Computer Graphics

– Programmable Shading in HW –

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Overview

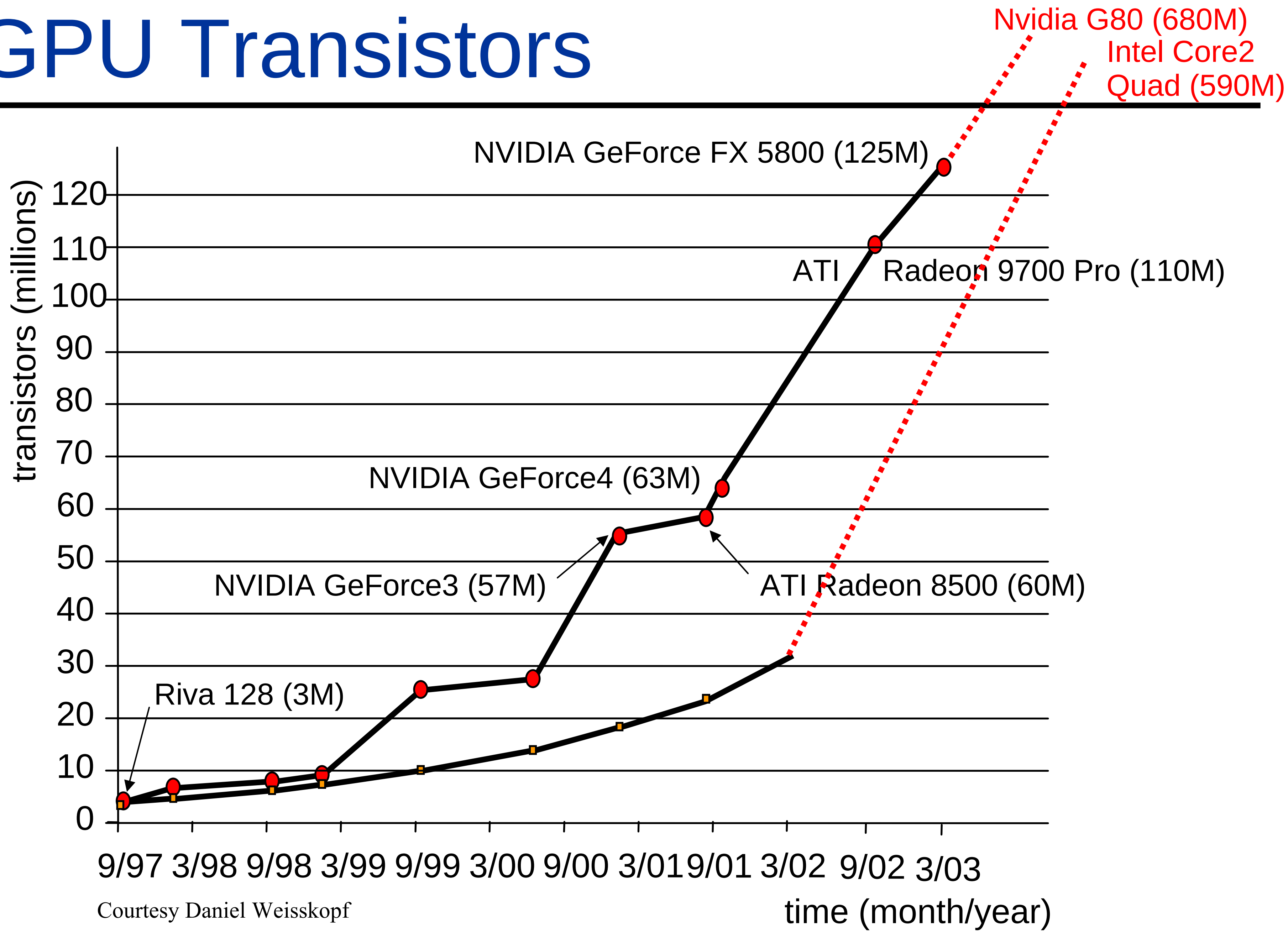
- **So far:**
  - OpenGL
  - Clipping
  - Rasterization

- **Today:**
  - Programmable graphics hardware
  - Shading Language: Cg

Resources

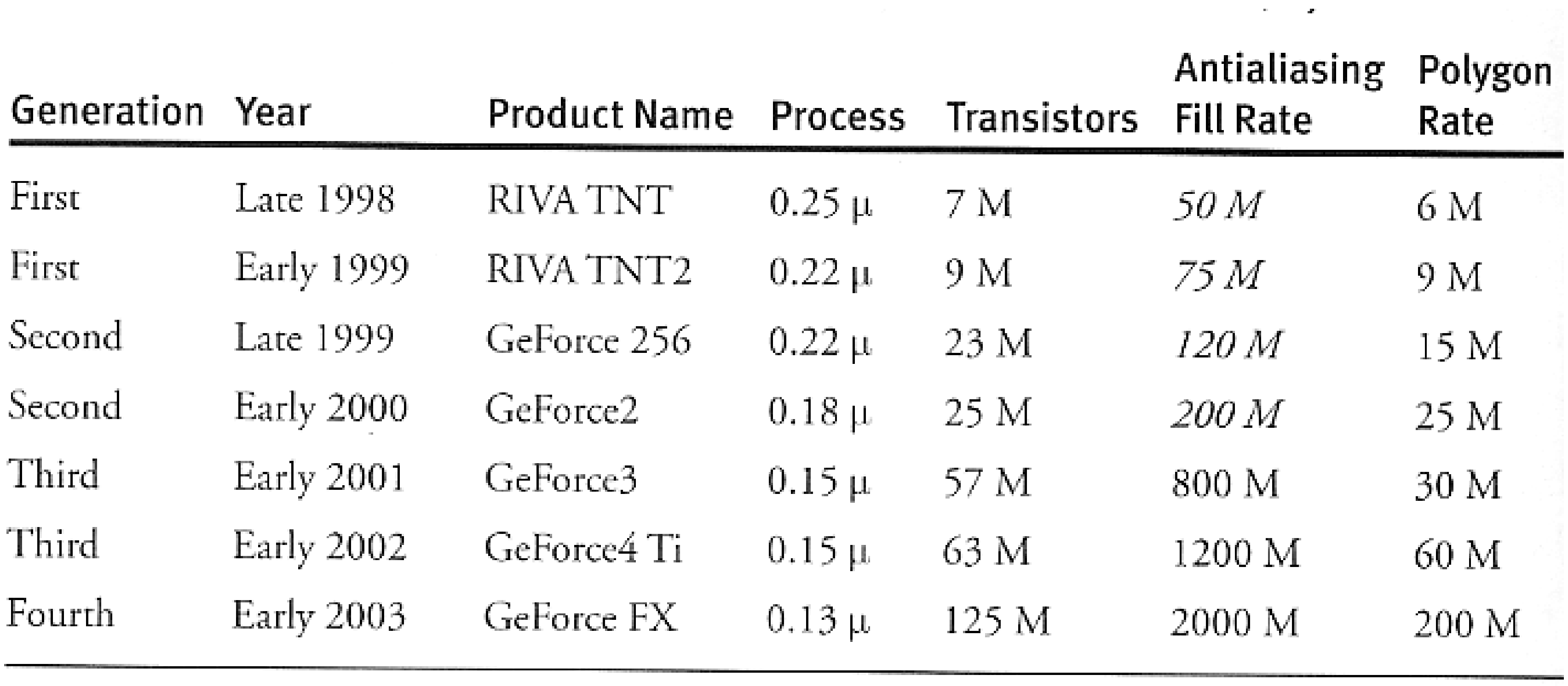
- **Fernando, Kilgard, “The Cg Tutorial”**
  - Addison-Wesley, 2003
- **http://developer.nvidia.com/Cg**
  - Whitepapers
  - Presentations
  - Cg tutorials http://developer.nvidia.com/object/cg_toolkit.html
  - Cg User’s Manual
  - Cg Language Specification
  - Cg Toolkit Downloads
  - Bug Reporting
- **www.CgShaders.org**
  - Forums
  - Shader Repository (Freeware)

GPU Transistors



Courtesy Daniel Weisskopf

Graphics Hardware



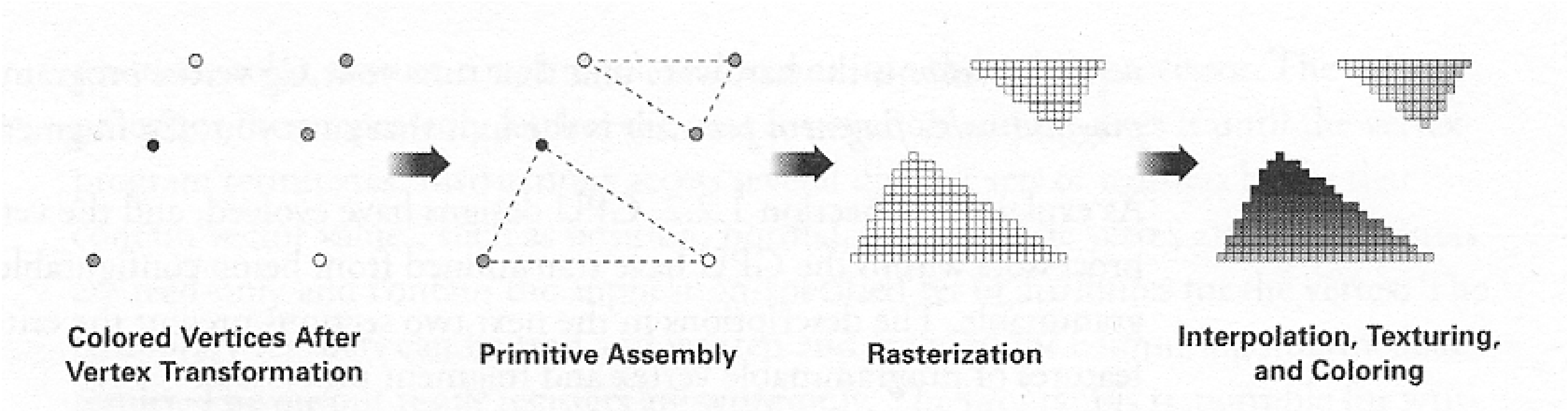
Generation	Year	Product Name	Process	Transistors	Antialiasing Fill Rate	Polygon Rate
First	Late 1998	RIVA TNT	0.25 µ	7 M	*50 M*	6 M
First	Early 1999	RIVA TNT2	0.22 µ	9 M	*75 M*	9 M
Second	Late 1999	GeForce 256	0.22 µ	23 M	*120 M*	15 M
Second	Early 2000	GeForce2	0.18 µ	25 M	*200 M*	25 M
Third	Early 2001	GeForce3	0.15 µ	57 M	800 M	30 M
Third	Early 2002	GeForce4 Ti	0.15 µ	63 M	1200 M	60 M
Fourth	Early 2003	GeForce FX	0.13 µ	125 M	2000 M	200 M
Eigth	Early 2007	GeForce 8800	0.090µ	681 M	13,800 M	10,800 M

History

- **Pre-GPU Graphics Acceleration**
  - SGI, Evans & Sutherland
  - Introduced concepts like vertex transformation and texture mapping.
- **First-Generation GPU (-1998)**
  - Nvidia TNT2, ATI Rage, Voodoo3
  - Vertex transformation on CPU, limited set of math operations.
- **Second-Generation GPU (1999-2000)**
  - GeForce 256, Geforce2, Radeon 7500, Savage3D
  - Transformation & Lighting. More configurable, still not programmable.
- **Third-Generation GPU (2001)**
  - Geforce3, Geforce4 Ti, Xbox, Radeon 8500
  - Vertex Programmability, pixel-level configurability.
- **Fourth-Generation GPU (2002)**
  - Geforce FX series, Radeon 9700 and on
  - Vertex-level and pixel-level programmability
- **Eigth-Generation GPU (2007)**
  - Geometry Programs, Unified Shaders, ...

