King Abdullah University of
Science and Technology

KAUST

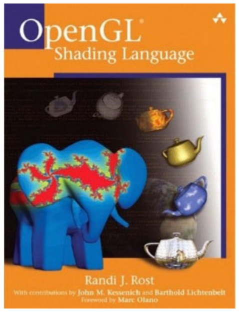
CS 380 - GPU and GPGPU Programming
Lecture 4: GPU Architecture, Pt. 1

Markus Hadwiger, KAUST

Reading Assignment #2 (until Sep 11)

Read (required):

- Orange book (GLSL), Chapter 4
  (*The OpenGL Programmable Pipeline*)



- Nice brief overviews of GLSL and legacy assembly shading language

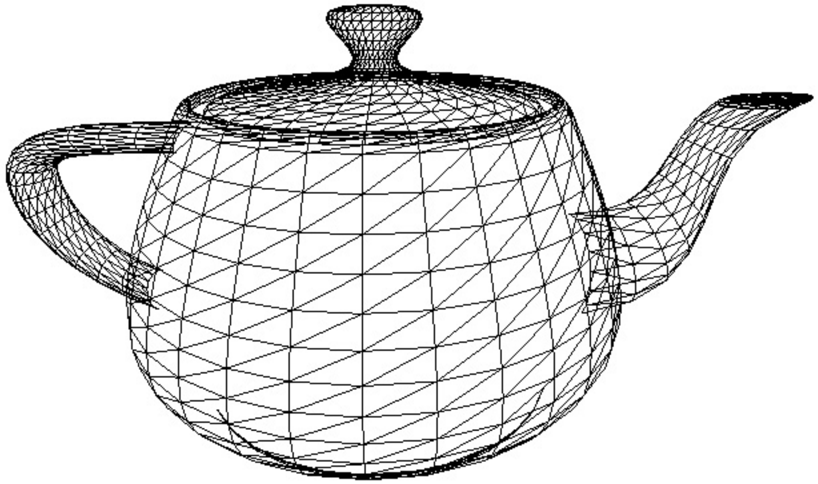
https://en.wikipedia.org/wiki/OpenGL_Shading_Language

https://en.wikipedia.org/wiki/ARB_assembly_language

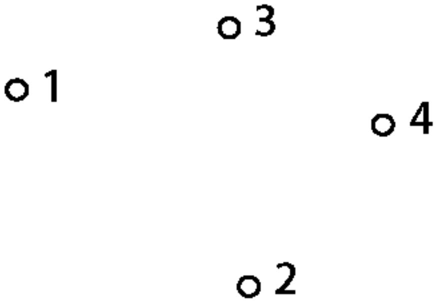
- GPU Gems 2 book, Chapter 30
  (*The GeForce 6 Series GPU Architecture*)

http://download.nvidia.com/developer/GPU_Gems_2/GPU_Gems2_ch30.pdf

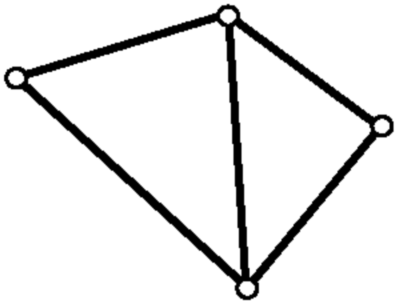
Real-time graphics primitives (entities)



Represent surface as a 3D triangle mesh



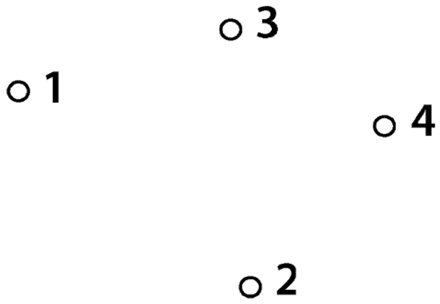
Vertices



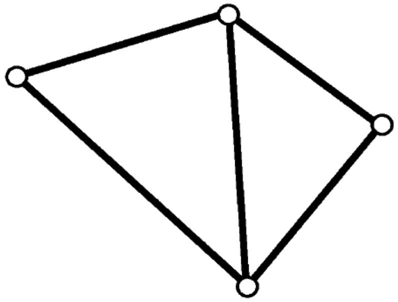
Primitives
(e.g., triangles, points, lines)

