational threads that have already resolved. See Section 34.2.3 of Chapter 34, "GPU Flow Control Idioms," for more details on this idea.

30.5.2 Exploit Texture Math When Loading Data

The texture unit filters data while loading it into the shader, thus reducing the total data needed by the shader. The texture unit's bilinear filtering can frequently be used to reduce the total work done by the shader if it's performing more sophisticated shading.

Often, large filter kernels can be dissected into groups of bilinear footprints, which are scaled and accumulated to build the large kernel. A few caveats here, most notably that all filter coefficients must be positive for bilinear footprint assembly to work properly. (See Chapter 20, “Fast Third-Order Texture Filtering,” for more information about this technique.)

30.5.3 Use Branching in Pixel Shaders Judiciously

Because the pixel shader is a SIMD machine operating on many pixels at a time, if some pixels in a given group take one branch and other pixels in that group take another branch, the pixel shader needs to take both branches. Also, there is a six-cycle overhead for if-else-endif control structures. These two effects can reduce the performance of branching programs if not considered carefully. Branching can be very beneficial, as long as the work avoided outweighs the cost of branching. Alternatively, conditional writes (that is, write if a condition code is set) can be used when branching is not performance-effective. In practice, the compiler will use the method that delivers higher performance when possible.

30.5.4 Use fp16 Intermediate Values Wherever Possible

Because GeForce 6 Series GPUs support a full-speed fp16 normalize instruction in parallel with the multiplies and adds, and because fp16 intermediate values reduce internal storage and data path requirements, using fp16 intermediate values wherever possible can be a performance win, saving fp32 intermediate values for cases where the precision is needed.

Excessive internal storage requirements can adversely affect performance in the following way: The shader pipeline is optimized to keep hundreds of pixels in flight given a fixed amount of register space per pixel (four fp32×4 registers or eight fp16×4 registers). If the register space is exceeded, then fewer pixels can remain in flight, reducing the latency tolerance for texture fetches, and adversely affecting performance. The GeForce 6 Series shader will have the maximum number of pixels in flight when shader programs use up to four fp32×4 temporary registers (or eight fp16×4 registers). That is, at any one time, a maximum of four temporary fp32×4 (or eight fp16×4 registers) are in use. This decision was based on the fact that for the overwhelming majority of analyzed shaders, four or fewer simultaneously active fp32×4 registers proved to be the sweet spot during the shaders’ execution. In addition, the architecture is designed so that performance degrades slowly if more registers are used.

Similarly, the register file has enough read and write bandwidth to keep all the units busy if reading fp16×4 values, but it may run out of bandwidth to feed all units if using fp32×4 values exclusively. NVIDIA’s compiler technology is smart enough to reduce this effect substantially, but fp16 intermediate values are never slower than fp32 values; because of the resource restrictions and the fp16 normalize hardware, they can often be much faster.

30.6 Conclusion

GeForce 6 Series GPUs provide the GPU programmer with unparalleled flexibility and performance in a product line that spans the entire PC market. After reading this chapter, you should have a better understanding of what GeForce 6 Series GPUs are capable of, and you should be able to use this knowledge to develop applications—either graphical or general purpose—in a more efficient way.

NVIDIA GPU Historical Data

Source: NVIDIA Corporation
Apr-06

Estimate for contemporary CPU-based vertex

Year	Product	New Features	OpenGL version	Direct3D version	Core Clk (Mhz)	Mem Clk (Mhz)	Mtri/sec	Mtri/sec per-year Increase	Mvert/sec	Mvert/sec per-year Increase
1998	Riva ZX	16-bit depth, color, and textures	1.1	DX5	100	100	3	-	1	-
1999	Riva TNT2	Dual-texturing, interpolated specular color, 32-bit depth/stencil, color, and texture	1.2	DX6	175	200	9	200%	2	100%
2000	GeForce2 GTS	Hardware transform & lighting, configurable fixed-point shading, cube maps, texture compression, 2x anisotropic texture filtering	1.3	DX7	166	333	25	178%	24	1086%
2001	GeForce3	Programmable vertex transformation, 4 texture units, dependent textures, 3D textures, shadow maps, multisampling, occlusion queries	1.4	DX8	200	460	30	20%	33	41%
2002	GeForce4 Ti 4600	Early Z culling, dual-monitor	1.4	DX8.1	300	650	60	100%	100	200%
2003	GeForce FX	Vertex program branching, floating-point fragment programs, 16 texture units, limited floating-point textures, color and depth compression	1.5	DX9	500	1000	167	178%	375	275%
2004	GeForce 6800 Ultra	Vetex textures, structured fragment branching, non-power-of-two textures, generalized floating-point textures, floating-point texture filtering and blending	2.0	DX9c	425	1100	170	2%	638	70%
2005	GeForce 7800 GTX	Transparent antialiasing, Quad SLI-capable	2.0	DX9c	430	1200	172	1%	860	35%
						Increase over 7 years	57.3		860.0	

Mhz for DDR memory is doubled

3 times Mvert/sec exceeds Mtri/sec but excess rate allows more vertex program instructions

assumes supersampling since no multisampling in ZX, TNT2 or GeForce2 GTS

assumes multi-pass since ZX has no multitexture

1,000,000 bytes per gigabyte (not 2^20 bytes)

Assumes 1/3 T, 1/3 C, 1/3 Z bandwidth base. Assumes 4:1 compression in all cases.

Mipmap bilinear on ZX and TNT2

No compression.

Year	Product	Single Texture Fill Mpix/sec	Single Texture Fill per-year Increase	Depth Stencil Only Fill Mpix/sec	4x FSAA Single Texture Fill Mpix/sec	4x FSAA Dual Texture Fill Mpix/sec	Texture Rate Mtex/sec	Texture Rate per-year increase	Bandwidth (GB/sec)	Effective Bandwidth (compressed) (GB/sec)	Process (um)	Transistor count (M)
1998	Riva ZX	100	-	100	25	13	100	-	1.6	1.6	0.35	4
1999	Riva TNT2	350	250%	350	88	44	350	250%	3.2	3.2	0.22	9
2000	GeForce2 GTS	664	90%	664	166	166	1,328	279%	5.3	10.7	0.18	25
2001	GeForce3	800	20%	800	400	400	1,600	20%	7.4	22.1	0.18	57
2002	GeForce4 Ti 4600	1,200	50%	1,200	600	600	2,400	50%	10.4	31.2	0.15	63
2003	GeForce FX	2,000	67%	4,000	2,000	2,000	4,000	67%	16.0	64.0	0.13	121
2004	GeForce 6800 Ultra	6,800	240%	13,600	6,800	3,400	6,800	70%	35.2	140.8	0.13	222
2005	GeForce 7800 GTX	10,320	52%	13,760	10,320	5,160	10,320	52%	38.4	153.6	0.11	302
		103.2		137.6	412.8	412.8	103.2		24.0	96.0		75.5

Exceeds 6880 Mpix/sec peak fill rate but excess rate allows more fragment program texture fetch instructions

Dual-textured trilinear

Double texture rate assumes two mipmap bilinear textures (not trilinear)

DXTC texture compression

DXTC texture compression, Z compression, color compression (for multisampling)

NVIDIA OpenGL 2.0 Support

Mark J. Kilgard
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These release notes explain NVIDIA's support for OpenGL 2.0. These notes are written mainly for OpenGL programmers writing OpenGL 2.0 applications. These notes may also be useful for OpenGL-savvy end-users seeking to understand the OpenGL 2.0 capabilities of NVIDIA GPUs.