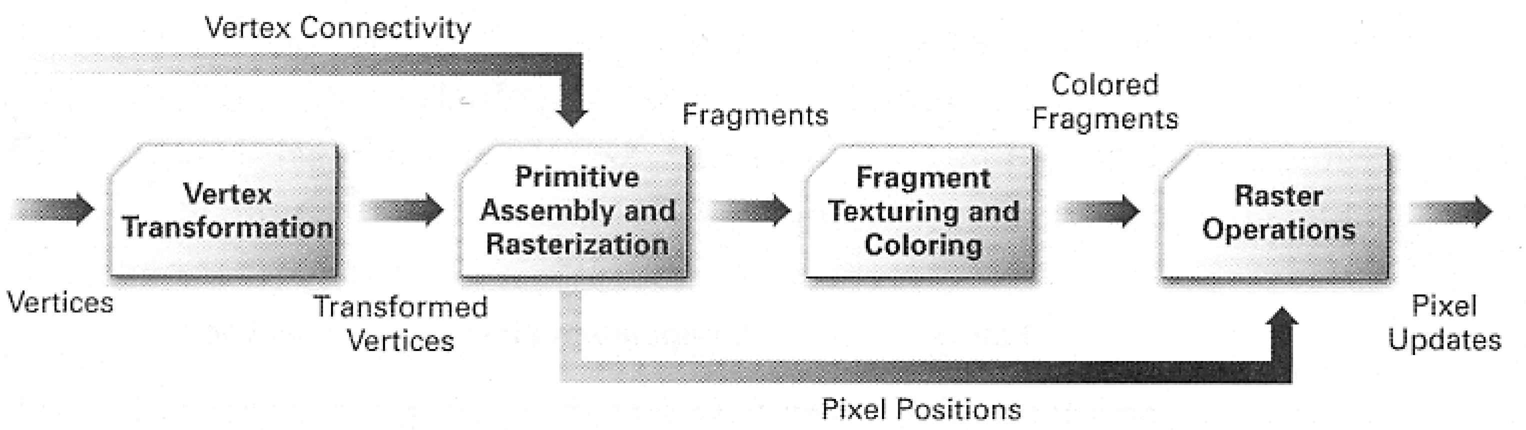
Before GPUs

- **All vertex transformations handled by CPU**
- **Limited the number of vertices in a scene**
- **Could still achieve many effects, but limited by CPU power**
- **Card “power” focused on fill rates**
- **Didn’t allow much room for AI, physics**

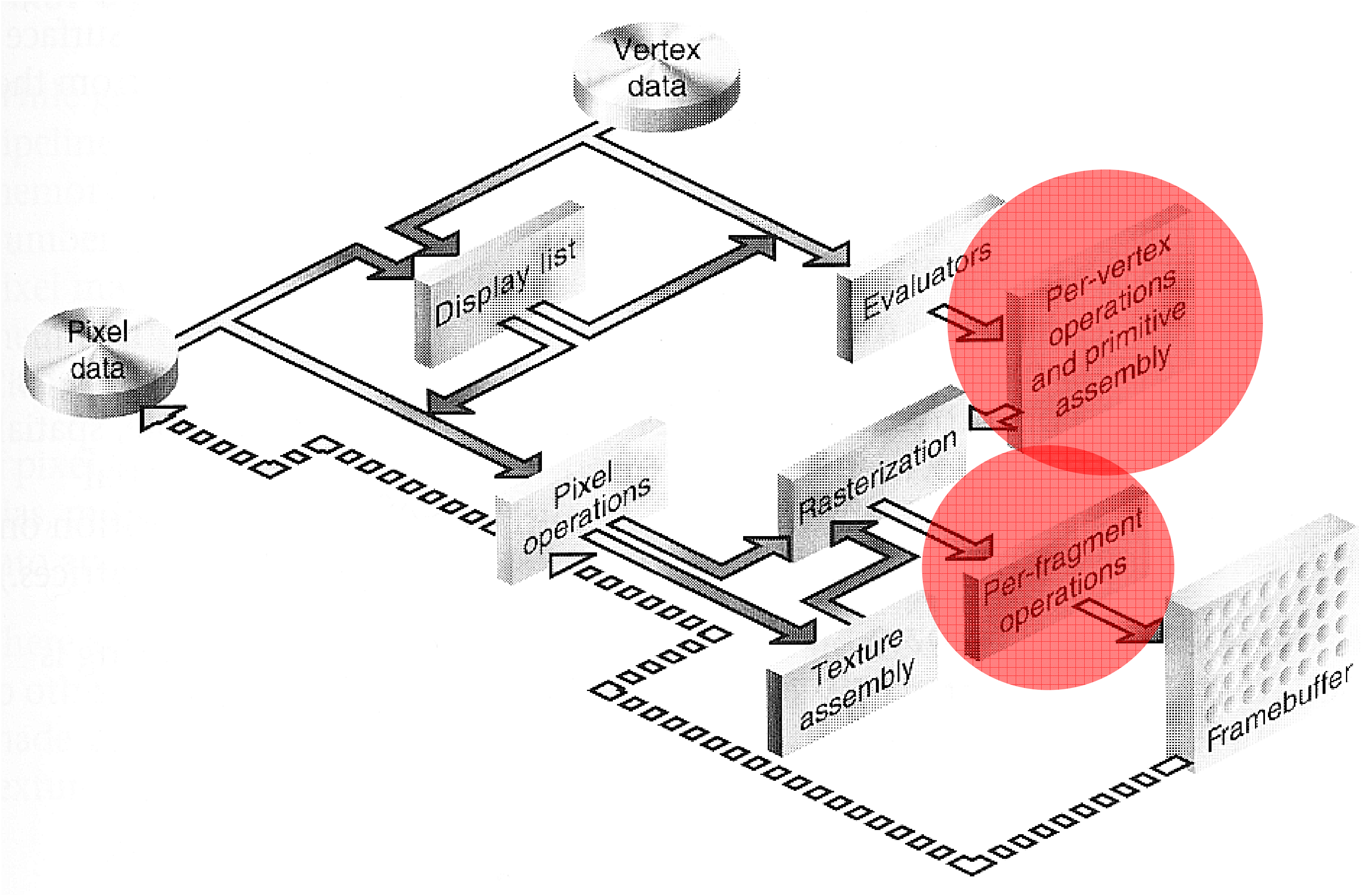


GeForce 256 – Hardware T&L

- **GPU now handled transformation of vertices**
- **Freed up CPU for AI and physics**
  - Allowed for other parts of the game to be made more realistic
- **Fixed function hardware**
  - Provides support for what OpenGL/DirectX did in the background
  - Could not be used to invent new techniques



Programmable Graphics Hardware



Geforce 3&4 – Vertex Shaders 1.0

- **Vertex Shaders**
  - Operate per-vertex
  - Allow customization of how vertices are transformed
  - Used in calculating per-vertex lighting
  - Support up to 128 instructions
    - No branching/conditional programming
    - 17 instructions available
    - All instructions operate on 4 float vectors (x,y,z,w)

Geforce 3&4 – Vertex Shaders 1.0

- **Vertex Shader Assembly Language**
  - Five types of registers
    - Address Register – 0 (VS 1.0) 1 (VS 1.1+)
      - Write/Use (cannot be read)
    - Constant Registers – 96
      - Read Only to GPU – set by host application
    - Temporary Registers – 12
      - Read/Write – cannot be used between vertices
    - Input Registers – 16
      - Read Only to GPU – set by application or vertex stream
    - Output Registers – 7 vector, 2 scalar
      - Write Only – position, diffuse color component, specular color component, texture coordinates (4), fog value & sprite size(scalar)

GeForce 3&4 – Vertex Shaders 1.0

Non-standard lighting

Classic Blinn lighting

GeForce 3&4 – Pixel Shaders 1.0

- **Pixel Shaders**
  - Operate per-pixel
  - Used to combine textures & calculate lighting
  - Commonly used for per-pixel bump mapping
  - Limited to 32 instructions
    - No conditional/branching operations

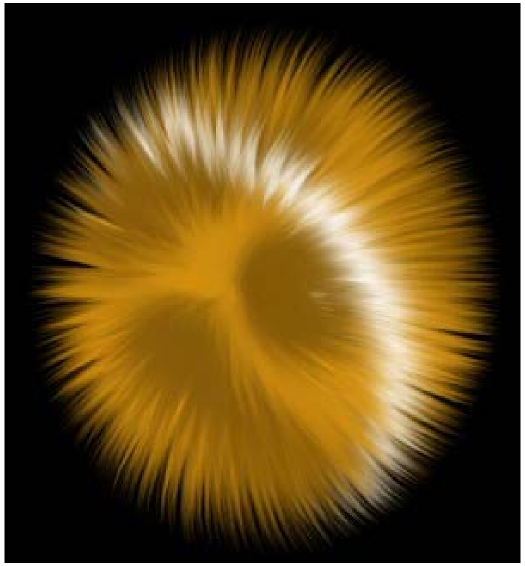
GeForce 3&4 – Pixel Shaders 1.0

- **Pixel Shader Assembly Language**
  - Four types of registers
    - Constants – 8
      - Read only (set by application)
    - Temporary – 2 (PS 1.4 has 8)
      - Read/Write (cannot be used by other pixels)
      - Output written to first temporary register (v0)
    - Textures – 4 (PS 1.4 has 6)
      - Read/Write (used to combine different texture)
    - Colors – 2
      - Read only
      - v0 for diffuse color
      - v1 for specular color