Courtesy Kayvon Fatahalian, CMU

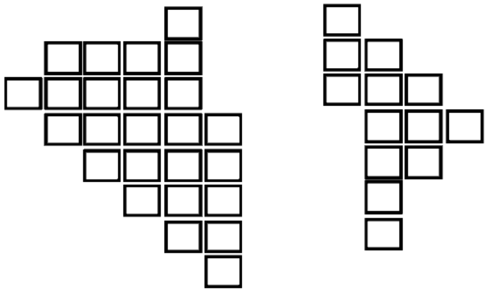
Real-time graphics primitives (entities)



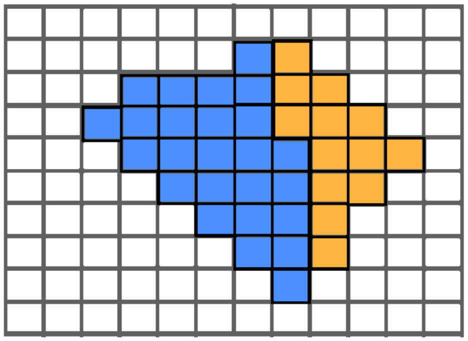
Vertices



Primitives
(e.g., triangles, points, lines)



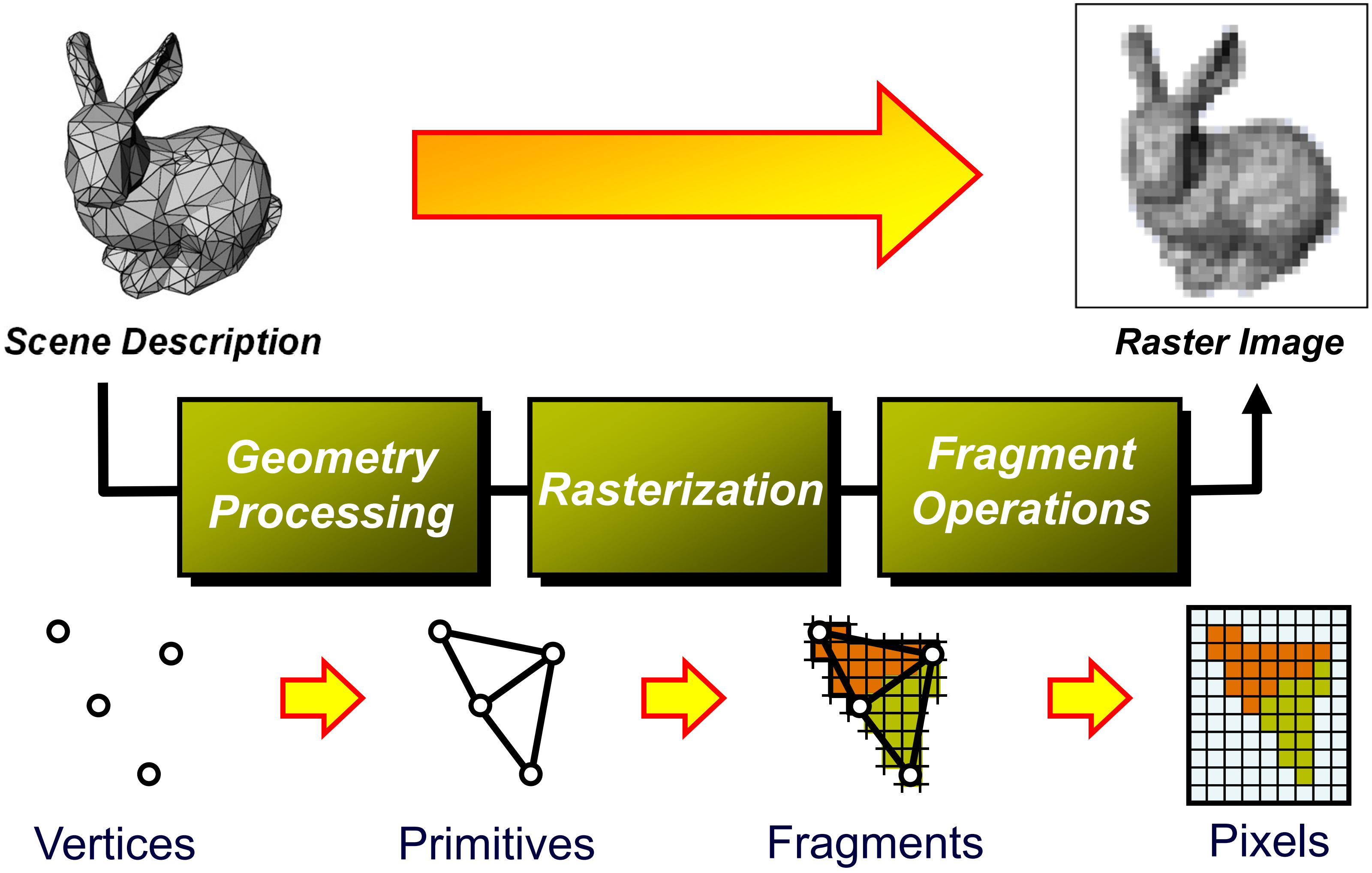
Fragments



Pixels (in an image)

