MIC-GPU: High-Performance Computing for Medical Imaging on Programmable Graphics Hardware (GPUs)

SPIE Medical Imaging

GPU Architecture, Programming Model and Programming Facilities

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Overview

SPIE Medical Imaging

Graphics-style
- parallelism exposed as fragments
- programming in CG, GLSL, HLSL
- utilizes the graphics sub-system of GPUs
- scatter operations (calculations affecting many targets) not possible

GPGPU-style
- parallelism exposed as threads
- programmed in CUDA (NVIDIA), CTM (AMD-ATI)
- does not utilize the graphics sub-system of GPUs
- provides a more elaborate application programmer interface (API)
- allows scatter operations

Overview

SPIE Medical Imaging

We will discuss two different programming models:
- graphics-style (first)
- GPGPU-style (second)

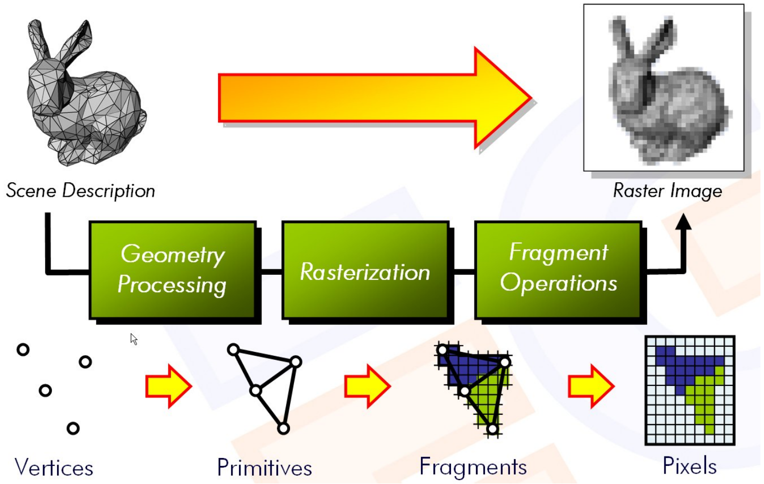
Note: both use the same underlying architecture (for example GeForce 8800)

Part 1

SPIE Medical Imaging

Graphics Style GPU Programming

Graphics Pipeline: Overview



Scene Description

Raster Image

Geometry Processing

Rasterization

Fragment Operations

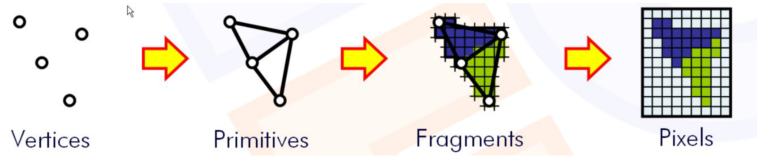
Vertices

Primitives

Fragments

Pixels

Graphics Pipeline: Overview



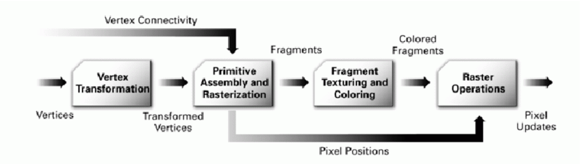
Vertices

Primitives

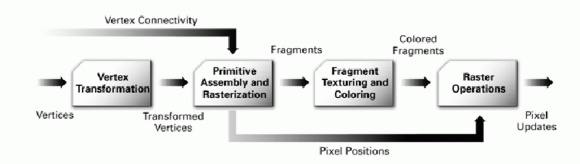
Fragments

Pixels

Graphics Hardware Pipeline



Vertex Stage



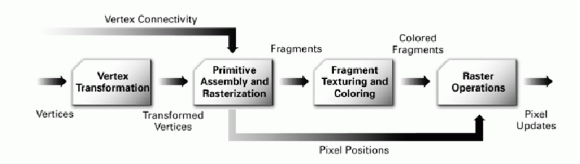
Vertex values:

- position, color, texture coordinate(s), normal vector

Operations (in a vertex program):

- perform a sequence of math ops on each vertex
- transform world position into screen position for rasterizer
- generate texture coordinates for texturing
- perform vertex lighting to determine its color

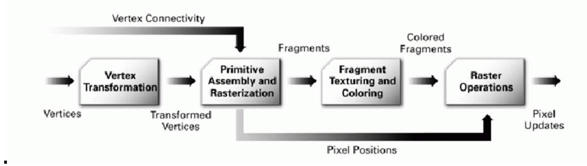
Primitive Assembly and Rasterizer



Operations:

- assemble vertices into geometric primitives (triangles, lines, points)
- clipping to the view frustrum and other clip planes
- eliminate backward-facing polygons (culling)
- rasterize geometric primitives into fragments

Primitive Assembly and Rasterizer



Rasterization:

- yields a set pixel locations and fragments

What is a fragment?

- *potential* pixel (still subject to fragment kill)
- values: color, depth, location, texture coordinate sets

Number of vertices and fragments are unrelated!

Early fragment kill

- set up *early depth culling* or *early stencil culling* to reject fragment before it is subjected to computations → major source of speedup

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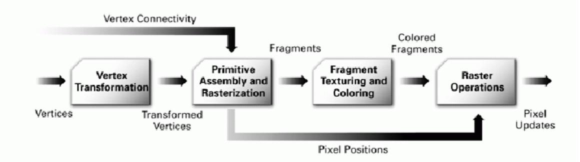
Fragment Stage



Operations (fragment program):

- interpolation, texturing, and coloring
- math operations

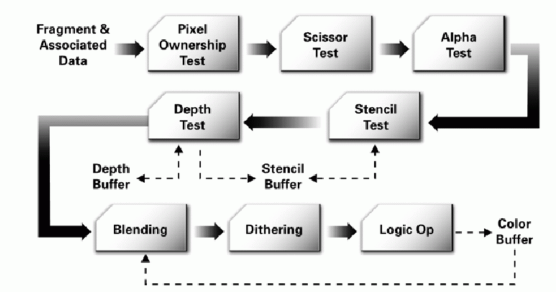
Output:

- final color (RGBA), depth
- output is either 1 or 0 fragments (may be discarded)

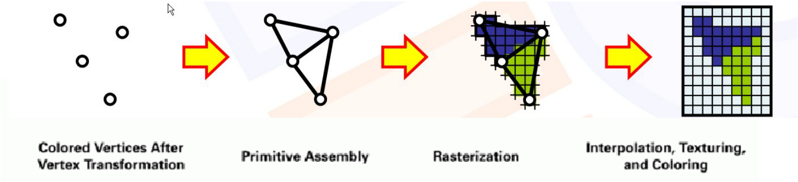
Raster Operations

Final sequence of per-fragment operations before updating the framebuffer

- fragment may be discarded here as well



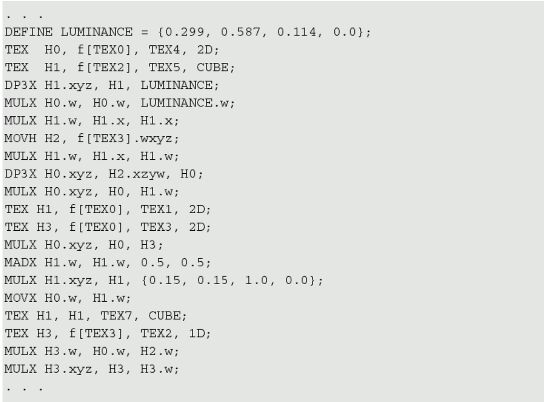
Graphics Pipeline: Summary



Vertices and fragments are vectors (up to dimension 4)