GeForce 3&4 – Pixel Shaders 1.0

Fresnel term

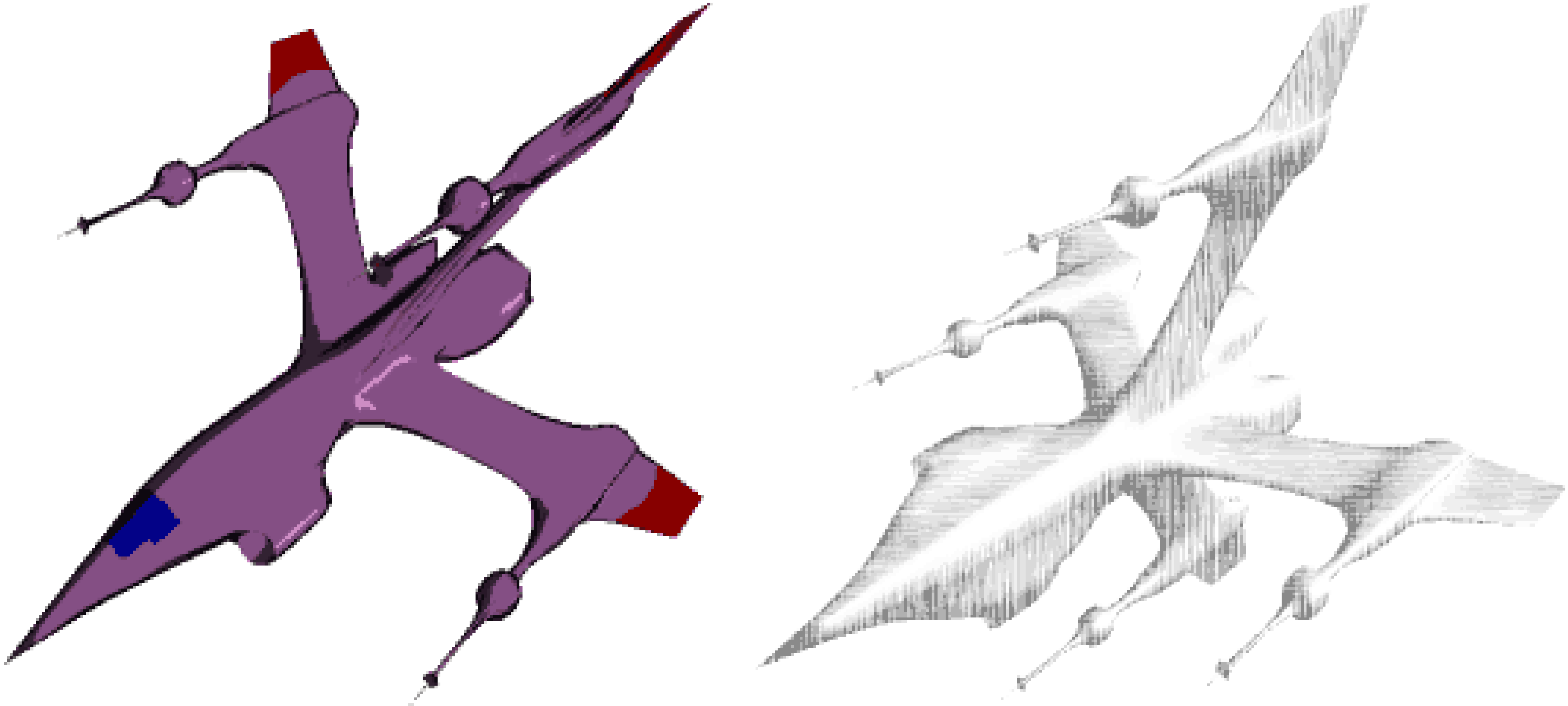
Fur/Hair



Refraction

GeForce 3&4 – Pixel Shaders 1.0

NPR Effects

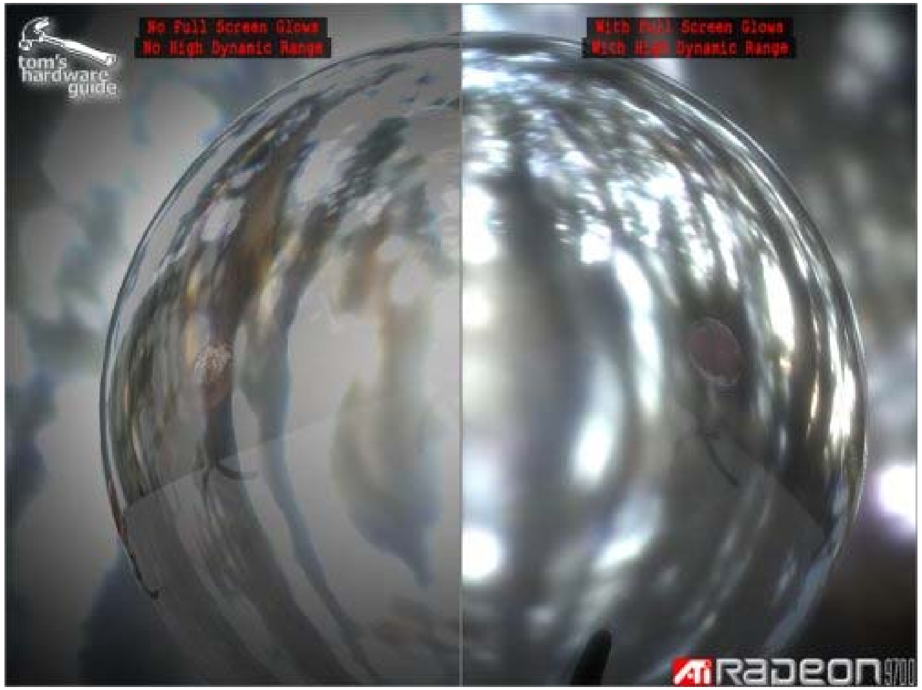


GeForce FX – Vertex Shaders 2.0

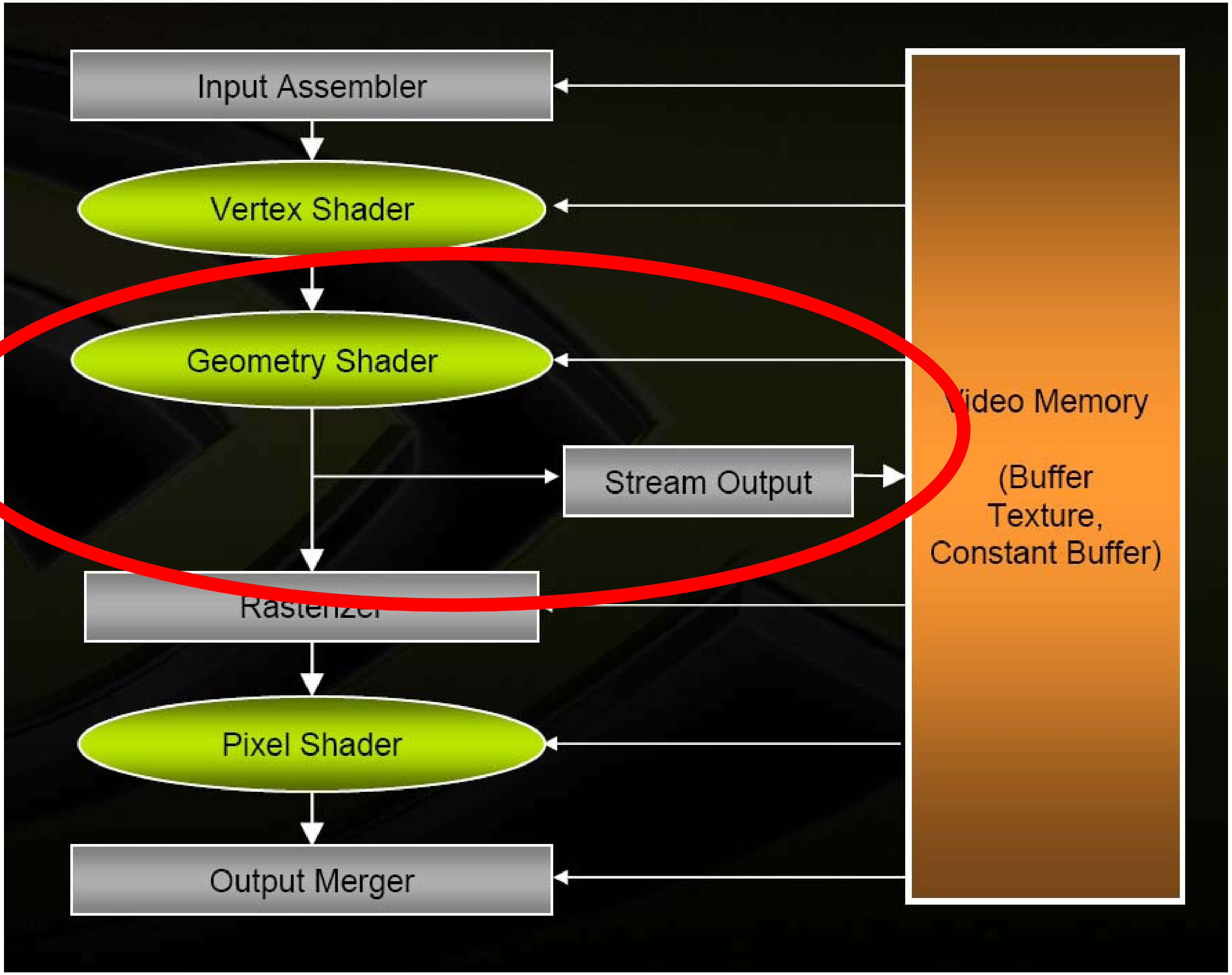
- **Now up to 1024 instructions**
  - (NVIDIA 2.0+ spec has up to 65536)
- **Supports Branching**
  - Conditional Jumps
  - Loops (up to 4 spec, NVIDIA up to 256)
  - Procedures
- **256 constants, 16 temporary registers**
- **128-bit floating point precision**
- **Supports N-patch ‘high order surface’ tessellation and ‘displacement mapped’ N-patch**