Courtesy Kayvon Fatahalian, CMU

Graphics Pipeline



Scene Description

Raster Image

Geometry Processing

Rasterization

Fragment Operations

Vertices

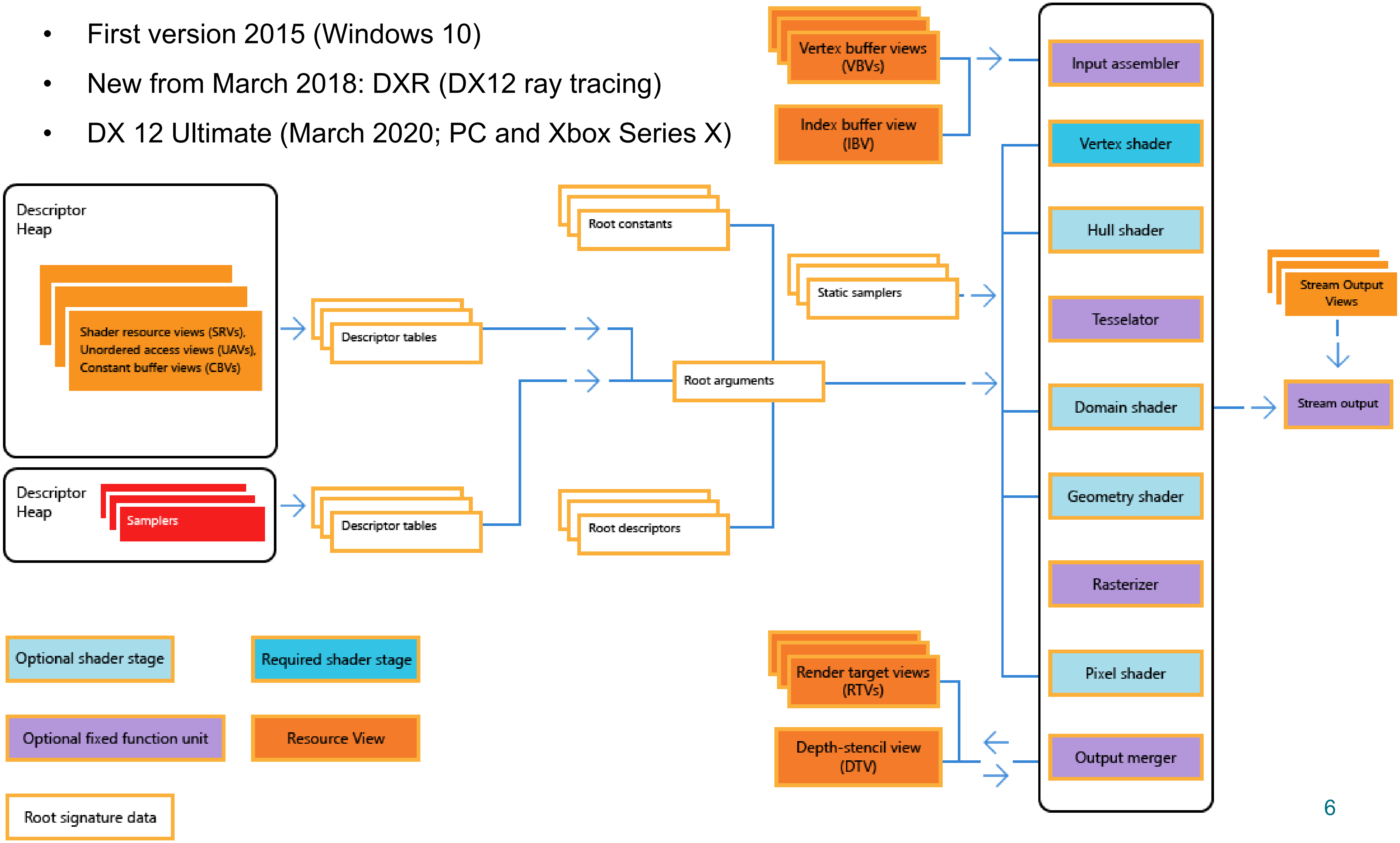
Primitives

Fragments

Pixels

Direct3D 12 Traditional Geometry Pipeline

- First version 2015 (Windows 10)
- New from March 2018: DXR (DX12 ray tracing)
- DX 12 Ultimate (March 2020; PC and Xbox Series X)



Descriptor Heap

Shader resource views (SRVs), Unordered access views (UAVs), Constant buffer views (CBVs)

Descriptor Heap

Samplers

Descriptor tables

Descriptor tables

Root constants

Root arguments

Root descriptors

Static samplers

Vertex buffer views (VBVs)