Vertex and fragment stage are programmable

Cg



```
. . .
DEFINE LUMINANCE = {0.299, 0.587, 0.114, 0.0};
TEX  H0, f[TEX0], TEX4, 2D;
TEX  H1, f[TEX2], TEX5, CUBE;
DP3X H1.xyz, H1, LUMINANCE;
MULX H0.w, H0.w, LUMINANCE.w;
MULX H1.w, H1.x, H1.x;
MOVH H2, f[TEX3].wxyz;
MULX H1.w, H1.x, H1.w;
DP3X H0.xyz, H2.xzyw, H0;
MULX H0.xyz, H0, H1.w;
TEX H1, f[TEX0], TEX1, 2D;
TEX H3, f[TEX0], TEX3, 2D;
MULX H0.xyz, H0, H3;
MADX H1.w, H1.w, 0.5, 0.5;
MULX H1.xyz, H1, {0.15, 0.15, 1.0, 0.0};
MOVX H0.w, H1.w;
TEX H1, H1, TEX7, CUBE;
TEX H3, f[TEX3], TEX2, 1D;
MULX H3.w, H0.w, H2.w;
MULX H3.xyz, H3, H3.w;
. . .
```

Cg available to overcome need for assembler programming

Cg

Developed by Nvidia

Can work with OpenGL as well as DirectX

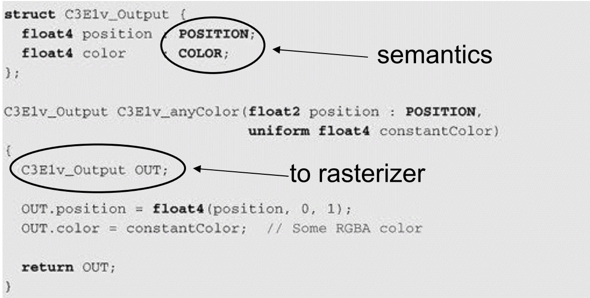
CG compiler produces OpenGL or DirectX code

- e.g., OpenGL's ARB_fragment_program language

OpenGL or DirectX drivers perform final translation into hardware-executable code

- core CG runtime library (CG prefix)
- cgGL and cgD3D libraries

Simple Vertex Program



```
struct C3E1v_Output {
  float4 position : POSITION;
  float4 color    : COLOR;
};

C3E1v_Output C3E1v_anyColor(float2 position : POSITION,
                            uniform float4 constantColor)
{
  C3E1v_Output OUT;

  OUT.position = float4(position, 0, 1);
  OUT.color = constantColor;  // Some RGBA color

  return OUT;
}
```

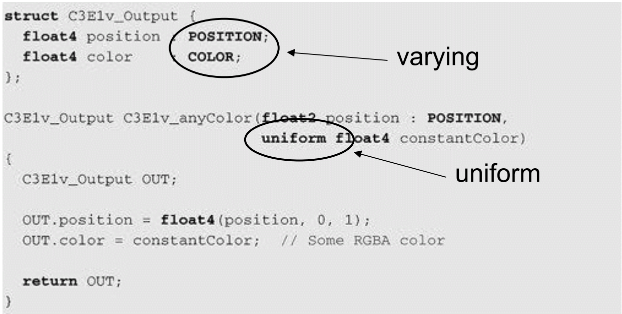
Semantics connect Cg program with graphics pipeline

- here: POSITION and COLOR

float4, float2, float4x4, etc, are packed arrays

- operations are most efficient

Uniform vs. Varying Parameters



```
struct C3E1v_Output {
  float4 position : POSITION;
  float4 color    : COLOR;
};

C3E1v_Output C3E1v_anyColor(float2 position : POSITION,
                            uniform float4 constantColor)
{
  C3E1v_Output OUT;

  OUT.position = float4(position, 0, 1);
  OUT.color = constantColor;  // Some RGBA color

  return OUT;
}
```

Varying: values vary per vertex or fragment

- interfaced via semantics

Uniform: remain constant

- interfaced via handles

Compilation

To interface Cg programs with application:

- compile the program with appropriate profile
  - dependent on underlying hardware
- range of profiles will grow with GPU advances
  - OpenGL: arbvp1 (basic), vp20, vp30, vp40 (advanced Nvidia)