GeForce FX – Vertex Shaders 2.0

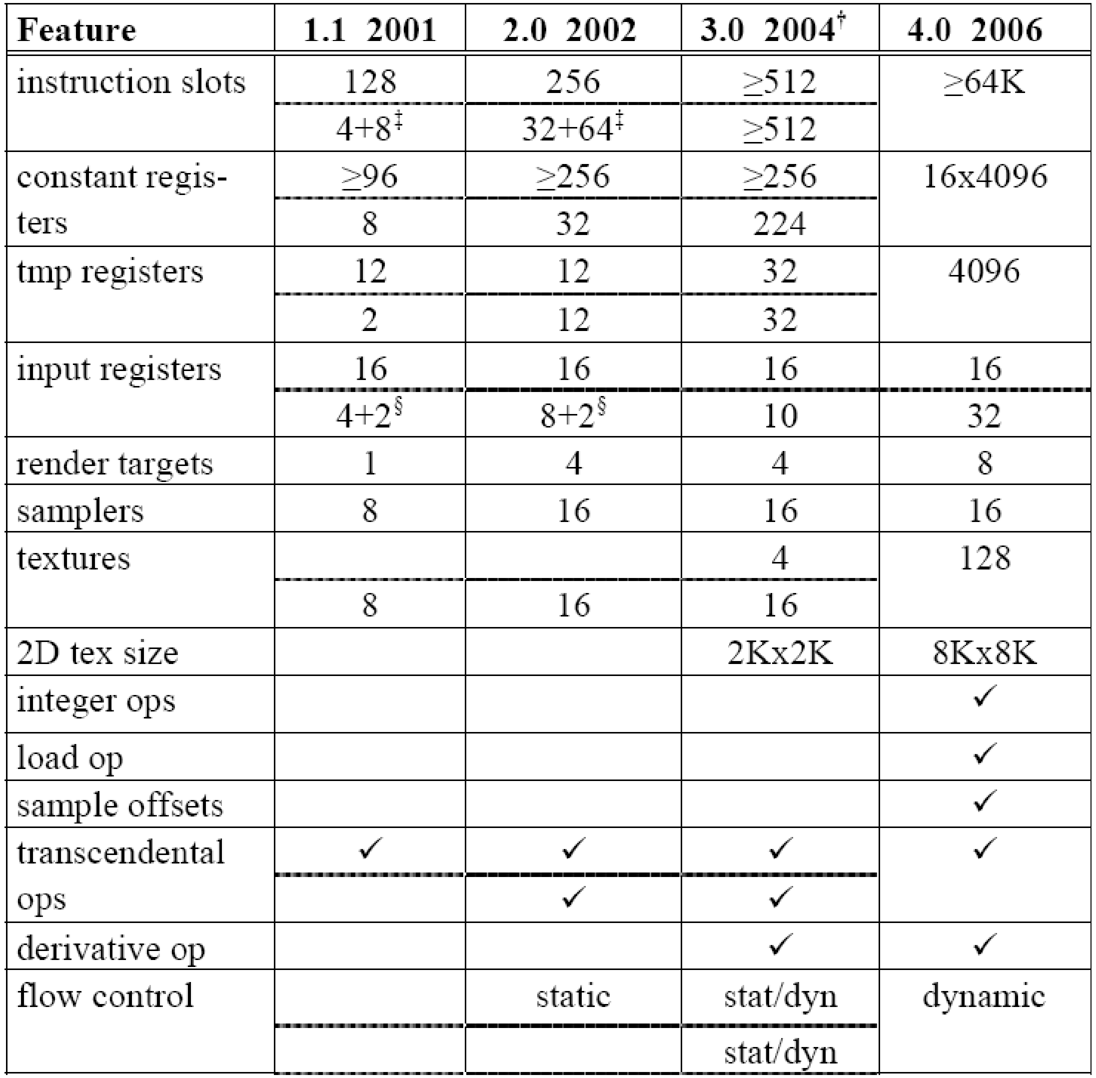
- **Supports 64-bit and 128-bit FP precision**
- **Adds Loops, Conditionals, Functions**
- **Max instructions increased to 96 (1024 on NV)**



DX-10 and Shader Model 4.0



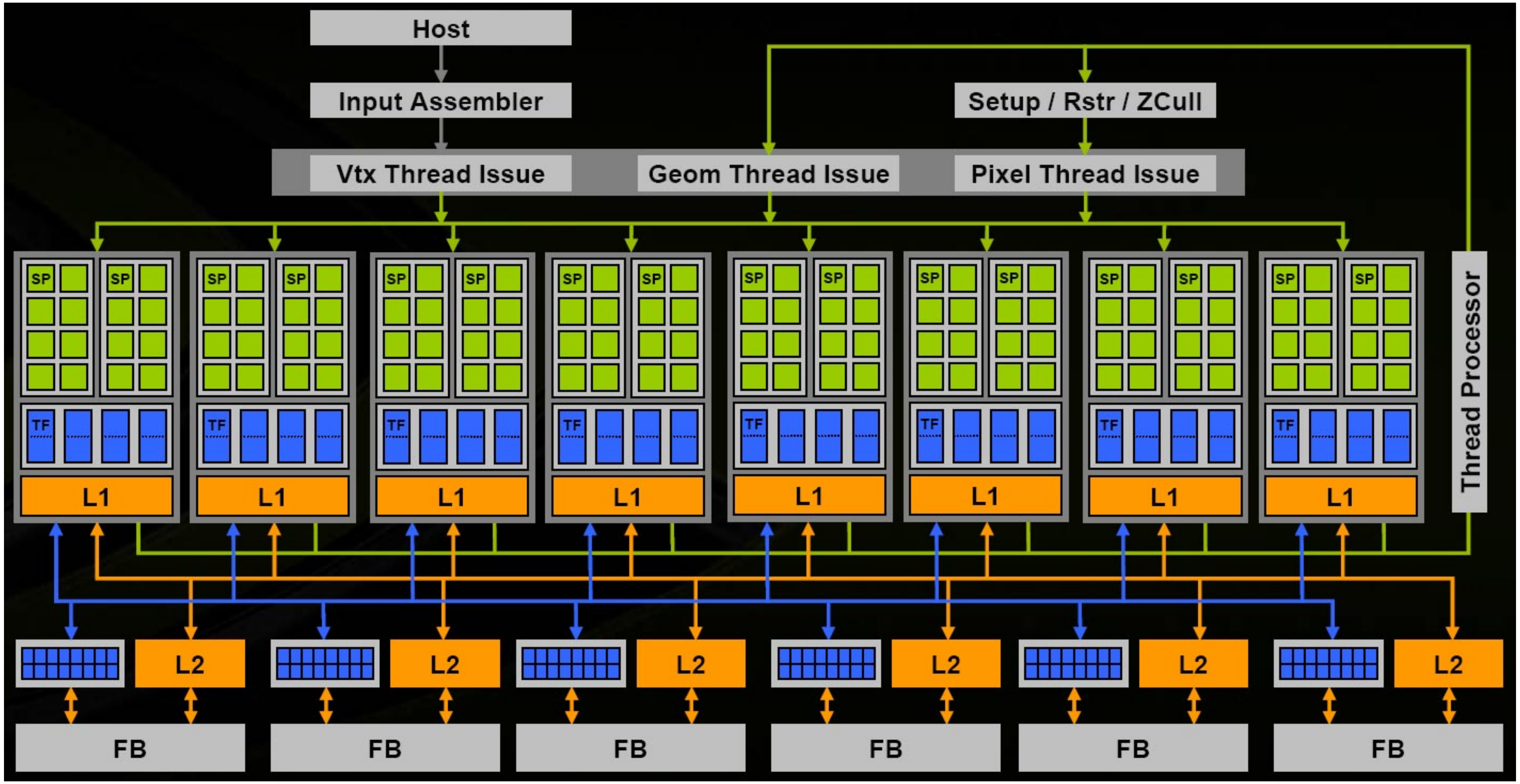
DX-10 and Shader Model 4.0



Feature	1.1 2001	2.0 2002	3.0 2004†	4.0 2006
instruction slots	128	256	≥512	≥64K
	4+8‡	32+64‡	≥512	
constant registers	≥96	≥256	≥256	16x4096
	8	32	224	
tmp registers	12	12	32	4096
	2	12	32	
input registers	16	16	16	16
	4+2§	8+2§	10	32
render targets	1	4	4	8
samplers	8	16	16	16
textures			4	128
	8	16	16	
2D tex size			2Kx2K	8Kx8K
integer ops				✓
load op				✓
sample offsets				✓
transcendental ops	✓	✓	✓	✓
		✓	✓	
derivative op			✓	✓
flow control		static	stat/dyn	dynamic
			stat/dyn	

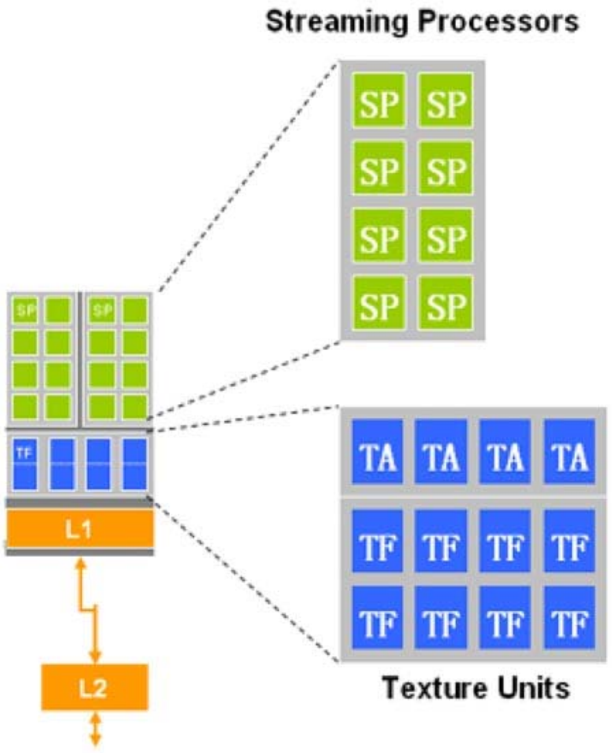
Table 1: Shader model feature comparison summary.