This document addresses

- What is OpenGL 2.0?
- What NVIDIA Drivers and GPUs support OpenGL 2.0?
- Programmable Shading API Updates for OpenGL 2.0
- Correctly Detecting OpenGL 2.0 in Applications
- Enabling OpenGL 2.0 Emulation on Older GPUs
- Key Known Issues
- OpenGL 2.0 API Declarations
- Distinguishing NV3xGL-based and NV4xGL-based Quadro FX GPUs by Product Names

1. What is OpenGL 2.0?

OpenGL 2.0 is the latest core revision of the OpenGL graphics system. The OpenGL 2.0 specification was finalized September 17, 2004 by the OpenGL Architectural Review Board (commonly known as "the ARB").

OpenGL 2.0 incorporates the following functionality into the core OpenGL standard:

- **High-level Programmable Shading.** The OpenGL Shading Language (commonly called GLSL) and the related APIs for creating, managing, and using shader and program objects defined with GLSL is now a core feature of OpenGL.

  This functionality was first added to OpenGL as a collection of ARB extensions, namely `ARB_shader_objects`, `ARB_vertex_shader`, and `ARB_fragment_shader`. OpenGL 2.0 updated the API from these original ARB extensions. These API updates are discussed in section 3.

- **Multiple Render Targets.** Previously core OpenGL supported a single RGBA color output from fragment processing. OpenGL 2.0 specifies a maximum number of draw buffers (though the maximum can be 1). When multiple draw buffers are provided, a low-level assembly fragment program or GLSL fragment shader can output multiple RGBA color outputs that update a specified set of draw buffers respectively. This functionality matches the `ARB_draw_buffers` extension.

- **Non-Power-Of-Two Textures.** Previously core OpenGL required texture images (not including border texels) to be a power-of-two size in width, height, and depth. OpenGL 2.0 allows arbitrary sizes for width, height, and depth. Mipmapping of such textures is supported. The functionality matches the `ARB_texture_non_power_of_two` extension.

- **Point Sprites.** Point sprites override the single uniform texture coordinate set values for a rasterized point with interpolated 2D texture coordinates that blanket the point with the full texture image. This allows application to define a texture pattern for rendered points. The functionality matches the `ARB_point_sprite` extension but with additional origin control.

- **Two-Sided Stencil Testing.** Previously core OpenGL provided a single set of stencil state for both front- and back-facing polygons. OpenGL 2.0 introduces separate front- and back-facing state. This can improve the performance of certain shadow volume and Constructive Solid Geometry (CSG) rendering algorithms. The functionality merges the capabilities of the `EXT_stencil_two_side` and `ATI_stencil_separate` extensions.

- **Separate RGB and Alpha Blend Equations.** Previously core OpenGL provided a blend equation (add, subtract, reverse subtract, min, or max) that applied to both the RGB and alpha components of a blended pixel. OpenGL 1.4 allowed separate RGB and alpha components to support distinct source and destination functions. OpenGL 2.0 generalizes the control to provide separate RGB and alpha blend equations.

- **Other Specification Changes.** OpenGL 2.0 includes several minor revisions and corrections to the specification. These changes are inconsequential to OpenGL programmers as the changes did not change the understood and implemented behavior of OpenGL. See appendix I.6 of the OpenGL 2.0 specification for details.

2. What NVIDIA Drivers and GPUs support OpenGL 2.0?

NVIDIA support for OpenGL 2.0 begins with the Release 75 series of drivers. GeForce FX (NV3x), GeForce 6 Series (NV4x), NV3xGL-based Quadro FX and NV4xGL-based Quadro FX GPUs, and all future NVIDIA GPUs support OpenGL 2.0.

Prior to Release 75, drivers for these OpenGL 2.0-capable GPUs advertised OpenGL 1.5 support but also exposed the feature set of OpenGL 2.0 through the corresponding extensions listed in section 1.

Earlier GPUs (such as GeForce2, GeForce3, and GeForce4) continue to support OpenGL 1.5 with no plans to ever support OpenGL 2.0 because the hardware capabilities of these GPUs are not sufficient to accelerate the OpenGL 2.0 feature set properly.

However, NVIDIA provides an option with Release 75 drivers to emulate OpenGL 2.0 features on these earlier GPUs. This option is further discussed in section 5. This emulation option is *not recommended for general users* because OpenGL 2.0 features will be emulated in software very, very slowly. OpenGL 2.0 emulation may be useful for developers and students without access to the latest NVIDIA GPU hardware.

2.1. Acceleration for GeForce 6 Series and NV4xGL-based Quadro FX

All key OpenGL 2.0 features are hardware-supported by NVIDIA’s GeForce 6 Series and NV4xGL-based Quadro FX GPUs. These GPUs offer the best OpenGL 2.0 hardware acceleration available from any vendor today.

2.1.1. Fragment-Level Branching

NVIDIA’s GeForce 6 Series and NV4xGL-based Quadro FX GPUs support structured fragment-level branching. Structured branching allows standard control-flow mechanisms such as loops, early exit from loops (comparable to a `break` statement in C), *if-then-else* decision making, and function calls. Specifically, the hardware can support data-dependent branching such as a loop where the different fragments early exit the loop after a varying number of iterations.

Much like compilers for CPUs, NVIDIA’s Cg-based compiler technology decides automatically whether to use the hardware’s structured branching capabilities or using simpler techniques such as conditional assignment, unrolling loops, and inlining functions.

Hardware support for fragment-level branching is not as general as vertex-level branching. Some flow control constructs are too complicated or cannot be expressed by the hardware’s structured branching capabilities. A few restrictions of note:

- Function calls can be nested at most 4 calls deep.

- *If-then-else* decision making can be nested at most 47 branches deep.

- Loops cannot be nested more than 4 loops deep.

- Each loop can have at most 255 iterations.

The compiler can often generate code that avoids these restrictions, but if not, the program object containing such a fragment shader will fail to compile. These restrictions are also discussed in the `NV_fragment_program2` OpenGL extension specification.

2.1.2. Vertex Textures

NVIDIA's GeForce 6 Series and NV4xGL-based Quadro FX GPUs accelerate texture fetches by GLSL vertex shaders.

The implementation-dependent constant `GL_MAX_VERTEX_TEXTURE_IMAGE_UNITS` is advertised to be 4 meaning these GPUs provide a maximum of 4 vertex texture image units.

2.1.2.1. Hardware Constraints

Keep in mind these various hardware constraints for vertex textures:

- While 1D and 2D texture targets for vertex textures are supported, the 3D, cube map, and rectangle texture targets are not hardware accelerated for vertex textures.

- Just these formats are accelerated for vertex textures: `GL_RGBA_FLOAT32_ARB`, `GL_RGB_FLOAT32_ARB`, `GL_ALPHA_FLOAT32_ARB`, `GL_LUMINANCE32_ARB`, `GL_INTENSITY32_ARB`, `GL_FLOAT_RGBA32_NV`, `GL_FLOAT_RGB32_NV`, `GL_FLOAT_RG32_NV`, or `GL_FLOAT_R32_NV`.

- Vertex textures with border texels are not hardware accelerated.