Link the program to the application program

Can perform compilation at

- compile time (static)
- runtime (dynamic)

Cg Runtime

Can take advantage of

- latest profiles
- optimization of existing profiles

No dependency issues

- register names, register allocations

In the following, use OpenGL to illustrate

- DirectX similar methods

More detailed information available when you download CG from the Nvidia developer website:

- http://developer.nvidia.com
- Cg toolkit 2.0 now available (including Cg compiler)

Preparing a Cg Program

First, create a context:

- context = cgCreateContext()

Compile a program by adding it to the context:

- program = cgCreateProgram(context, programString, profile, name, args)

Loading a program (pass to the 3D API):

- cgGLLoadProgram(program)

Running a Cg Program

Executing the profile:

- cgEnableProfile(CG_PROFILE_ARBVP1)

Bind the program:

- cgGLBindProgram(program)

After binding, the program will execute in subsequent drawing calls

- for every vertex (for vertex programs)
- for every fragment (for fragment programs)
- these programs are often called *shaders*

Running a Cg Program

Only one vertex / fragment program can be bound at a time

- the same program will execute unless another program is bound

Disable a profile by:

- cgGLDisableProfile(CG_PROFILE_ARBVP1)

Release resources:

- cgDestroyProgram(program)
- cgDestroyContext(context)
- the latter destroys all programs as well

Error Handling

There are core CG routines that retrieve global error variables:

- error = cgGetError()
- cgGetErrorString(error)
- cgSet ErrorCallback(MyErrorCallback)

Passing Parameters into CG Programs

Assume these shader variables:

- float4 position : POSITION
- float4 color : COLOR0

Get the handle for color by:

- color = cgGetNamedParameter(program, "IN.color")

Can set the value for color by:

- cgGLSetParameter4f(color, 0.5f, 1.0f, 0.5f, 1.0f)

Uniform variables are set infrequently:

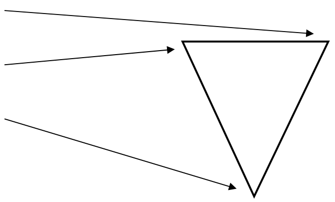
- example: modelViewMatrix

Passing Parameters into CG Programs

Set other variables via OpenGL semantics:

- glVertex, glColor, glTexCoord, glNormal,…

Example: rendering a triangle with OpenGL:



```
glBegin(GL_TRIANGLES);
  glVertex( 0.8,  0.8);
  glVertex(-0.8,  0.8);
  glVertex( 0.0, -0.8);
glEnd();
```

glVertex affects POSITION semantics and updates/sets related parameter in vertex shader

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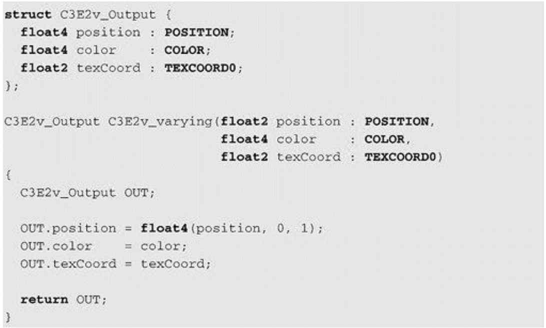
Example 1

Vertex program



```
struct C3E2v_Output {
  float4 position : POSITION;
  float4 color    : COLOR;
  float2 texCoord : TEXCOORD0;
};

C3E2v_Output C3E2v_varying(float2 position : POSITION,
                           float4 color    : COLOR,
                           float2 texCoord : TEXCOORD0)
{
  C3E2v_Output OUT;

  OUT.position = float4(position, 0, 1);
  OUT.color    = color;
  OUT.texCoord = texCoord;

  return OUT;
}
```

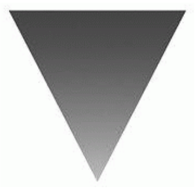
- OUT parameter values are passed to fragment shader