G80 – Unified Shaders



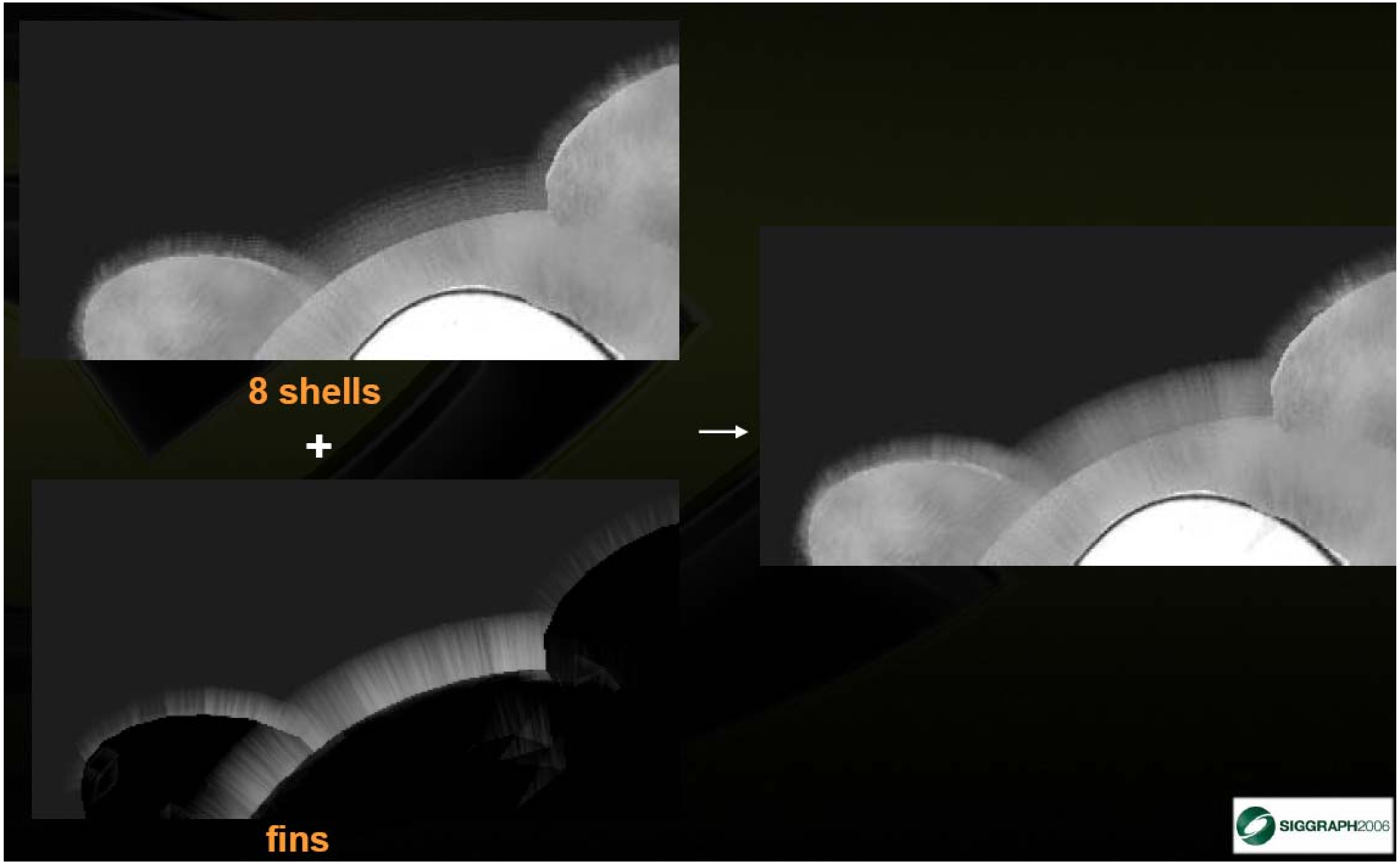
G80 – Unified Shaders

Streaming Processors, Texture Units, and On-chip Caches

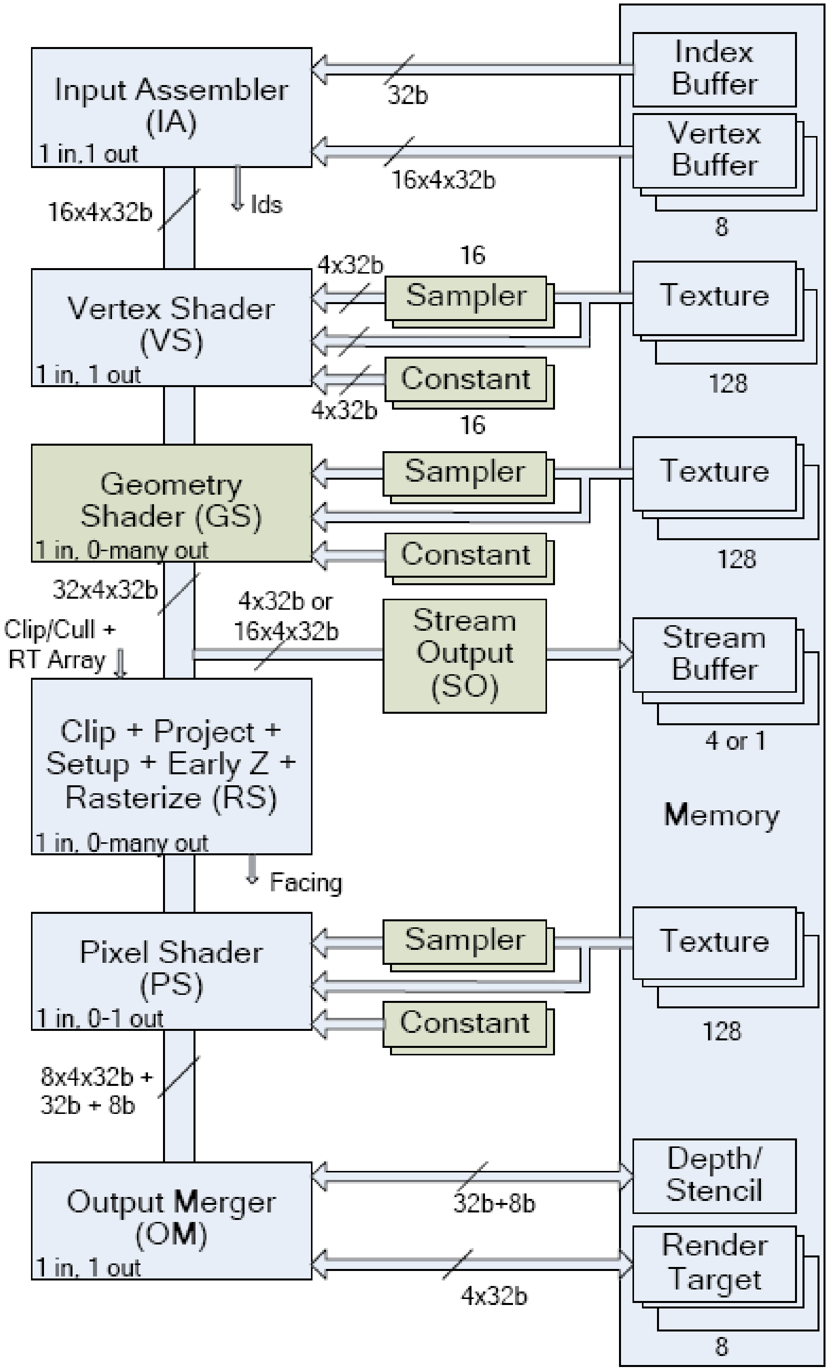


- **SP = Streaming Processors**
- **TF = Texture Filtering Unit**
- **TA = Texture Address Unit**
- **L1/L2 = Caches**

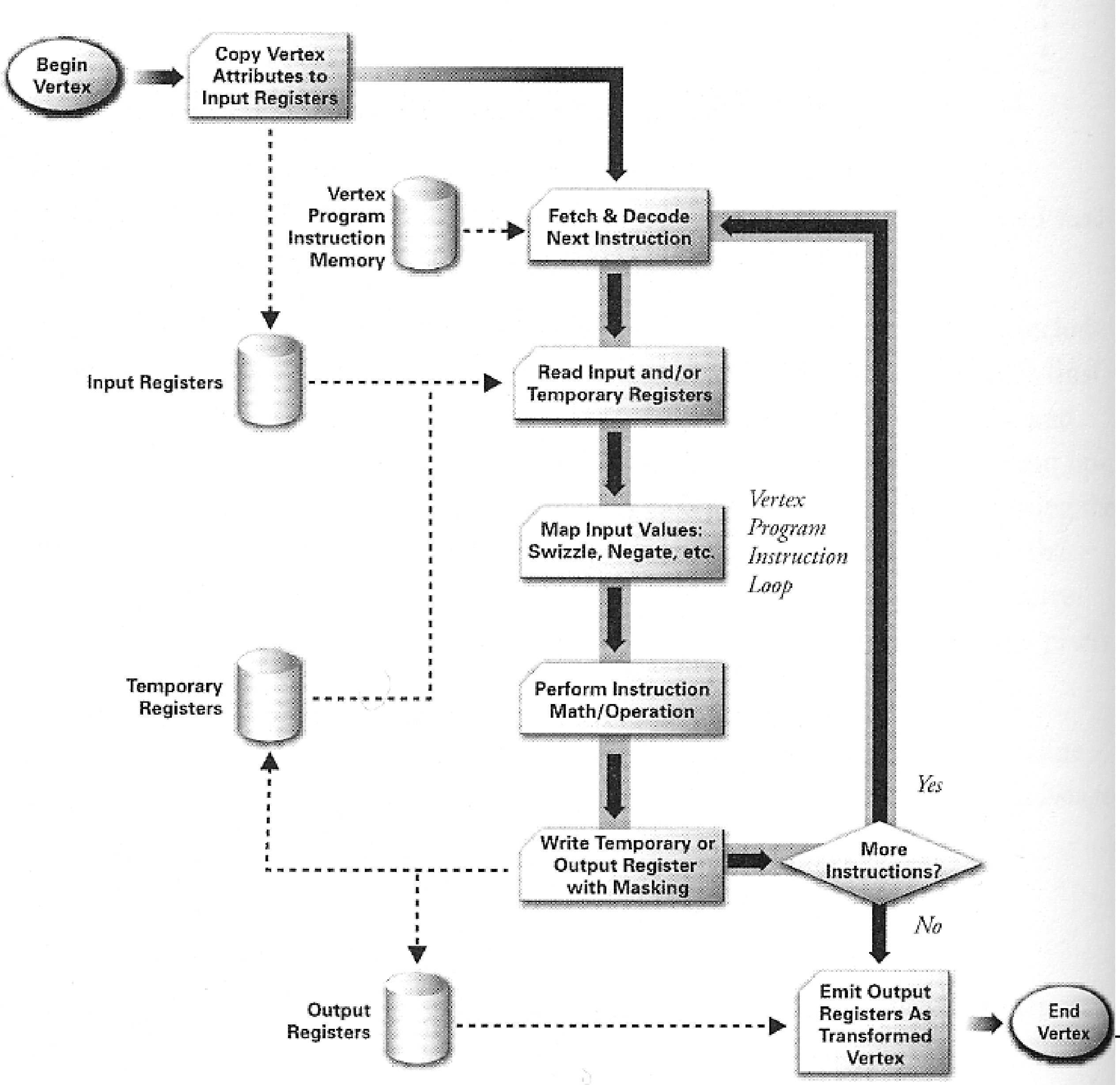
Figure 18. Streaming Processors and Texture Units