Index buffer view (IBV)

Input assembler

Vertex shader

Hull shader

Tesselator

Domain shader

Geometry shader

Rasterizer

Pixel shader

Output merger

Stream Output Views

Stream output

Render target views (RTVs)

Depth-stencil view (DTV)

Optional shader stage

Required shader stage

Optional fixed function unit

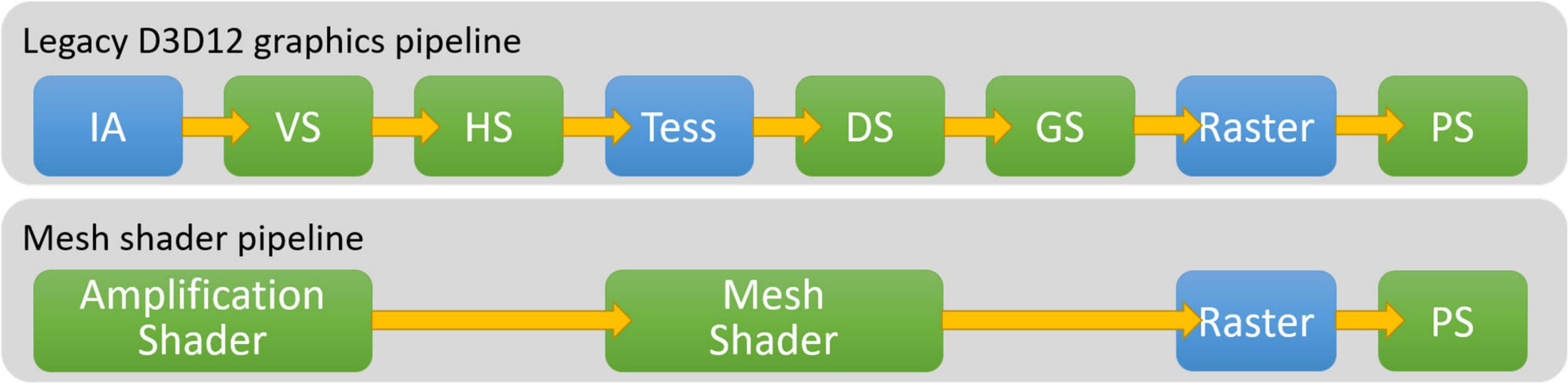
Resource View

Root signature data

Direct3D 12 Mesh Shader Pipeline

Reinventing the Geometry Pipeline

- Mesh and amplification shaders: new high-performance geometry pipeline based on compute shaders (DX 12 Ultimate / feature level 12.2)
- Compute shader-style replacement of IA/VS/HS/Tess/DS/GS