Example 1

Result, assuming:

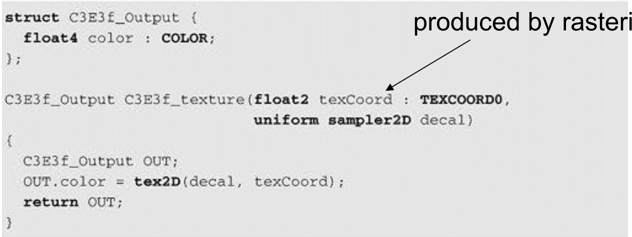
- a fragment shader that just passes values through
- OpenGl program

```
glBegin(GL_TRIANGLES);
  glVertex( 0.8,  0.8); glColor(dark);
  glVertex(-0.8,  0.8); glColor(dark);
  glVertex( 0.0, -0.8); glColor(light);
glEnd();
```



Example 2

Fragment program, following example 1 vertex program



```
struct C3E3f_Output {
  float4 color : COLOR;
};

C3E3f_Output C3E3f_texture(float2 texCoord : TEXCOORD0,
                           uniform sampler2D decal)
{
  C3E3f_Output OUT;
  OUT.color = tex2D(decal, texCoord);
  return OUT;
}
```

produced by rasterizer

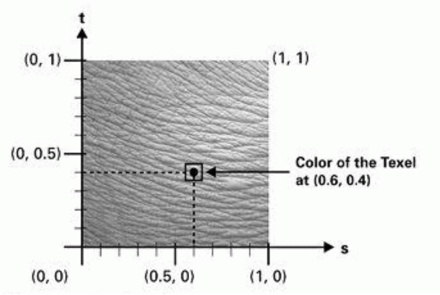
Sampler2D is a texture object

- other types exist: sampler3D, samplerCUBE, etc.

Example 2

Tex2D(decal, texCoord) performs a texture-lookup

- sampling, filtering, and interpolation depends on texture type and texture parameters
- advanced fragment profiles allow sampling using texture coordinate sets from other texture units (*dependent textures*)



Example 2

Result

Math Support

A rich set of math operators and library functions

- +-/*, sin, cos, floor, etc.…
- no bit-wise operators yet, but operators reserved

Latest hardware full floating point on framebuffer operations

- half-floats are also available

Function overloading frequent

- for example, abs() function accepts float4, float2

Syntax

IN keyword

- call by value
- parameter passing by value

OUT keyword

- indicates when the program returns

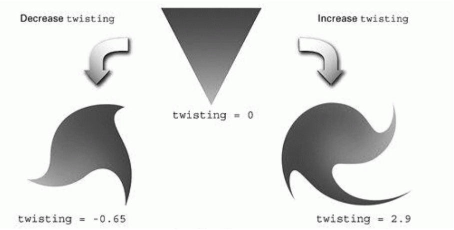
Example 3

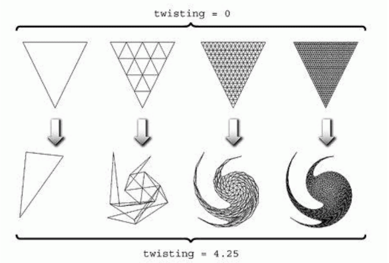
2D Twisting (vertex program)

```
struct C3E4_Output {
  float4 position : POSITION;
  float4 color    : COLOR;
};

C3E4_Output C3E4v_twist(float2 position : POSITION,
                        float4 color    : COLOR,

                        uniform float twisting)
{
  C3E4_Output OUT;
  float angle = twisting * length(position);
  float cosLength, sinLength;
  sincos(angle, sinLength, cosLength);
  OUT.position[0] = cosLength * position[0] +
                   -sinLength * position[1];
  OUT.position[1] = sinLength * position[0] +
                    cosLength * position[1];
  OUT.position[2] = 0;
  OUT.position[3] = 1;
  OUT.color = color;
  return OUT;
}
```