- Since no depth texture formats are hardware accelerated, shadow mapping by vertex textures is not hardware accelerated

The vertex texture functionality precluded from hardware acceleration in the above list will still operate as specified but it will require the vertex processing be performed on the CPU rather than the GPU. This will substantially slow vertex processing. However, rasterization and fragment processing can still be fully hardware accelerated.

2.1.2.2. Unrestricted Vertex Texture Functionality

These features are supported for hardware-accelerated vertex textures:

- All wrap modes for S and T including all the clamp modes, mirrored repeat, and the three “mirror once then clamp” modes. Any legal border color is allowed.
- Level-of-detail (LOD) bias and min/max clamping.
- Non-power-of-two sizes for the texture image width and height.
- Mipmapping.

Because vertices are processed as ideal points, vertex textures accesses require an explicit LOD to be computed; otherwise the base level is sampled. Use the bias parameter of GLSL’s `texture2DLod`, `texture1DLod`, and related functions to specify an explicit LOD.

2.1.2.3. Linear and Anisotropic Filtering Caveats

NVIDIA’s GeForce 6 Series and NV4xGL-based Quadro FX GPUs do not hardware accelerate linear filtering for vertex textures. If vertex texturing is otherwise hardware accelerated, `GL_LINEAR` filtering operates as `GL_NEAREST`. The mipmap minification filtering modes (`GL_LINEAR_MIPMAP_LINEAR`, `GL_NEAREST_MIPMAP_LINEAR`, or `GL_LINEAR_MIPMAP_NEAREST`) operate as if `GL_NEAREST_MIPMAP_NEAREST` so as not to involve any linear filtering. Anisotropic filtering is also ignored for hardware-accelerated vertex textures.

These same rules reflect hardware constraints that apply to vertex textures whether used through GLSL or `NV_vertex_program3` or Cg’s `vp40` profile.

2.1.3. Multiple Render Targets

NVIDIA’s GeForce 6 Series and NV4xGL-based Quadro FX GPUs support a maximum of 4 simultaneous draw buffers (indicated by `GL_MAX_DRAW_BUFFERS`). Typically, you should request a pixel format for your framebuffer with one or more auxiliary buffers (commonly called *aux* buffers) to take advantage of multiple render targets.

Most pixel formats have an option for 4 auxiliary buffers. These buffers are allocated lazily so configuring with a pixel format supporting 4 auxiliary buffers but using fewer buffers in your rendering will not require video memory be allocated to never used buffers.

2.1.4. Non-Power-Of-Two Textures

NVIDIA's GeForce 6 Series and NV4xGL-based Quadro FX GPUs fully support non-power-of-two textures at the fragment level. All texture formats (including compressed formats) and all texture modes such as shadow mapping, all texture filtering modes (including anisotropic filtering), borders, LOD control, and all clamp modes work as expected with non-power-of-two texture sizes. Non-power-of-two textures are also supported for vertex textures but with the limitations discussed in section 2.1.2.

2.1.4.1. Rendering Performance and Texture Memory Usage

For memory layout and caching reasons, uncompressed non-power-of-two textures may be slightly slower than uncompressed power-of-two textures of comparable size. However, non-power-of-two textures *compressed with S3TC* should have very comparable rendering performance to similarly compressed power-of-two textures.

For non-mipmapped non-power-of-two textures (as well as non-mipmapped power-of-two textures), the size of the texture in memory is roughly the width × height × depth (if 3D) × bytes-per-texel as you would expect. So in this case, a 640x480 non-power-of-two-texture *without mipmaps*, will take just 59% of the memory required if the image was rounded up to the next power-of-two size (1024×512).

Mipmapped power-of-two sized 2D or 3D textures take up roughly four-thirds times (1.333x) the memory of a texture's base level memory size. However, mipmapped non-power-of-two 2D or 3D textures take up roughly **two times** (2x) the memory of a texture's base level memory size. For these reasons, developers are discouraged from changing (for example) a 128x128 mipmapped texture into a 125×127 mipmapped texture hoping the slightly smaller texture size is an advantage.

The compressed S3TC formats are based on 4×4 pixel blocks. This means the width and height of non-power-of-two textures compressed with S3TC are rounded up to the nearest multiple of 4. So for example, there is no memory footprint advantage to using a non-mipmapped 13×61 texture compressed with S3TC compared to a similarly compressed non-mipmapped 16×64 texture.

2.1.4.2. Mipmap Construction for Non-Power-of-Two-Textures

The size of each smaller non-power-of-two mipmap level is computed by halving the lower (larger) level's width, height, and depth and rounding down (flooring) to the next smaller integer while never reducing a size to less than one. For example, the level above a 17×10 mipmap level is 8×5. The OpenGL non-power-of-two mipmap reduction convention is identical to that of DirectX 9.

The standard `gluBuild1DMipmaps`, `gluBuild2DMipmaps`, and `gluBuild3DMipmaps` routines accept a non-power-of-two image but automatically rescale the image (using a box filter) to the next largest power-of-two in all dimensions if necessary. If you want to specify true non-power-of-two mipmapped texture images, these routines should be avoided.

Instead, you can set the `GL_GENERATE_MIPMAP` texture parameter to `GL_TRUE` and let the OpenGL driver generate non-power-of-two mipmaps for you automatically.

NVIDIA's OpenGL driver today uses a slow-but-correct recursive box filter (each iteration is equivalent to what `gluScaleImage` does) when generating non-power-of-two mipmap chains. Expect driver mipmap generation for non-power-of-two textures to be measurably slower than driver mipmap generation for non-power-of-two textures. Future driver releases may optimize non-power-of-two mipmap generation.

Applications using static non-power-of-two textures can reduce time spent generating non-power-of-two mipmap chains by loading pre-computing mipmap chains.

2.1.5. Point Sprites

OpenGL 2.0 introduces a new point sprite mode called `GL_POINT_SPRITE_COORD_ORIGIN` that can be set to `GL_UPPER_LEFT` (the default) or `GL_LOWER_LEFT`. The earlier `ARB_point_sprite` and `NV_point_sprite` extensions lack this mode.

When rendering to windows, leave the `GL_POINT_SPRITE_COORD_ORIGIN` state set to its default `GL_UPPER_LEFT` setting. Using `GL_LOWER_LEFT` with windowed rendering will force points to be transformed on the CPU.

When rendering to pixel buffers (commonly called *pbuffers*) or frame buffer objects (commonly called FBOs), change the `GL_POINT_SPRITE_COORD_ORIGIN` state set to `GL_LOWER_LEFT` setting for fully hardware accelerated rendering. Using `GL_UPPER_LEFT` with pbuffer and FBO rendering will force points to be transformed on the CPU.

NVIDIA supports (on all its GPUs) the `NV_point_sprite` extension that provides one additional point sprite control beyond what OpenGL 2.0 provides. This extension provides an additional `GL_POINT_SPRITE_R_MODE_NV` that controls how the R texture coordinate is set for points. You have the choice to zero R (`GL_ZERO`, the default), use the vertex's S coordinate for R prior to S being overridden for the point sprite mode (`GL_S`), or the vertex's R coordinate (`GL_R`).

2.1.6. Two-Sided Stencil Testing

NVIDIA's GeForce 6 Series and NV4xGL-based Quadro FX GPUs fully support all OpenGL 2.0 two-sided stencil testing modes.