8 shells
+
fins
→
SIGGRAPH2006

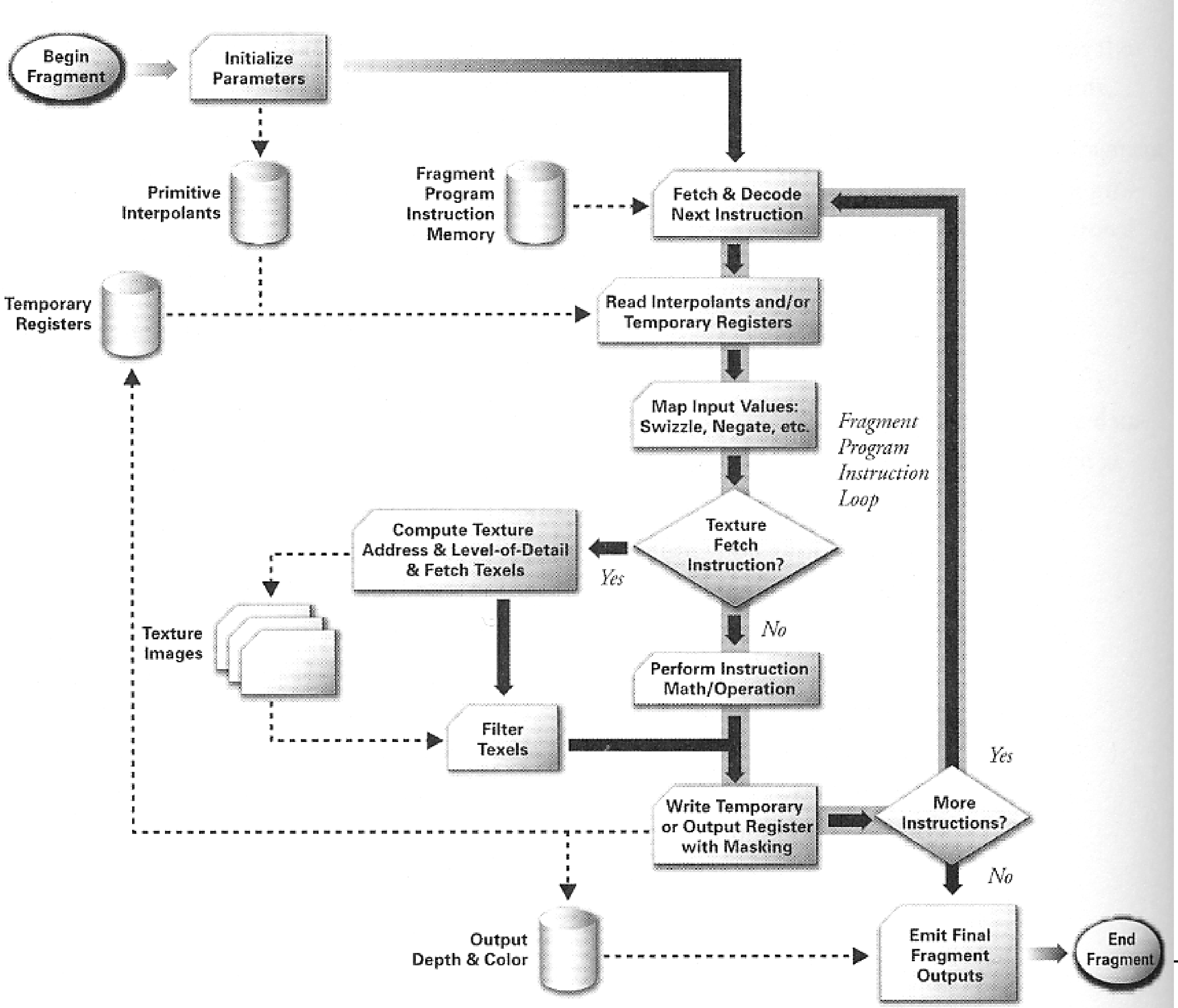
Shader Model 4



Vertex Processor Flow Chart



Fragment Processor Flow Chart



High Level Shader Languages

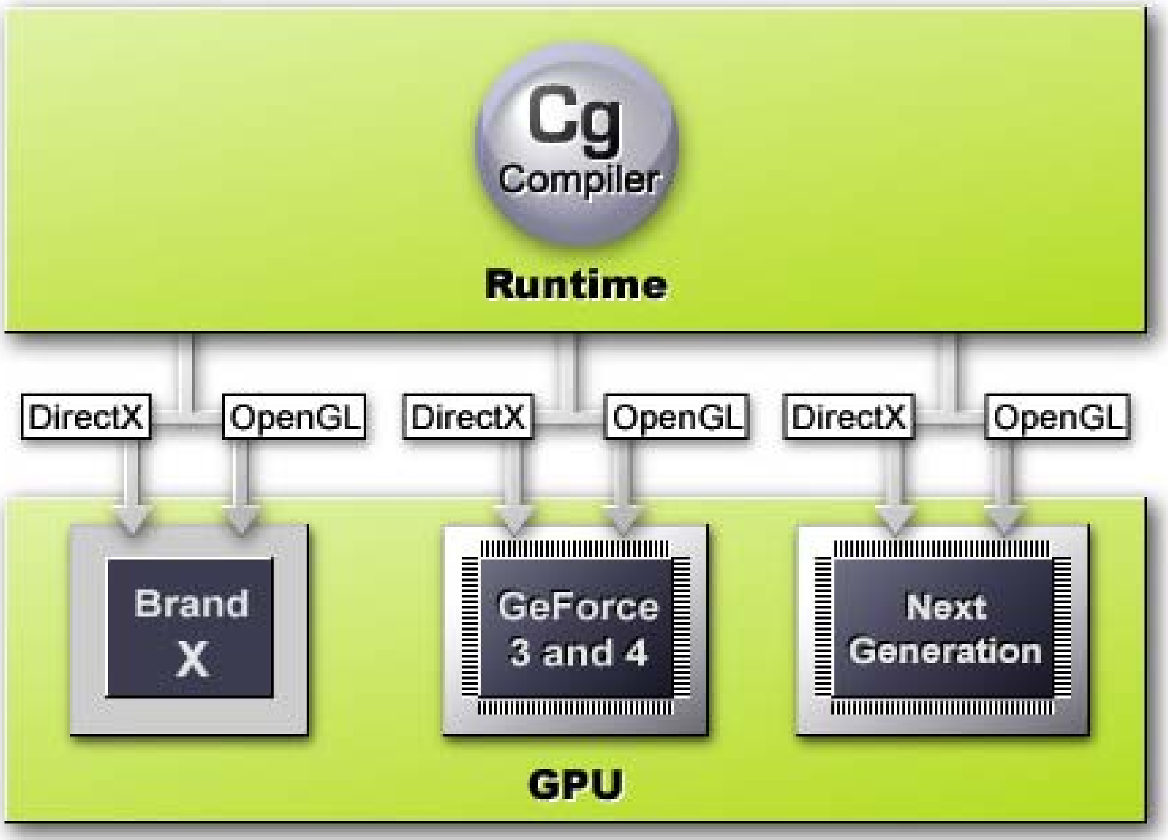
- **Programming shaders in machine code isn’t easy**
- **DirectX 10 HLSL & NVIDIA Cg**
  - Writing shaders in C-like code
  - Supports C-like syntax
  - Open source compiler
    - New compilers can be written to compile the same code for different architectures
  - Optimization of code for different levels of hardware
  - Allows compiling for DirectX & OpenGL

Cg

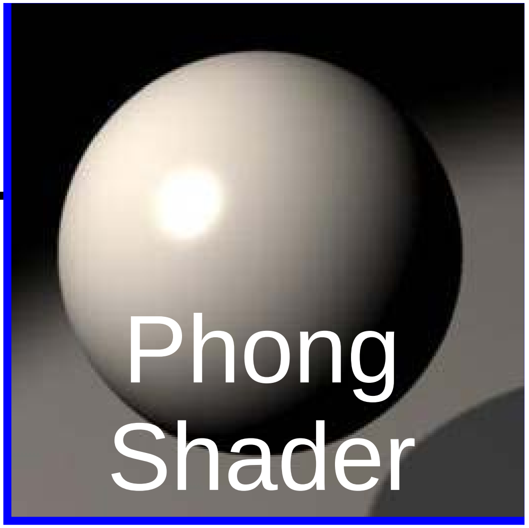
- **"C for Graphics"**
  - high-level, cross-platform language for graphics programming
- **C-like language**
  - Replaces tedious assembly coding
  - compiler generates assembler code
- **Cross-API, cross-platform language**
  - OpenGL and DirectX
  - Windows and Linux
  - NVIDIA, ATI, Matrox, any other programmable hardware that supports OpenGL or DirectX
- **Cg Runtime**
  - simplifies parameter passing from application to vertex and fragment programs

Cg

- **Forward compatibility**
- **Works with all programmable GPUs supporting DirectX 8/9 or OpenGL 1.5/2.0**



What does Cg look like ?



Assembly

```
…
DP3 R0, c[11].xyzx, c[11].xyzx;
RSQ R0, R0.x;
MUL R0, R0.x, c[11].xyzx;
MOV R1, c[3];
MUL R1, R1.x, c[0].xyzx;
DP3 R2, R1.xyzx, R1.xyzx;
RSQ R2, R2.x;
MUL R1, R2.x, R1.xyzx;
ADD R2, R0.xyzx, R1.xyzx;
DP3 R3, R2.xyzx, R2.xyzx;
RSQ R3, R3.x;
MUL R2, R3.x, R2.xyzx;
DP3 R2, R1.xyzx, R2.xyzx;
MAX R2, c[3].z, R2.x;
MOV R2.z, c[3].y;
MOV R2.w, c[3].y;
LIT R2, R2;
...
```

Cg

```
COLOR cPlastic = Ca + Cd * dot(Nf, L) +
        Cs * pow(max(0, dot(Nf, H)), phongExp);
```

Why Cg ?

- **Simplifies developing OpenGL and DirectX applications with programmable shading**
  - Easier than assembly
  - Simplified parameter management
  - Abstraction from hardware and graphics API
- **Flexible—use as little or as much of it as you want**
  - Cg language only
  - API-independent libraries
  - API-dependent libraries
- **Productivity increase for graphics development**
  - Game developers
  - DCC (Digital Content Creation) artists
  - Artists & shader writers
  - CAD and visualization application developers

Compiling Cg at Runtime

At Development Time

```
//
// Diffuse lighting
//
float d = dot(normalize(frag.N), normalize(frag.L));
if (d < 0)
  d = 0;
c = d*tex2D(t, frag.uv)*diffuse;
…
```

Cg program source code

At Runtime

- At initialization:
  - Compile and load Cg program
- For every frame:
  - Load program parameters with the Cg Runtime API
  - Set rendering state
  - Load geometry
  - Render

Cg Runtime Compilation

- **Pros:**
  - Future compatibility: The application does not need to change to benefit from future compilers (future optimizations, future hardware)
  - Easy parameter management

- **Cons:**
  - Loading takes more time because of compilation
  - Cannot tweak the result of the compilation

OpenGL Cg Runtime

- **Makes the necessary OpenGL calls for you**
- **Allows you to:**
  - Load a program into OpenGL: `cgGLLoadProgram()`
  - Enable a profile: `cgGLEnableProfile()`
  - Tell OpenGL to render with it: `cgGLBindProgram()`
  - Set parameter values: `cgGLSetParameter{1234}{fd}{v}()`, `cgGLSetParameterArray{1234}{fd}()`, `cgGLSetTextureParameter()`, etc...