Example 3

Result





finer meshes give better results

Example 4

Double Vision: vertex program

```
void C3E5v_twoTextures(float2 position : POSITION,
                       float2 texCoord : TEXCOORD0,

                   out float4 oPosition : POSITION,
                   out float2 leftTexCoord : TEXCOORD0,
                   out float2 rightTexCoord : TEXCOORD1,

               uniform float2 leftSeparation,
               uniform float2 rightSeparation)
{
  C3E5v_Output OUT;

  oPosition     = float4(position, 0, 1);
  leftTexCoord  = texCoord + leftSeparation;
  rightTexCoord = texCoord + rightSeparation;

  return OUT;
}
```

OUT is defined via semantics in the prototype

- optional

Example 4

Double Vision: fragment program #1

- advanced fragment profiles
- samples the same texture (named *decal*) twice

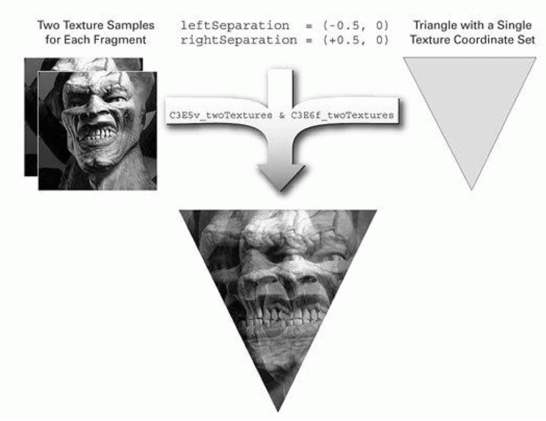
lerp(a, b, weight)

- result = (1-weight) · a + weight · b

```
void C3E6f_twoTextures(float2 leftTexCoord  : TEXCOORD0,
                       float2 rightTexCoord : TEXCOORD1,

                   out float4 color : COLOR,

               uniform sampler2D decal)
{
  float4 leftColor  = tex2D(decal, leftTexCoord);
  float4 rightColor = tex2D(decal, rightTexCoord);
  color = lerp(leftColor, rightColor, 0.5);
}
```

Example 4

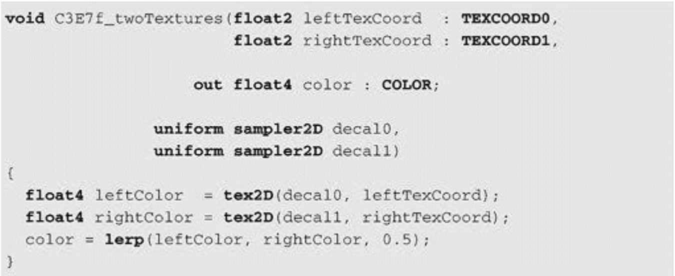
Result



Example 4

Double Vision: fragment program #2

- basic fragment profiles
- samples two different textures (*decal0* and *decal1*)
- textures must be bound to two texture units in advance



```
void C3E7f_twoTextures(float2 leftTexCoord  : TEXCOORD0,
                       float2 rightTexCoord : TEXCOORD1,

                   out float4 color : COLOR;

               uniform sampler2D decal0,
               uniform sampler2D decal1)
{
  float4 leftColor  = tex2D(decal0, leftTexCoord);
  float4 rightColor = tex2D(decal1, rightTexCoord);
  color = lerp(leftColor, rightColor, 0.5);
}
```

HelloWorld.cg

Prerequisites:

- NVIDIA GeForce FX or an ATI RADEON 9500
- Visual Studio .NET 2003 or your favourite compiler
  (we provide project files for VS.Net2003)
- GLUT (simple GUI library) and GLEW (extension library)
- NVidia Cg toolkit (for Cg)

```
fragout main( float4 TexCoords                         : TEXCOORD0,
              float4 WinPos                            : WPOS,
              uniform samplerRECT  inputTexture        : TEXUNIT0)
{
          fragout OUT;
          int xx=(int)(WinPos.x/8);
          int yy=(int)(WinPos.y/8);
          if(xx %2 ==yy %2){    // if in even (x,y) box write texture
                   OUT.col=texRECT(inputTexture, TexCoords.xy);
          }else{    // else write grey color
                   OUT.col=float4(0.5,0.5,0.5,1);
          }
          return OUT;
}
```

Renders the given texture covered by a chess-board pattern.