NVIDIA drivers support both the `EXT_stencil_two_side` extension and the OpenGL 2.0 functionality. Two sets of back-sided stencil state are maintained. The EXT extension's state is set by `glStencil*` commands when `glActiveStencilFaceEXT` is set to `GL_BACK`. The 2.0 back-facing state is set by the `glStencil*Separate` commands when the `face` parameter is `GL_BACK` (or `GL_FRONT_AND_BACK`). When `GL_STENCIL_TWO_SIDE_EXT` is enabled, the EXT back-facing stencil state takes priority.

2.1.7. Separate RGB and Alpha Blend Equations

NVIDIA's GeForce 6 Series and NV4xGL-based Quadro FX GPUs fully support *all* OpenGL 2.0 blend modes including separate RGB and alpha blend equations.

2.2. Acceleration for GeForce FX and NV3xGL-based Quadro FX

2.2.1. Fragment-Level Branching

Unlike NVIDIA's GeForce 6 Series and NV4xGL-based Quadro FX GPUs, GeForce FX and NV3xGL-based Quadro FX GPUs do not have hardware support for fragment-level branching.

Apparent support for flow-control constructs in GLSL (and Cg) is based entirely on conditional assignment, unrolling loops, and inlining functions.

The compiler can often generate code for programs with flow control that can be simulated with conditional assignment, unrolling loops, and inlining functions, but for more complex flow control, the program object containing a fragment shader may simply fail to compile. The hardware's branch-free execution model with condition-code instructions is discussed in the `NV_fragment_program` OpenGL extension specification.

2.2.2. Vertex Textures

NVIDIA's GeForce FX and NV3xGL-based Quadro FX GPUs lack hardware support for vertex fetching. GLSL vertex shaders that perform vertex texture fetches will fail to compile.

The implementation-dependent constant `GL_MAX_VERTEX_TEXTURE_IMAGE_UNITS` is advertised as zero (OpenGL 2.0 allows a minimum of zero to be advertised).

Future driver revisions may successfully compile GLSL vertex shaders with texture fetches but perform the vertex shader completely or partially with the CPU. In this case, the GPU can still accelerate rasterization and fragment processing.

2.2.3. Multiple Render Targets

NVIDIA's GeForce FX and NV3xGL-based Quadro FX GPUs can output only a single RGBA color per fragment processed so the maximum number of draw buffers (indicated by `GL_MAX_DRAW_BUFFERS`) is just one.

Effectively, this means GeForce FX and NV3xGL-based Quadro FX GPUs do not support the spirit of multiple render targets. However, OpenGL 2.0 permits an implementation to advertise support for just one draw buffer (see the 1+ minimum for `GL_MAX_DRAW_BUFFERS` in table 6.35 of the OpenGL 2.0 specification).

Applications that desire rendering to multiple rendering targets must resort to multiple rendering passes using `glDrawBuffer` to switch to a different buffer for each pass.

2.2.4. Non-Power-Of-Two Textures

GeForce FX and NV3xGL-based Quadro FX GPUs lack hardware support for non-power-of-two textures (excepting the texture rectangle functionality provided by the `ARB_texture_rectangle` extension). If any texture unit could sample a bound 1D, 2D, 3D, or cube map texture object with non-power-of-two size, the driver will automatically render with software rendering, which is correct but extremely slow.

To determine if non-power-of-two textures are slow, examine the `GL_EXTENSIONS` string. If `GL_VERSION` reports that 2.0 but `GL_ARB_texture_non_power_of_two` is not listed in the `GL_EXTENSIONS` string, assume that using non-power-of-two-textures is slow and avoid the functionality.

The discussion in section 2.1.4.2 about non-power-of-two mipmap discussion apply to GeForce FX and NV3xGL-based Quadro FX GPUs too even if these GPUs do not hardware accelerate non-power-of-two texture rendering.

2.2.5. Point Sprites

GeForce FX and NV3xGL-based Quadro FX GPUs have the identical caveats as the GeForce 6 Series and NV4xGL-based Quadro FX GPUs discussed in section 2.1.5.

2.2.6. Two-Sided Stencil Testing

GeForce FX and NV3xGL-based Quadro FX GPUs have full hardware acceleration for two-sided stencil testing just like the GeForce 6 Series and NV4xGL-based Quadro FX GPUs. The same discussion in section 2.1.6 applies.

2.2.7. Separate RGB and Alpha Blend Equations

GeForce FX and NV3xGL-based Quadro FX GPUs lack hardware support for separate RGB and alpha blend equations. If the RGB and alpha blend equations are different, the driver will automatically render with full software rasterization, which is correct but extremely slow.

To determine if separate blend equations is slow, examine the `GL_EXTENSIONS` string. If `GL_VERSION` reports that 2.0 but `GL_EXT_blend_equation_separate` is not listed in the

`GL_EXTENSIONS` string, assume that using separate distinct blend equations is slow and avoid the functionality.

3. Programmable Shading API Updates for OpenGL 2.0

The command and token names in the original ARB extensions for programmable shading with GLSL are verbose and used an object model inconsistent with other types of objects (display lists, texture objects, vertex buffer objects, occlusion queries, etc.).

3.1. Type Name Changes

The `GLhandleARB` type has been deprecated in preference to `GLuint` for program and shader object names. The underlying type for the `GLhandleARB` is a 32-bit unsigned integer so the two types have compatible representations.

Old ARB extensions type	New OpenGL 2.0 type
`GLhandleARB`	`GLuint`

3.2. Token Name Changes

Old ARB extensions tokens	New OpenGL 2.0 tokens
`GL_PROGRAM_OBJECT_ARB`	*Unnecessary*
`GL_SHADER_OBJECT_ARB`	*Unnecessary*
`GL_OBJECT_TYPE_ARB`	*Instead* `glIsProgram` *and* `glIsShader`
`GL_OBJECT_SUBTYPE_ARB`	`GL_SHADER_TYPE`
`GL_OBJECT_DELETE_STATUS_ARB`	`GL_DELETE_STATUS`
`GL_OBJECT_COMPILE_STATUS_ARB`	`GL_COMPILE_STATUS`
`GL_OBJECT_LINK_STATUS_ARB`	`GL_LINK_STATUS`
`GL_OBJECT_VALIDATE_STATUS_ARB`	`GL_VALIDATE_STATUS`
`GL_OBJECT_INFO_LOG_LENGTH_ARB`	`GL_INFO_LOG_LENGTH`
`GL_OBJECT_ATTACHED_OBJECTS_ARB`	`GL_ATTACHED_SHADERS`
`GL_OBJECT_ACTIVE_UNIFORMS_ARB`	`GL_ACTIVE_UNIFORMS`
`GL_OBJECT_ACTIVE_UNIFORM_MAX_LENGTH_ARB`	`GL_ACTIVE_UNIFORM_MAX_LENGTH`
`GL_OBJECT_SHADER_SOURCE_LENGTH_ARB`	`GL_SHADER_SOURCE_LENGTH`
No equivalent	`GL_CURRENT_PROGRAM`

For other `ARB_shader_objects`, `ARB_vertex_shader`, and `ARB_fragment_shader` tokens, the OpenGL 2.0 names are identical to the ARB extension names except without the ARB suffix.