Legacy D3D12 graphics pipeline

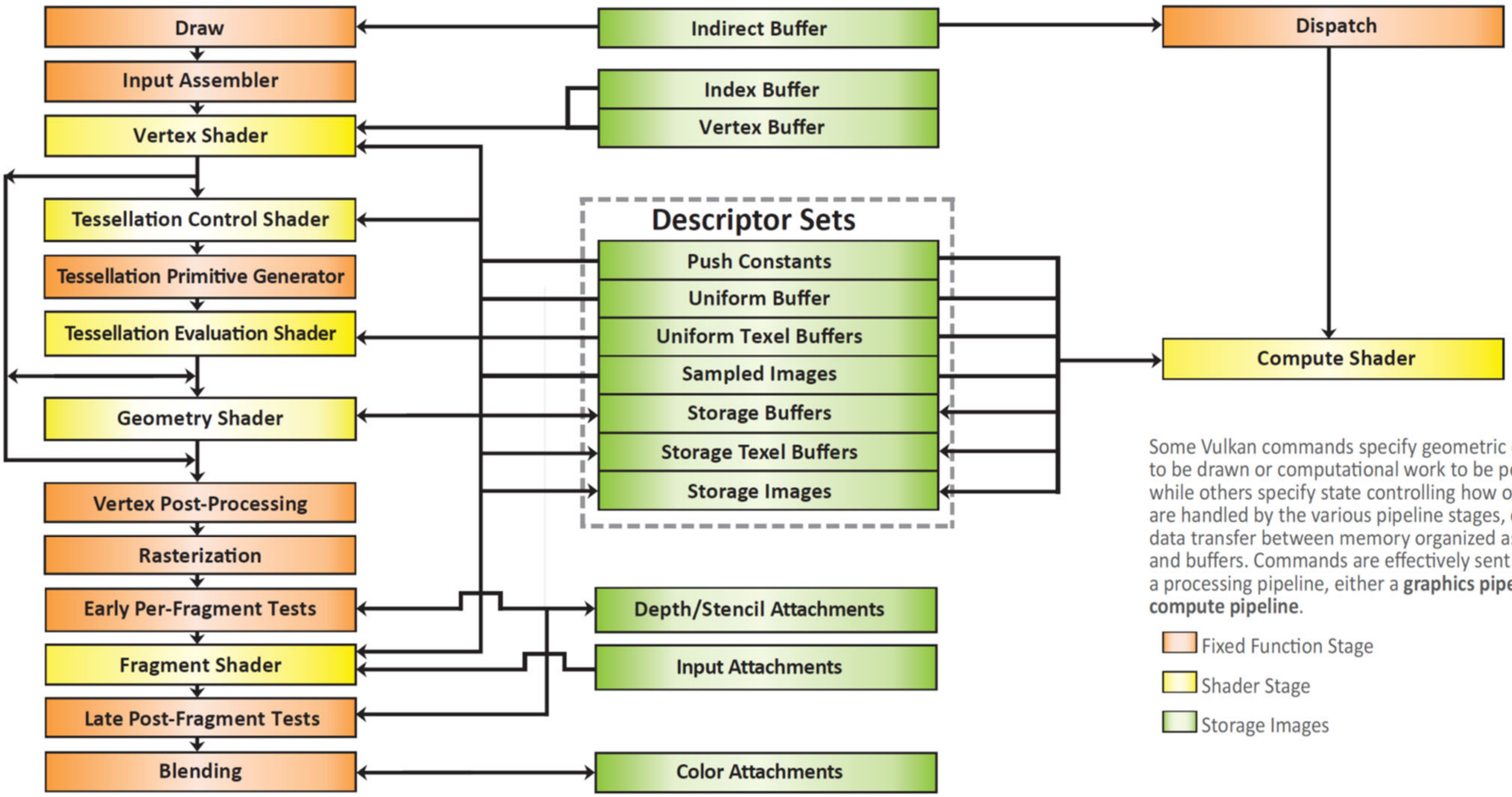
IA → VS → HS → Tess → DS → GS → Raster → PS

Mesh shader pipeline

Amplification Shader → Mesh Shader → Raster → PS

See talk by Shawn Hargreaves: `https://www.youtube.com/watch?v=CFXKTXtil34`

Vulkan (1.3)



Draw
Input Assembler
Vertex Shader
Tessellation Control Shader
Tessellation Primitive Generator
Tessellation Evaluation Shader
Geometry Shader
Vertex Post-Processing
Rasterization
Early Per-Fragment Tests
Fragment Shader
Late Post-Fragment Tests
Blending

Indirect Buffer
Index Buffer
Vertex Buffer

Descriptor Sets
Push Constants
Uniform Buffer
Uniform Texel Buffers
Sampled Images
Storage Buffers
Storage Texel Buffers
Storage Images