Rendering to Texture

Use FBO (Frame Buffer Object). Steps:

1. Create FBO Object
   `glGenFramebuffersEXT(1, &fbo);`
2. Create the destination texture
   ```
   glGenTextures(1, &color);
   glBindTexture(GL_TEXTURE_2D, color);
   glTexImage2D(GL_TEXTURE_2D, 0, GL_RGBA8, width, height,
   0, GL_RGBA, GL_UNSIGNED_BYTE, NULL);
   ```
3. Bind FBO and attach the texture
   ```
   glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, fbo);
   glFramebufferTexture2DEXT(GL_FRAMEBUFFER_EXT,
   GL_COLOR_ATTACHMENT0_EXT, GL_TEXTURE_2D, color, 0);
   ```
4. Make the FBO the current destination for rendering
   `glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, fbo);`
5. When done rendering, make the FrameBuffer into rendering dest.
   `glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, 0);`

Multiple Render Targets

Steps using FBO:

1. Create FBO Object
2. Create the destination textures

```
glGenTextures(4, colors);
glBindTexture(GL_TEXTURE_2D, color[0]);
    … … … … … …
```

3. Attach destination textures

```
glFramebufferTexture2DEXT(GL_FRAMEBUFFER_EXT,
GL_COLOR_ATTACHMENT0_EXT, GL_TEXTURE_2D, color[0], 0);
glFramebufferTexture2DEXT(GL_FRAMEBUFFER_EXT,
GL_COLOR_ATTACHMENT1_EXT, GL_TEXTURE_2D, color[1], 0);
```

4. Setup DrawBuffers

```
GLuint drawBuffers[4] = {GL_COLOR_ATTACHMENT0_EXT,
GL_COLOR_ATTACHMENT1_EXT,GL_COLOR_ATTACHMENT2_EXT,
GL_COLOR_ATTACHMENT3_EXT};
glDrawBuffers(4, drawBuffers);
```

5. Make the FBO the current destination for rendering
6. When done rendering, make the FrameBuffer into rendering dest.

Optimizations: Branching

What NVidia said about the 6800 series:

SIMD branching

- incoherent branching can hurt performance
- should have coherent regions of ~1000 pixels
  - that is, only about 30x30 pixels, so still very useable!

Don't ignore overhead of branch instructions

- branching over < 5 instructions may not be worth it

Use branching for early exit from loops

- saves a lot of computation

Our Experience:

- incoherent branching in Volume Rendering causes severe slowdowns 6X – 8X
- exercise caution in designing/analyzing Scientific-Viz applications

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Debugging tips

"Printf" debugging:

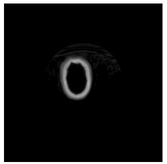
- display coordinates
- normals
- variable values
- map to [0…1] and show colors

Tools, suitable for our development:

- Graphic Remedy gDebugger
  - useful for state debugging
  - free for students/academic (ARB license program)
- Microsoft Shader Debugger Tool
  - software emulation →slow
- Imdebug – The Image Debugger [B. Baxter]
  - dumps textures to images relatively easily, and lets user explore values.
- Shadesmith – [T. Purcell, P. Sen]
  - discontinued, not current.