3.3. Command Name Changes

Old ARB extensions commands	New OpenGL 2.0 commands
`glAttachObjectARB`	`glAttachShader`
`glCreateProgramObjectARB`	`glCreateProgram`
`glCreateShaderObjectARB`	`glCreateShader`
`glDeleteObjectARB`	`glDeleteShader` for shader objects, `glDeleteProgram` for program objects
`glDetachObjectARB`	`glDetachShader`
`glGetAttachedObjectsARB`	`glGetAttachedShaders`
`glGetHandleARB`	`glGetIntegerv(GL_CURRENT_PROGRAM, &retval)`
`glGetInfoLogARB`	`glGetShaderInfoLog` for shader objects, `glGetProgramInfoLog` for program objects
`glGetObjectParameterfvARB`	*No equivalent*
`glGetObjectParameterivARB`	`glGetShaderiv` for shader objects, `glGetProgramiv` for program objects
No equivalent	`glIsProgram`
No equivalent	`glIsShader`
`glUseProgramObjectARB`	`glUseProgram`

For other `ARB_shader_objects`, `ARB_vertex_shader`, and `ARB_fragment_shader` commands, the OpenGL 2.0 names are identical to the ARB extension names except without the ARB suffix.

4. Correctly Detecting OpenGL 2.0 in Applications

To determine if OpenGL 2.0 or better is supported, an application must parse the implementation-dependent string returned by calling `glGetString(GL_VERSION)` .

4.1. Version String Formatting

OpenGL version strings are laid out as follows:

<version number> <space> <vendor-specific information>

The version number is either of the form *major_number.minor_number* or *major_number.minor_number.release_number*, where the numbers all have one or more digits. The *release_number* and *vendor-specific information*, along with its preceding space, are optional. If present, the interpretation of the *release_number* and *vendor-specific information* depends on the vendor.

NVIDIA does not provide *vendor-specific information* but uses the *release_number* to indicate how many NVIDIA major driver releases (counting from zero) have supported this particular major and minor revision of OpenGL. For example, the drivers in the Release 75 series report `2.0.0` indicating Release 75 is the first driver series to support

OpenGL 2.0. Release 80 will likely advertise `2.0.1` for its `GL_VERSION` string. Major NVIDIA graphics driver releases typically increment by 5.

4.2. *Proper Version String Parsing*

Early application testing by NVIDIA has encountered a few isolated OpenGL applications that incorrectly parse the `GL_VERSION` string when the OpenGL version changed from 1.5 to 2.0.

OpenGL developers are *strongly* urged to examine their application code that parses the `GL_VERSION` string to make sure pairing the application with an OpenGL 2.0 implementation will not confuse or crash the application.

Use the routine below to correctly test if at least a particular major and minor version of OpenGL is available.

```
static int
supportsOpenGLVersion(int atLeastMajor, int atLeastMinor)
{
    const char *version;
    int major, minor;

    version = (const char *) glGetString(GL_VERSION);
    if (sscanf(version, "%d.%d", &major, &minor) == 2) {
        if (major > atLeastMajor)
            return 1;
        if (major == atLeastMajor && minor >= atLeastMinor)
            return 1;
    } else {
        /* OpenGL version string malformed! */
    }
    return 0;
}
```

For example, the above routine returns true if OpenGL 2.0 or better is supported (and false otherwise) when the routine is called like this:

```
int hasOpenGL20 = supportsOpenGLVersion(2, 0);
```

Be sure your OpenGL applications behave correctly with OpenGL 2.0.

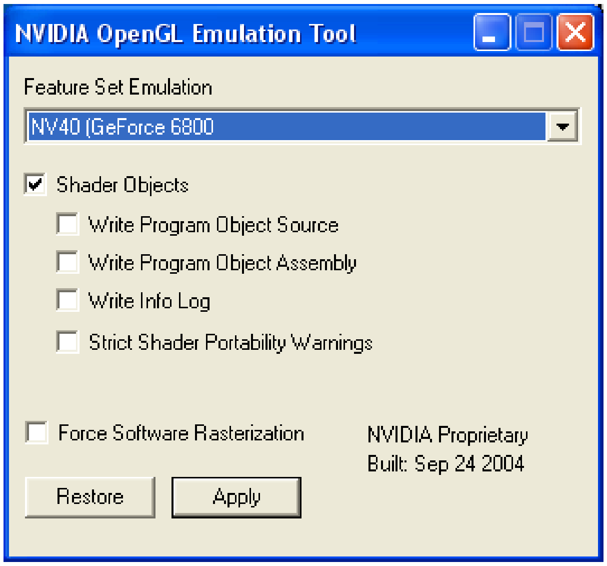
5. Enabling OpenGL 2.0 Emulation on Older GPUs

Developers and students using Microsoft Windows wishing to work with OpenGL 2.0 on pre-NV3x GPUs can use a utility called `nvemulate.exe` to force these older drivers to expose the feature sets of newer GPUs. When forcing emulation of an NV3x or NV4x GPU with a Release 75-based driver, you can expose OpenGL 2.0.

OpenGL features the GPU can support natively will be hardware accelerated as usual. But GPU features not natively supported will be slowly emulated by the OpenGL driver.

OpenGL extensions, implementation-dependent limits, and core OpenGL version for the GPU being emulated will be advertised.

So if you enable “NV40 (GeForce 6800)” emulation, as shown in the image below, on a old GeForce3 GPU, you will see OpenGL 2.0 advertised by the `GL_VERSION` string along with all the NV40 OpenGL extensions listed in the `GL_EXTENSIONS` string and implementation-dependent limits returned by `glGetIntegerv`.



NVIDIA OpenGL Emulation Tool

Feature Set Emulation

NV40 (GeForce 6800

☑ Shader Objects
  ☐ Write Program Object Source
  ☐ Write Program Object Assembly
  ☐ Write Info Log
  ☐ Strict Shader Portability Warnings

☐ Force Software Rasterization

NVIDIA Proprietary
Built: Sep 24 2004

5.1. Programmable Shading Debug Options

Additional check boxes can be enabled and disabled to aid in debugging GLSL applications. The “Shader Objects” check box determines whether the ARB extensions for programmable shading (`ARB_shader_objects`, etc.) are advertised or not.

The “Write Program Object Source” check box causes `vsrc_%u.txt` and `fsrc_%u.txt` files containing the concatenated source string for GLSL shaders to be written to the application’s current directory where the %u is `GLuint` value for the shader name.

The “Write Program Object Assembly” check box causes `vasm_%u.txt` and `fasm_%u.txt` files containing the compiled assembly text for linked GLSL program objects to be written to the application’s current directory where the %u is `GLuint` value for the program name.

The “Write Info Log” check box causes `ilog_%u.txt` files containing the info log contents for linked GLSL program objects to be written to the application’s current directory where the %u is `GLuint` value for the program name.

The “Strict Shader Portability Warnings” causes the compiler to generate portability warnings in the info log output. These warnings are not particularly thorough yet.

5.2. Forcing the Software Rasterizer

With the “Force Software Rasterizer” check box set, the driver does **all** OpenGL rendering in software. If you suspect a driver bug resulting in incorrect rendering, you might try this option and see if the rendering anomaly manifests itself in the software rasterizer. This information is helpful when reporting bugs to NVIDIA.

If the hardware and software rendering paths behave more-or-less identically, it may be an indication that the rendering anomaly is due to your application mis-programming OpenGL state or incorrect expectations about how OpenGL should behave.