Cg and C

- **Syntax, operators, functions from C**
- **Conditionals and flow control**
- **Particularly suitable for GPUs**
  - Expresses data flow of the pipeline/stream architecture of GPUs (e.g. vertex-to-pixel)
  - Vector and matrix operations
  - Supports hardware data types for maximum performance
  - Exposes GPU functions for convenience and speed:
    - Intrinsic: (mul, dot, sqrt…)
    - Built-in: extremely useful and GPU optimized math, utility and geometric functions (noise, mix, reflect, sin…)
  - Language reserves keywords to support future hardware implementations (e.g., pointers, switch, case…)
  - Compiler uses *hardware profiles* to subset Cg as required for particular hardware capabilities (or lack thereof)

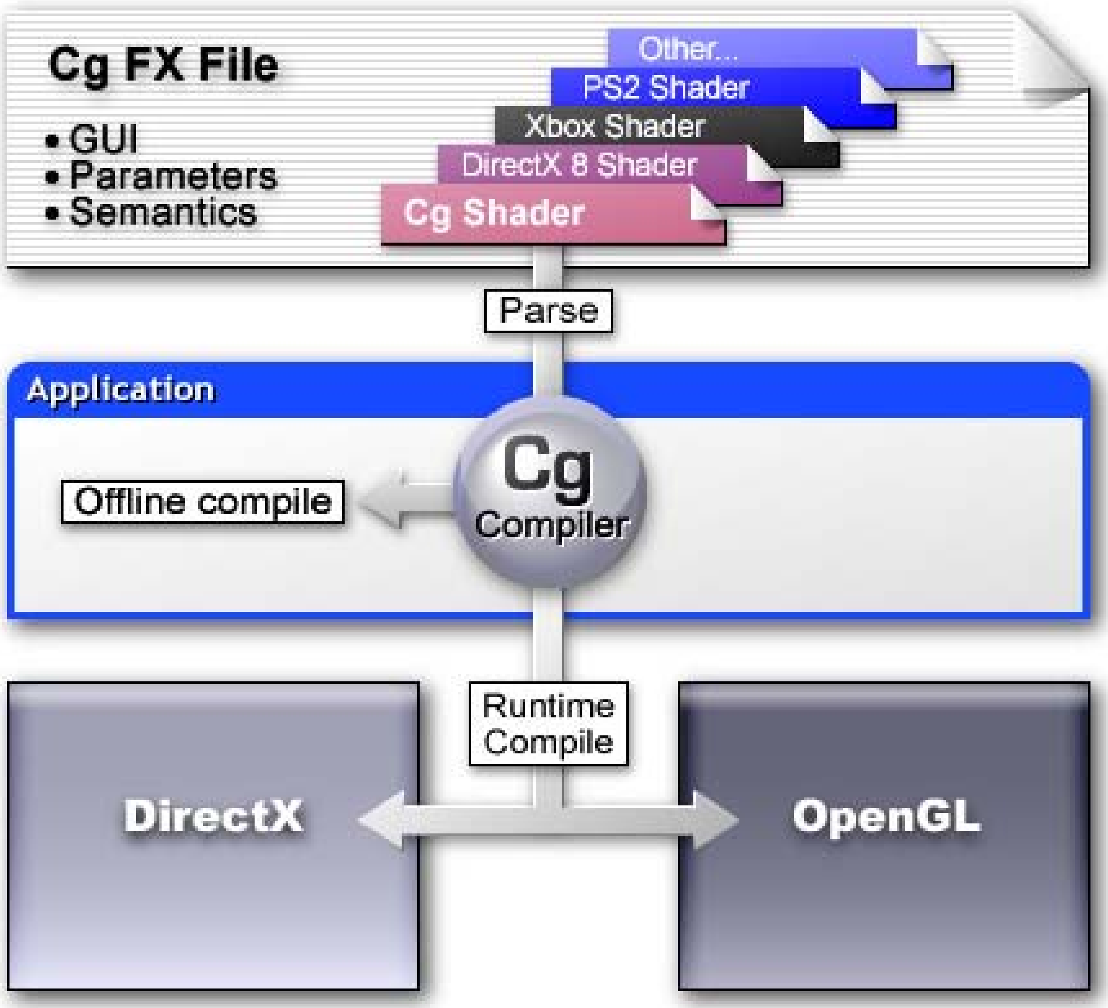
Cg and CgFX

- **One Cg vertex & pixel program together describe a single rendering pass**

- **CgFX shaders can describe multiple passes**
  - Although CineFX architecture supports 1024 pixel instructions in a single pass!

  - CgFX also contains multiple implementations
    - For different APIs
    - For various HW
    - For Shader LOD

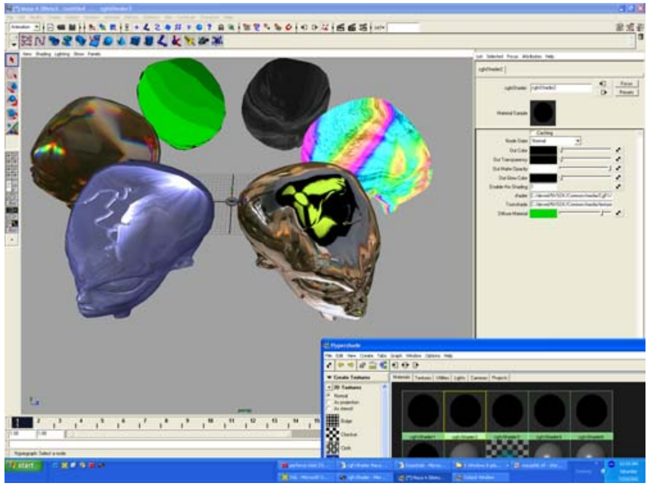
CgFX



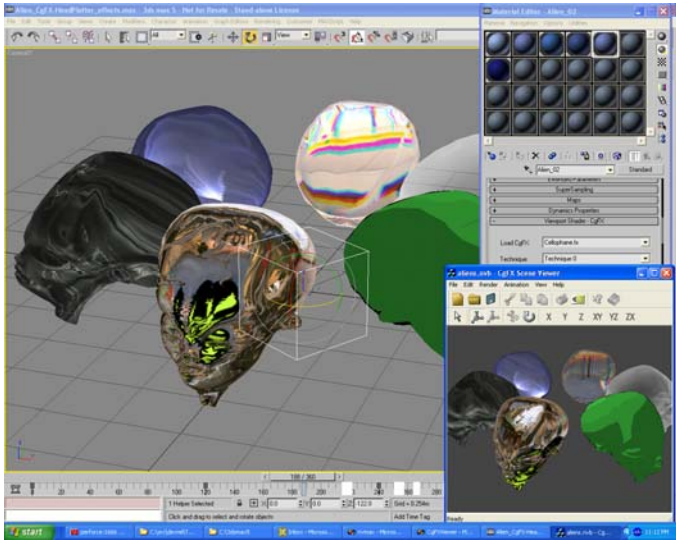
- **CgFX files contain shaders and the supplementary data required to use them**
- **Unlimited multiple implementations**
  - API (D3D vs. OpenGL)
  - Platform (Xbox, PC, …)
  - Shader Level of Detail
- **NVIDIA's Compiler includes a CgFX parser for easy integration**

Cg in Professional Graphics Software

Maya®



3ds max™



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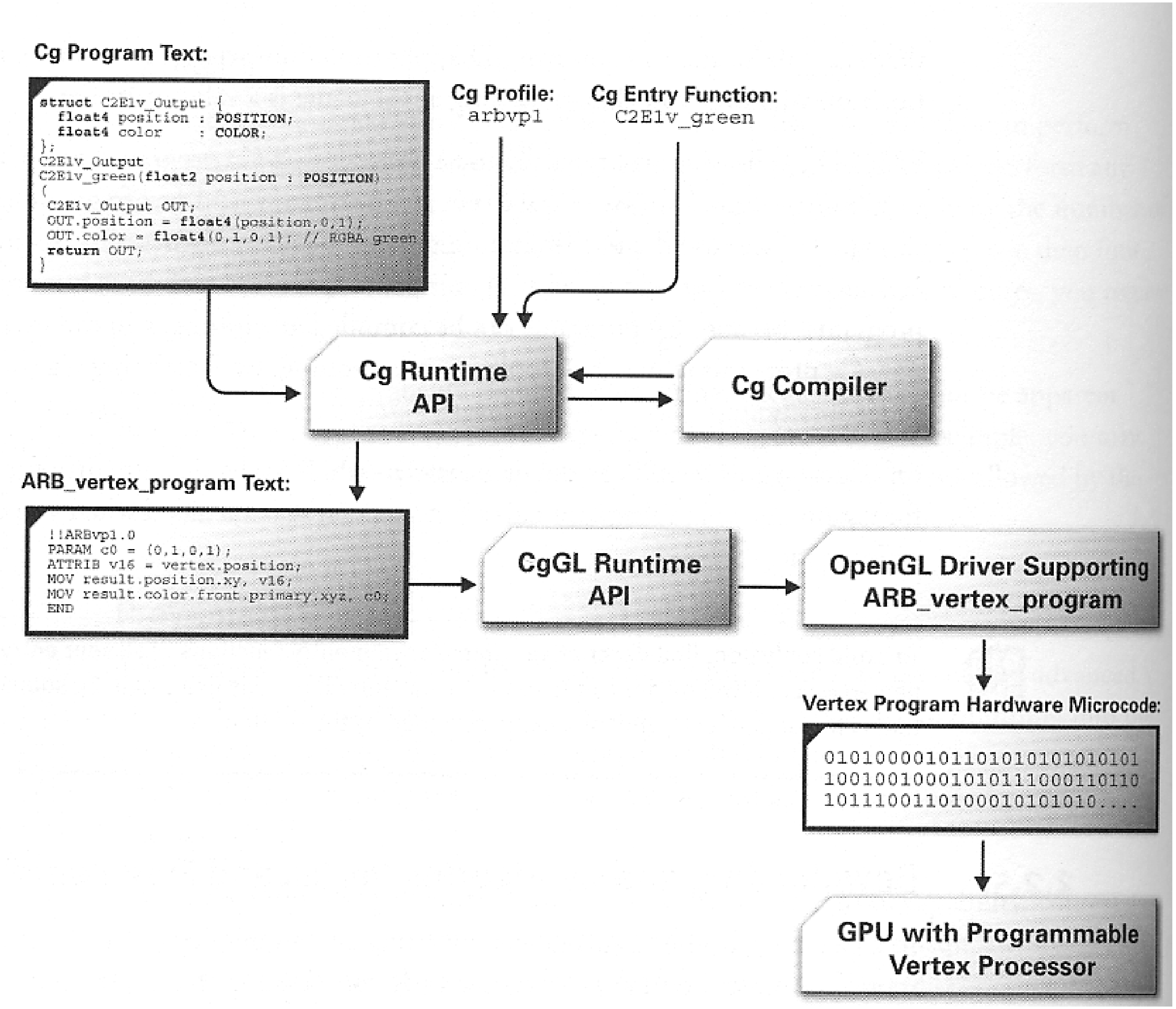
Cg Compiler Profiles