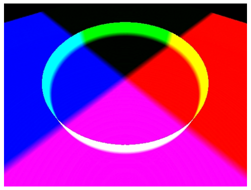
Performance "debugging"

- vary data load / compute load and observe performance change

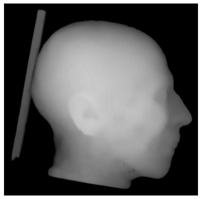


Current Rendering Slice

Depth Buffer to debug early-z



Debugging texture coordinates



Debugging Screen-Space Shading

Part 2

GPGPU Style GPU Programming

The GPU Architecture

Viewed as a highly parallel co-processor to the CPU (the host)

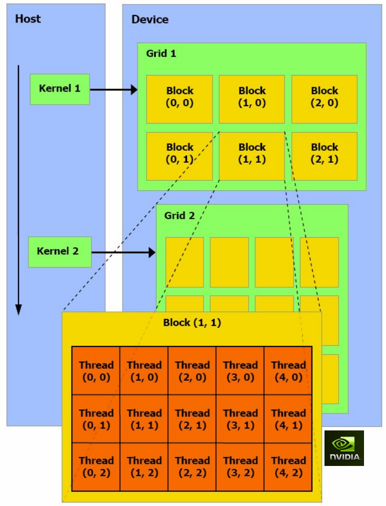
Host (CPU) tasks:

- control program flow
- perform thread management
- load SIMD kernels

Co-processor (GPU) tasks:

- load data
- perform computations

The GPU Architecture



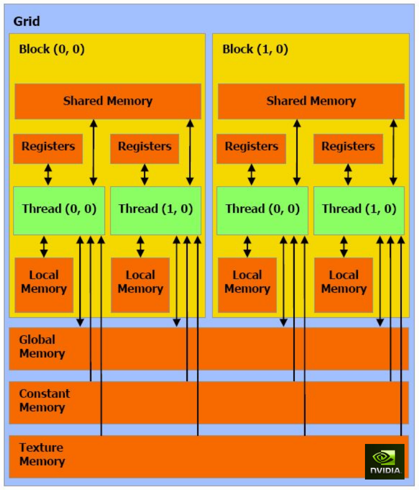
each kernel is executed as a batch of threads (G80 up to 768 threads)

this batch is organized as a grid of thread blocks

the threads in each block cooperate, share memory, and can be synchronized
→ there is a limit on the maximum number of threads within a block

each thread and each block have an ID

The GPU Architecture



each multi-processor executes a batch of blocks in sequence
→ the number of these *active* blocks is determined by the amount of registers and shared memory needed per block

each active block is split into a SIMD group of threads, called *warps*
→ each warp contains the same number of threads (the *warp-size*, 32 in G80)

the warps of the active blocks (called *active warps*) are time-sliced (switched in execution)
→ this maximizes use of computational resources (e.g., when waiting for data from memory)

note: the order of execution of blocks and warps is undefined

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Optimizing Performance

For each multiprocessor (for G80):

- number of 32-bit registers, N_regs = 8192
- shared memory: 16 KB (16 banks)

Thread occupancy:

- determined by the amount of shared memory and registers used by each thread block (compiler helps to minimize these)
- N_regs ≤ N_regs_per_thread · N_threads, else kernel will not load
- similar holds for shared memory
- want to maximize occupacy (# active warps / maximum # warps)
- maximizing occupancy covers latencies in global memory fetches

CUDA Occupancy Calculator (see references in Section 3):

- a spreadheet to help users in choosing best thread block size for a given kernel in order to achieve highest occupancy of the GPU

Programming Facilities

CUDA is a C-like language

- uses C-syntax
- can be used within C/C++ (and GL, DirectX)

Compilation using nvcc

Profiler available

gdb debugger for the GPU available in March, 2008

Course Schedule

1:30 – 2:00:	Introduction
2:00 – 2:30:	GPU architecture, programming model, and programming facilties
2:30 – 3:00:	GPU programming examples (image processing)
	Coffee Break
3:30 – 4:00:	CT reconstruction pipeline components
4:00 – 4:30:	GPU-acceleration of individual components
4:30 – 5:00:	Various CT reconstruction pipelines, load balancing and load estimation
5:00 – 5:30:	Reconstruction visualization and final remarks