6. Key Known Issues

6.1. OpenGL Shading Language Issues

NVIDIA’s GLSL implementation is a work-in-progress and still improving. Current limitations and known bugs are discussed in the *Release Notes for NVIDIA OpenGL Shading Language Support*. Developers should be aware of these key issues:

6.1.1. Noise Functions Always Return Zero

The GLSL standard library contains several noise functions of differing dimensions: `noise1`, `noise2`, `noise3`, and `noise4`.

NVIDIA’s implementation of these functions (currently) always returns zero results.

6.1.2. Vertex Attribute Aliasing

GLSL attempts to eliminate aliasing of vertex attributes but this is integral to NVIDIA’s hardware approach and necessary for maintaining compatibility with existing OpenGL applications that NVIDIA customers rely on.

NVIDIA’s GLSL implementation therefore does not allow built-in vertex attributes to collide with a generic vertex attributes that is assigned to a particular vertex attribute index with `glBindAttribLocation`. For example, you should not use `gl_Normal` (a built-in vertex attribute) and also use `glBindAttribLocation` to bind a generic vertex attribute named “whatever” to vertex attribute index 2 because `gl_Normal` aliases to index 2.

This table below summarizes NVIDIA's vertex attribute aliasing behavior:

Built-in vertex attribute name	**Incompatible aliased vertex attribute index**
`gl_Vertex`	0
`gl_Normal`	2
`gl_Color`	3
`gl_SecondaryColor`	4
`gl_FogCoord`	5
`gl_MultiTexCoord0`	8
`gl_MultiTexCoord1`	9
`gl_MultiTexCoord2`	10
`gl_MultiTexCoord3`	11
`gl_MultiTexCoord4`	12
`gl_MultiTexCoord5`	13
`gl_MultiTexCoord6`	14
`gl_MultiTexCoord7`	15

Vertex attribute aliasing is also explained in the `ARB_vertex_program` and `NV_vertex_program` specifications.

6.1.3. gl_FrontFacing Is Not Available to Fragment Shaders

The built-in fragment shader varying parameter `gl_FrontFacing` is supported by GeForce 6 Series and NV4xGL-based Quadro FX GPUs but not GeForce FX and NV3xGL-based Quadro FX GPUs.

As a workaround, enable with `glEnable` the `GL_VERTEX_PROGRAM_TWO_SIDE` mode and, in your vertex shader, write a 1 to the alpha component of the front-facing primary color (`gl_FrontColor`) and 0 to the alpha component of the back-facing primary color (`gl_BackColor`). Then, read alpha component of the built-in fragment shader varying parameter `gl_Color`. Just like `gl_FrontFacing`, 1 means front-facing; 0 means back-facing.

6.1.4. Reporting GLSL Issues and Bugs

NVIDIA welcomes email pertaining to GLSL. Send suggestions, feedback, and bug reports to glsl-support@nvidia.com

7. OpenGL 2.0 API Declarations

NVIDIA provides `<GL/gl.h>` and `<GL/glext.h>` header files with the necessary OpenGL 2.0 API declarations on the OpenGL 2.0 page in NVIDIA's Developer web site, `developer.nvidia.com`

Your OpenGL 2.0 application will need to call `wglGetProcAddress` (Windows) or `glXGetProcAddress` (Linux) to obtain function pointers to the new OpenGL 2.0 commands just as is necessary for other OpenGL extensions.

7.1. *Programmable Shading*

7.1.1. New Tokens Defines

7.1.1.1. Program and Shader Object Management

```
#define GL_CURRENT_PROGRAM                0x8B8D
#define GL_SHADER_TYPE                    0x8B4E
#define GL_DELETE_STATUS                  0x8B80
#define GL_COMPILE_STATUS                 0x8B81
#define GL_LINK_STATUS                    0x8B82
#define GL_VALIDATE_STATUS                0x8B83
#define GL_INFO_LOG_LENGTH                0x8B84
#define GL_ATTACHED_SHADERS               0x8B85
#define GL_ACTIVE_UNIFORMS                0x8B86
#define GL_ACTIVE_UNIFORM_MAX_LENGTH      0x8B87
#define GL_SHADER_SOURCE_LENGTH           0x8B88
#define GL_VERTEX_SHADER                  0x8B31
#define GL_ACTIVE_ATTRIBUTES              0x8B89
#define GL_ACTIVE_ATTRIBUTE_MAX_LENGTH    0x8B8A
#define GL_FRAGMENT_SHADER                0x8B30
```

7.1.1.2. Uniform Types

```
#define GL_FLOAT_VEC2                     0x8B50
#define GL_FLOAT_VEC3                     0x8B51
#define GL_FLOAT_VEC4                     0x8B52
#define GL_INT_VEC2                       0x8B53
#define GL_INT_VEC3                       0x8B54
#define GL_INT_VEC4                       0x8B55
#define GL_BOOL                           0x8B56
#define GL_BOOL_VEC2                      0x8B57
#define GL_BOOL_VEC3                      0x8B58
#define GL_BOOL_VEC4                      0x8B59
#define GL_FLOAT_MAT2                     0x8B5A
#define GL_FLOAT_MAT3                     0x8B5B
#define GL_FLOAT_MAT4                     0x8B5C
#define GL_SAMPLER_1D                     0x8B5D
#define GL_SAMPLER_2D                     0x8B5E
#define GL_SAMPLER_3D                     0x8B5F
#define GL_SAMPLER_CUBE                   0x8B60
#define GL_SAMPLER_1D_SHADOW              0x8B61
#define GL_SAMPLER_2D_SHADOW              0x8B62
```

7.1.1.3. Vertex Attrib Arrays

```
#define GL_VERTEX_ATTRIB_ARRAY_ENABLED    0x8622
#define GL_VERTEX_ATTRIB_ARRAY_SIZE       0x8623
#define GL_VERTEX_ATTRIB_ARRAY_STRIDE     0x8624
#define GL_VERTEX_ATTRIB_ARRAY_TYPE       0x8625
#define GL_VERTEX_ATTRIB_ARRAY_NORMALIZED 0x886A
#define GL_CURRENT_VERTEX_ATTRIB          0x8626
#define GL_VERTEX_ATTRIB_ARRAY_POINTER    0x8645
```

```
#define GL_VERTEX_ATTRIB_ARRAY_BUFFER_BINDING 0x889F
```

7.1.1.4. Hints

```
#define GL_FRAGMENT_SHADER_DERIVATIVE_HINT 0x8B8B
```

7.1.1.5. Enables for Rasterization Control

```
#define GL_VERTEX_PROGRAM_POINT_SIZE      0x8642
#define GL_VERTEX_PROGRAM_TWO_SIDE        0x8643
```

7.1.1.6. Implementation Dependent Strings and Limits

```
#define GL_SHADING_LANGUAGE_VERSION       0x8B8C
#define GL_MAX_VERTEX_ATTRIBS             0x8869
#define GL_MAX_FRAGMENT_UNIFORM_COMPONENTS 0x8B49
#define GL_MAX_VERTEX_UNIFORM_COMPONENTS  0x8B4A
#define GL_MAX_VARYING_FLOATS             0x8B4B
#define GL_MAX_VERTEX_TEXTURE_IMAGE_UNITS 0x8B4C
#define GL_MAX_COMBINED_TEXTURE_IMAGE_UNITS 0x8B4D
#define GL_MAX_TEXTURE_COORDS             0x8871
#define GL_MAX_TEXTURE_IMAGE_UNITS        0x8872
```