- **Different graphics cards have different capabilities**
  - Exploit individual hardware

- **Programs must be compiled to a certain profile**
  - Input: Cg program + profile to compile to
  - Output: Assembly language for the specified hardware

Compiling & Loading Cg Program



```
struct C2E1v_Output {
  float4 position : POSITION;
  float4 color    : COLOR;
};
C2E1v_Output
C2E1v_green(float2 position : POSITION)
{
 C2E1v_Output OUT;
 OUT.position = float4(position,0,1);
 OUT.color = float4(0,1,0,1); // RGBA green
 return OUT;
}
```

```
!!ARBvp1.0
PARAM c0 = {0,1,0,1};
ATTRIB v16 = vertex.position;
MOV result.position.xy, v16;
MOV result.color.front.primary.xyz, c0;
END
```

A First Cg Example

Vertex Program

```
struct C2E1v_Output {
  float4 position : POSITION;
  float4 color    : COLOR;
};

C2E1v_Output C2E1v_green(
     float2 position : POSITION)
{
  C2E1v_Output OUT;

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

  return OUT;
}
```

Fragment Program

```
struct C2E2f_Output {
  float4 color : COLOR;
};

C2E2f_Output C2E2f_passthrough(
     float4 color : COLOR)
{
  C2E2f_Output OUT;

  OUT.color = color;
  return OUT;
}
```

Data Types

- **float = 32-bit IEEE floating point**
- **half = 16-bit IEEE-like floating point**
- **fixed = 12-bit fixed [-2,2) clamping (*OpenGL only*)**
- **bool = Boolean**
- **sampler* = Handle to a texture sampler**

Arrays, Matrices, Vectors

- **Declare vectors (up to length 4) and matrices (up to size 4x4) using built-in data types:**

```
float4   mycolor;
float3x3 mymatrix;
```

- **Not the same as arrays :**

```
float mycolor[4];
float mymatrix[3][3];
```

- **Arrays are first-class types, not pointers**

Function Overloading

- **Examples:**

```
float myfuncA(float3 x);
float myfuncA(half3 x);

float myfuncB(float2 a, float2 b);
float myfuncB(float3 a, float3 b);
float myfuncB(float4 a, float4 b);
```

- **Very useful with all the different Cg data types**

Vector and Matrix Arithmetics

- **Component-wise +, -, *, /, >, <, ==, ?:**
  - for vectors
- **Dot product**
  - `dot(v1,v2);` // returns a scalar

- **Matrix multiplications**
  - assuming `float4x4 M` and `float4 v`
  - matrix-vector: `mul(M, v);` // returns a vector
  - vector-matrix: `mul(v, M);` // returns a vector
  - matrix-matrix: `mul(M, N);` // returns a matrix

New Vector Operators

- **Swizzle operator extracts elements from vector**

```
a = b.xxyy;
```

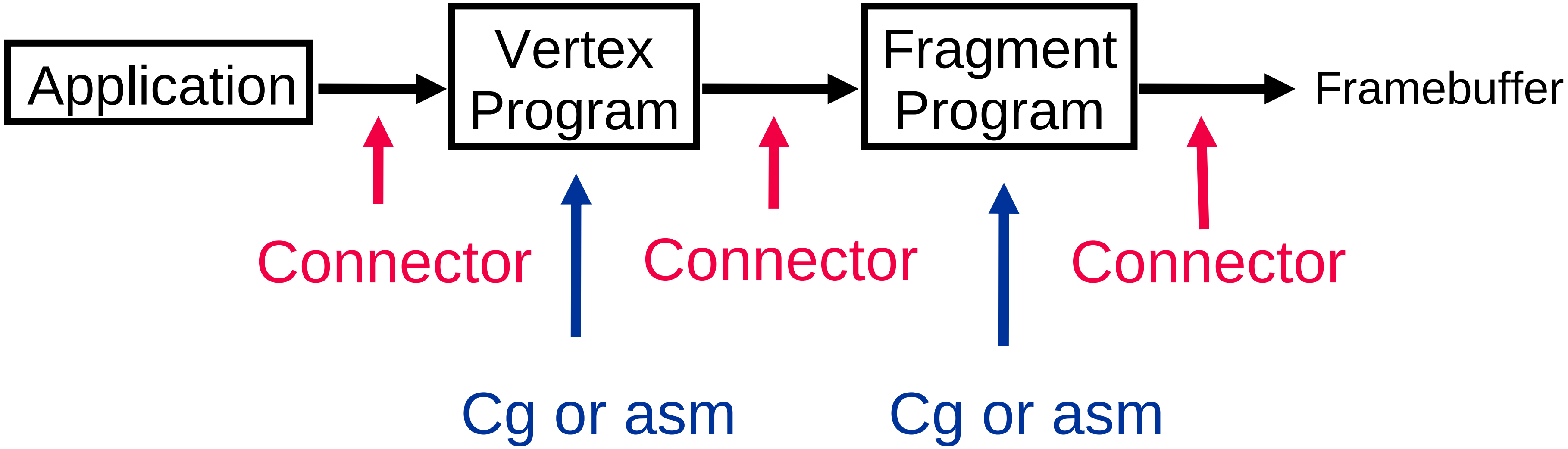
- **Vector constructor builds vector**

```
a = float4(1.0, 0.0, 0.0, 1.0);
```

- **Masking operator specifies which elements are overwritten**

```
a.wx = b.xy;
```

The Big Picture



Application

Vertex Program

Fragment Program

Framebuffer

Connector

Connector

Connector

Cg or asm

Cg or asm

What is a Connector ?

- **Describes shader inputs and outputs**
- **Defines an interface that allows mixing-and-matching of programs**
- **It’s a struct, but with optional extra information**

Connecting Cg to C++

- **#include <Cg/cgGL.h>**
- **Create context**
  ```
  cgContext* context = cgCreateContext();
  ```
- **Create a Program**
  ```
  cgProgramIter* vertexProg = cgCreateProgramFromFile(context,
     CG_SOURCE,  "Skinning.cg", CG_PROFILE_VP30, “main”, NULL );
  ```
- **Get pointer to parameter**
  ```
  cgBindIter* ModelViewProjBind =
                 cgGetBindByName(vertexProg, "modelViewProj");
  ```

Enabling Cg Programs

- **Bind program**

  `cgGLBindProgram(vertexProg);`

- **Enable program**

  `cgGLEnableProgramType(cgVertex30Profile);`

- **Disable program**

  `cgGLDisableProgramType(cgVertex30Profile);`

➢ **Just like OpenGL states**

Cg Input

- **Two types of input**
  - Varying
  - Uniform
- **Can be defined in either a struct or just as input parameter to the function**
- **No predefined names**
  - Input, program name and output can be named freely
  - Program must have specified input and output
- **Example**

```
struct app2vert {
        float4 position             : POSITION;
        float4 normal               : NORMAL;
        float4 TexCoord0            : TEXCOORD0;
};
```

Sending Data to Cg Vertex Program

- **Uniform**

```
cgGLBindUniformStateMatrix(vertexProg, ModelViewProjBind,
                                cgGLModelViewProjectionMatrix,
   cgGLMatrixIdentity);

cgGLBindUniform4fv(vertexProg, lightBind, float [4]);
```

- **Varying**

```
glVertex3f, glNormal3f, glTexCoord2f, glColor3f, …
glVertexAttrib4fNV(x, float[4]);
```

Defining a Vertex Program

output connector

Input connector

```
v2f skinning(myappdata vin,
             uniform float4x4 m1,
             uniform float4x4 m2)
{
    v2f vout;
    // skinning
    vout.pos   =  vin.w1*(mul(m1,vin.pos)) +
                  vin.w2*(mul(m2,vin.pos));
    vout.color = vin.color;
    vout.uv    = vin.uv;
    return vout;
}
```

Note that “uniform” variables don’t come in via a connector.

Connecting Vertex Program to Fragment Program

- **Returned from vertex program**

name of connector

```
struct v2f
{
  float4 pos : POSITION;
  float4 color;
  float2 uv;
};
```

Must have POSITION

Defining a Fragment Program

predefined output connector

input connector

```
f2fb do_texture(v2f fragin,
                uniform sampler2D tex)
{
    f2fb fragout;
    fragout.COL = fragin.color * f4tex2D(tex, fragin.uv);
    return fragout;
}
```

- **Predefined output connector**

```
struct f2fb {
        half4 col          : COLOR;
        float depth        : DEPTH;
}
```

Optional: Specify Connector Registers

```
struct v2f
{
  float4 pos       : POSITION;
  float4 color     : TEXCOORD0;
  float2 uv        : TEXCOORD1;
};
```

These **`semantics`** allow mix & match with manually-written assembly code.

Vertex-Fragment Programs: Differences

- **Specific hardware limitations**
  - Removed in latest versions !!!
- **Vertex profiles**
  - No “half” or “fixed” data type
  - No texture-mapping functions
- **Fragment/pixel profiles**
  - No “for” or “while” loops (unless they’re unrollable)

Features

- **Static function calls and static loops in all profiles**
- **Lots of library functions (e.g. cos, sin, sqrt)**
- **Non static loops and function calls in NV30**

Limitations

- **No pointers**
  - not supported by HW
- **Function parameters are passed by value/result**
  - not by reference as in C++
  - use `out` or `inout` to declare output parameter
  - aliased parameters are written in order
- **No unions or bit-fields**
- **No `int` data type**

Wrap-Up

- **Cg: C-like language**
  - succeeds assembly code
- **Vertex & fragment programs**
- **Different profiles for different HW**
- **Compiler optimizes usage of parallel pipelines**
- **Various HW-supported data types**
- **Supports vector and matrix operations**
- **Uniform vs. varying parameters**