7.1.2. New Command Prototypes

7.1.2.1. Shader Objects

```
void GLAPI glDeleteShader (GLuint shader);
void GLAPI glDetachShader (GLuint program, GLuint shader);
GLuint GLAPI glCreateShader (GLenum type);
void GLAPI glShaderSource (GLuint shader, GLsizei count, const GLchar* *string, const
GLint *length);
void GLAPI glCompileShader (GLuint shader);
```

7.1.2.2. Program Objects

```
GLuint GLAPI glCreateProgram (void);
void GLAPI glAttachShader (GLuint program, GLuint shader);
void GLAPI glLinkProgram (GLuint program);
void GLAPI glUseProgram (GLuint program);
void GLAPI glDeleteProgram (GLuint program);
void GLAPI glValidateProgram (GLuint program);
```

7.1.2.3. Uniforms

```
void GLAPI glUniform1f (GLint location, GLfloat v0);
void GLAPI glUniform2f (GLint location, GLfloat v0, GLfloat v1);
void GLAPI glUniform3f (GLint location, GLfloat v0, GLfloat v1, GLfloat v2);
void GLAPI glUniform4f (GLint location, GLfloat v0, GLfloat v1, GLfloat v2, GLfloat
v3);
void GLAPI glUniform1i (GLint location, GLint v0);
void GLAPI glUniform2i (GLint location, GLint v0, GLint v1);
void GLAPI glUniform3i (GLint location, GLint v0, GLint v1, GLint v2);
void GLAPI glUniform4i (GLint location, GLint v0, GLint v1, GLint v2, GLint v3);
void GLAPI glUniform1fv (GLint location, GLsizei count, const GLfloat *value);
```

```
void GLAPI glUniform2fv (GLint location, GLsizei count, const GLfloat *value);
void GLAPI glUniform3fv (GLint location, GLsizei count, const GLfloat *value);
void GLAPI glUniform4fv (GLint location, GLsizei count, const GLfloat *value);
void GLAPI glUniform1iv (GLint location, GLsizei count, const GLint *value);
void GLAPI glUniform2iv (GLint location, GLsizei count, const GLint *value);
void GLAPI glUniform3iv (GLint location, GLsizei count, const GLint *value);
void GLAPI glUniform4iv (GLint location, GLsizei count, const GLint *value);
void GLAPI glUniformMatrix2fv (GLint location, GLsizei count, GLboolean transpose,
const GLfloat *value);
void GLAPI glUniformMatrix3fv (GLint location, GLsizei count, GLboolean transpose,
const GLfloat *value);
void GLAPI glUniformMatrix4fv (GLint location, GLsizei count, GLboolean transpose,
const GLfloat *value);
```

7.1.2.4. Attribute Locations

```
void GLAPI glBindAttribLocation (GLuint program, GLuint index, const GLchar *name);
GLint GLAPI glGetAttribLocation (GLuint program, const GLchar *name);
```

7.1.2.5. Vertex Attributes

```
void GLAPI glVertexAttrib1d (GLuint index, GLdouble x);
void GLAPI glVertexAttrib1dv (GLuint index, const GLdouble *v);
void GLAPI glVertexAttrib1f (GLuint index, GLfloat x);
void GLAPI glVertexAttrib1fv (GLuint index, const GLfloat *v);
void GLAPI glVertexAttrib1s (GLuint index, GLshort x);
void GLAPI glVertexAttrib1sv (GLuint index, const GLshort *v);
void GLAPI glVertexAttrib2d (GLuint index, GLdouble x, GLdouble y);
void GLAPI glVertexAttrib2dv (GLuint index, const GLdouble *v);
void GLAPI glVertexAttrib2f (GLuint index, GLfloat x, GLfloat y);
void GLAPI glVertexAttrib2fv (GLuint index, const GLfloat *v);
void GLAPI glVertexAttrib2s (GLuint index, GLshort x, GLshort y);
void GLAPI glVertexAttrib2sv (GLuint index, const GLshort *v);
void GLAPI glVertexAttrib3d (GLuint index, GLdouble x, GLdouble y, GLdouble z);
void GLAPI glVertexAttrib3dv (GLuint index, const GLdouble *v);
void GLAPI glVertexAttrib3f (GLuint index, GLfloat x, GLfloat y, GLfloat z);
void GLAPI glVertexAttrib3fv (GLuint index, const GLfloat *v);
void GLAPI glVertexAttrib3s (GLuint index, GLshort x, GLshort y, GLshort z);
void GLAPI glVertexAttrib3sv (GLuint index, const GLshort *v);
void GLAPI glVertexAttrib4Nbv (GLuint index, const GLbyte *v);
void GLAPI glVertexAttrib4Niv (GLuint index, const GLint *v);
void GLAPI glVertexAttrib4Nsv (GLuint index, const GLshort *v);
void GLAPI glVertexAttrib4Nub (GLuint index, GLubyte x, GLubyte y, GLubyte z, GLubyte
w);
void GLAPI glVertexAttrib4Nubv (GLuint index, const GLubyte *v);
void GLAPI glVertexAttrib4Nuiv (GLuint index, const GLuint *v);
void GLAPI glVertexAttrib4Nusv (GLuint index, const GLushort *v);
void GLAPI glVertexAttrib4bv (GLuint index, const GLbyte *v);
void GLAPI glVertexAttrib4d (GLuint index, GLdouble x, GLdouble y, GLdouble z,
GLdouble w);
void GLAPI glVertexAttrib4dv (GLuint index, const GLdouble *v);
void GLAPI glVertexAttrib4f (GLuint index, GLfloat x, GLfloat y, GLfloat z, GLfloat
w);
void GLAPI glVertexAttrib4fv (GLuint index, const GLfloat *v);
void GLAPI glVertexAttrib4iv (GLuint index, const GLint *v);
void GLAPI glVertexAttrib4s (GLuint index, GLshort x, GLshort y, GLshort z, GLshort
w);
void GLAPI glVertexAttrib4sv (GLuint index, const GLshort *v);
void GLAPI glVertexAttrib4ubv (GLuint index, const GLubyte *v);
void GLAPI glVertexAttrib4uiv (GLuint index, const GLuint *v);
void GLAPI glVertexAttrib4usv (GLuint index, const GLushort *v);
```

```
void GLAPI glVertexAttribPointer (GLuint index, GLint size, GLenum type, GLboolean
normalized, GLsizei stride, const GLvoid *pointer);
void GLAPI glEnableVertexAttribArray (GLuint index);
void GLAPI glDisableVertexAttribArray (GLuint index);
void GLAPI glGetVertexAttribdv (GLuint index, GLenum pname, GLdouble *params);
void GLAPI glGetVertexAttribfv (GLuint index, GLenum pname, GLfloat *params);
void GLAPI glGetVertexAttribiv (GLuint index, GLenum pname, GLint *params);
void GLAPI glGetVertexAttribPointerv (GLuint index, GLenum pname, GLvoid* *pointer);
```

7.1.2.6. Queries

```
GLboolean GLAPI glIsShader (GLuint shader);
GLboolean GLAPI glIsProgram (GLuint program);
void GLAPI glGetShaderiv (GLuint program, GLenum pname, GLint *params);
void GLAPI glGetProgramiv (GLuint program, GLenum pname, GLint *params);
void GLAPI glGetAttachedShaders (GLuint program, GLsizei maxCount, GLsizei *count,
GLuint *shaders);
void GLAPI glGetShaderInfoLog (GLuint shader, GLsizei bufSize, GLsizei *length, GLchar
*infoLog);
void GLAPI glGetProgramInfoLog (GLuint program, GLsizei bufSize, GLsizei *length,
GLchar *infoLog);
GLint GLAPI glGetUniformLocation (GLuint program, const GLchar *name);
void GLAPI glGetActiveUniform (GLuint program, GLuint index, GLsizei bufSize, GLsizei
*length, GLsizei *size, GLenum *type, GLchar *name);
void GLAPI glGetUniformfv (GLuint program, GLint location, GLfloat *params);
void GLAPI glGetUniformiv (GLuint program, GLint location, GLint *params);
void GLAPI glGetShaderSource (GLuint shader, GLsizei bufSize, GLsizei *length, GLchar
*source);
void GLAPI glGetActiveAttrib (GLuint program, GLuint index, GLsizei bufSize, GLsizei
*length, GLsizei *size, GLenum *type, GLchar *name);
```

7.2. Non-Power-Of-Two Textures

Support for non-power-of-two textures introduces no new tokens or commands. Rather the error conditions that previously restricted the width, height, and depth (excluding the border) to be power-of-two values is eliminated.

The relaxation of errors to allow non-power-of-two texture sizes affects the following commands: `glTexImage1D`, `glCopyTexImage1D`, `glTexImage2D`, `glCopyTexImage2D`, and `glTexImage3D`. You can also render to non-power-of-two pixel buffers (*pbuffers*) using the `WGL_ARB_render_texture` extension.

7.3. Multiple Render Targets

7.3.1. New Tokens Defines

```
#define GL_MAX_DRAW_BUFFERS              0x8824
#define GL_DRAW_BUFFER0                  0x8825
#define GL_DRAW_BUFFER1                  0x8826
#define GL_DRAW_BUFFER2                  0x8827
#define GL_DRAW_BUFFER3                  0x8828
#define GL_DRAW_BUFFER4                  0x8829
#define GL_DRAW_BUFFER5                  0x882A
#define GL_DRAW_BUFFER6                  0x882B
#define GL_DRAW_BUFFER7                  0x882C
```

```
#define GL_DRAW_BUFFER8                     0x882D
#define GL_DRAW_BUFFER9                     0x882E
#define GL_DRAW_BUFFER10                    0x882F
#define GL_DRAW_BUFFER11                    0x8830
#define GL_DRAW_BUFFER12                    0x8831
#define GL_DRAW_BUFFER13                    0x8832
#define GL_DRAW_BUFFER14                    0x8833
#define GL_DRAW_BUFFER15                    0x8834
```

7.3.2. New Command Prototypes

```
void GLAPI glDrawBuffers (GLsizei n, const GLenum *bufs);
```

7.4. Point Sprite

7.4.1. New Tokens Defines

```
#define GL_POINT_SPRITE                     0x8861
#define GL_COORD_REPLACE                    0x8862
#define GL_POINT_SPRITE_COORD_ORIGIN        0x8CA0
#define GL_LOWER_LEFT                       0x8CA1
#define GL_UPPER_LEFT                       0x8CA2
```

7.4.2. Usage

Point sprite state is set with the `glPointParameteri`, `glPointParameteriv`, `glPointParameterf`, `glPointParameterfv` API originally introduced by OpenGL 1.4 to control point size attenuation.

7.5. Two-Sided Stencil Testing

7.5.1. New Tokens Defines

These tokens can be used with `glGetIntegerv` to query back-facing stencil state.

```
#define GL_STENCIL_BACK_FUNC                0x8800
#define GL_STENCIL_BACK_VALUE_MASK          0x8CA4
#define GL_STENCIL_BACK_REF                 0x8CA3
#define GL_STENCIL_BACK_FAIL                0x8801
#define GL_STENCIL_BACK_PASS_DEPTH_FAIL     0x8802
#define GL_STENCIL_BACK_PASS_DEPTH_PASS     0x8803
#define GL_STENCIL_BACK_WRITEMASK           0x8CA5
```

7.5.2. New Command Prototypes

```
void GLAPI glStencilFuncSeparate (GLenum face, GLenum func, GLint ref, GLuint mask);
void GLAPI glStencilOpSeparate (GLenum face, GLenum fail, GLenum zfail, GLenum zpass);
void GLAPI glStencilMaskSeparate (GLenum face, GLuint mask);
```

7.6. Separate RGB and Alpha Blend Equations

7.6.1. New Tokens Defines

These tokens can be used with `glGetIntegerv` to query blend equation state. The `GL_BLEND_EQUATION` token has the same value as the new `GL_BLEND_EQUATION_RGB`.

```
#define GL_BLEND_EQUATION_RGB              0x8009
#define GL_BLEND_EQUATION_ALPHA            0x883D
```

7.6.2. New Command Prototypes

```
void GLAPI glBlendEquationSeparate (GLenum modeRGB, GLenum modeAlpha);
```

A. Distinguishing NV3xGL-based and NV4xGL-based Quadro FX GPUs by Product Names

As discussed in section 2, while NV3x- and NV3xGL-based GPUs support OpenGL 2.0, the NV4x- and NV4xGL-based GPUs have the best industry-wide hardware-acceleration and support for OpenGL 2.0.

For the consumer GeForce product lines, GeForce FX and GeForce 6 Series GPUs are easily distinguished based on their product names and numbering. Any NVIDIA GPU product beginning with GeForce FX is NV3x-based. Such GPUs also typically have a 5000-based product number, such as 5200 or 5950. GeForce GPUs with a 6000-based product name, such as 6600 or 6800, are NV4x-based.

However, the Quadro FX product name applies to both NV3xGL-based and NV4xGL-based GPUs and there is no simple rule to differentiate NV3xGL-based and NV4xGL-based using the product name. The lists below will help OpenGL 2.0 developers correctly distinguish the two NV3xGL- and NV4xGL-based Quadro FX product lines.

A.1. NV3xGL-based Quadro FX GPUs

Quadro FX 330 (PCI Express)
Quadro FX 500 (AGP)
Quadro FX 600 (PCI)
Quadro FX 700 (AGP)
Quadro FX 1000 (AGP)
Quadro FX 1100 (AGP)
Quadro FX 1300 (PCI)
Quadro FX 2000 (AGP)
Quadro FX 3000 (AGP)

A.2. NV4xGL-based Quadro FX GPUs

Quadro FX 540 (PCI Express)
Quadro FX 1400 (PCI Express)
Quadro FX Go1400 (PCI Express)
Quadro FX 3400 (PCI Express)
Quadro FX 4000 (AGP)
Quadro FX 4400 (PCI Express)
Quadro FX 3450 (PCI Express)
Quadro FX 4450 (PCI Express)

A.3. How to Use and How to Not Use These Lists

These lists are for informational purposes to help OpenGL 2.0 developers instruct end-users as to which NVIDIA products will support OpenGL 2.0 and accelerate the OpenGL 2.0 feature set the best. These lists are not complete and are subject to change.

OpenGL developers should **not** query and parse the `GL_RENDERER` string returned by `glGetString` to determine if a given GPU supports NV3x-based or NV4x-based functionality and performance.

Instead, query the `GL_EXTENSIONS` string and look for the `GL_NV_fragment_program2` and/or `GL_NV_vertex_program3` substrings. These extensions imply the functional feature set of NV4x-based GPUs.