Depth/Stencil Attachments
Input Attachments
Color Attachments

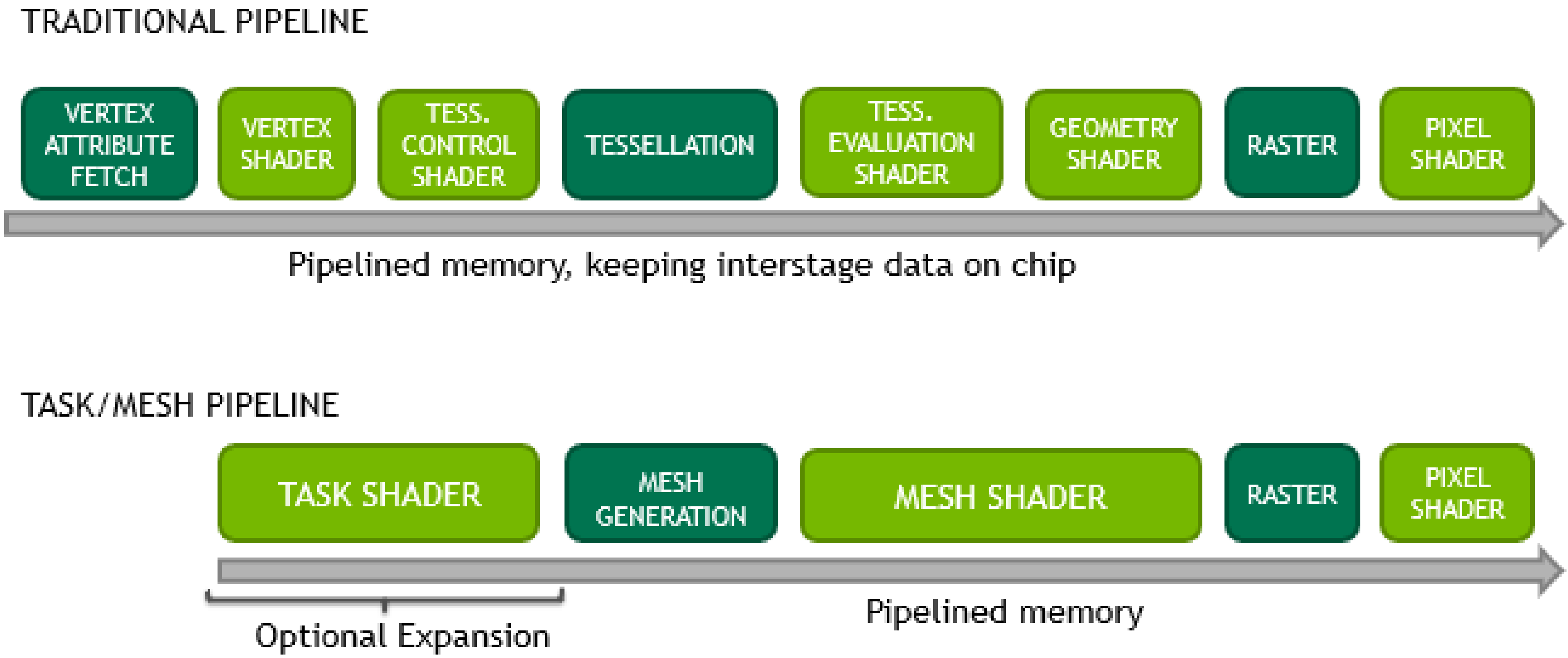
Dispatch
Compute Shader

Some Vulkan commands specify geometric objects to be drawn or computational work to be performed, while others specify state controlling how objects are handled by the various pipeline stages, or control data transfer between memory organized as images and buffers. Commands are effectively sent through a processing pipeline, either a **graphics pipeline** or a **compute pipeline**.

- 🟧 Fixed Function Stage
- 🟨 Shader Stage
- 🟩 Storage Images

Vulkan (1.3)

- Mesh and task shaders: new high-performance geometry pipeline based on compute shaders
  (Mesh and task shaders also available as OpenGL 4.5/4.6 extension: `GL_NV_mesh_shader`)



TRADITIONAL PIPELINE

VERTEX ATTRIBUTE FETCH → VERTEX SHADER → TESS. CONTROL SHADER → TESSELLATION → TESS. EVALUATION SHADER → GEOMETRY SHADER → RASTER → PIXEL SHADER

Pipelined memory, keeping interstage data on chip

TASK/MESH PIPELINE

TASK SHADER → MESH GENERATION → MESH SHADER → RASTER → PIXEL SHADER

Optional Expansion

Pipelined memory

vulkan.org
github.com/KhronosGroup/Vulkan-Guide
https://www.khronos.org/blog/mesh-shading-for-vulkan

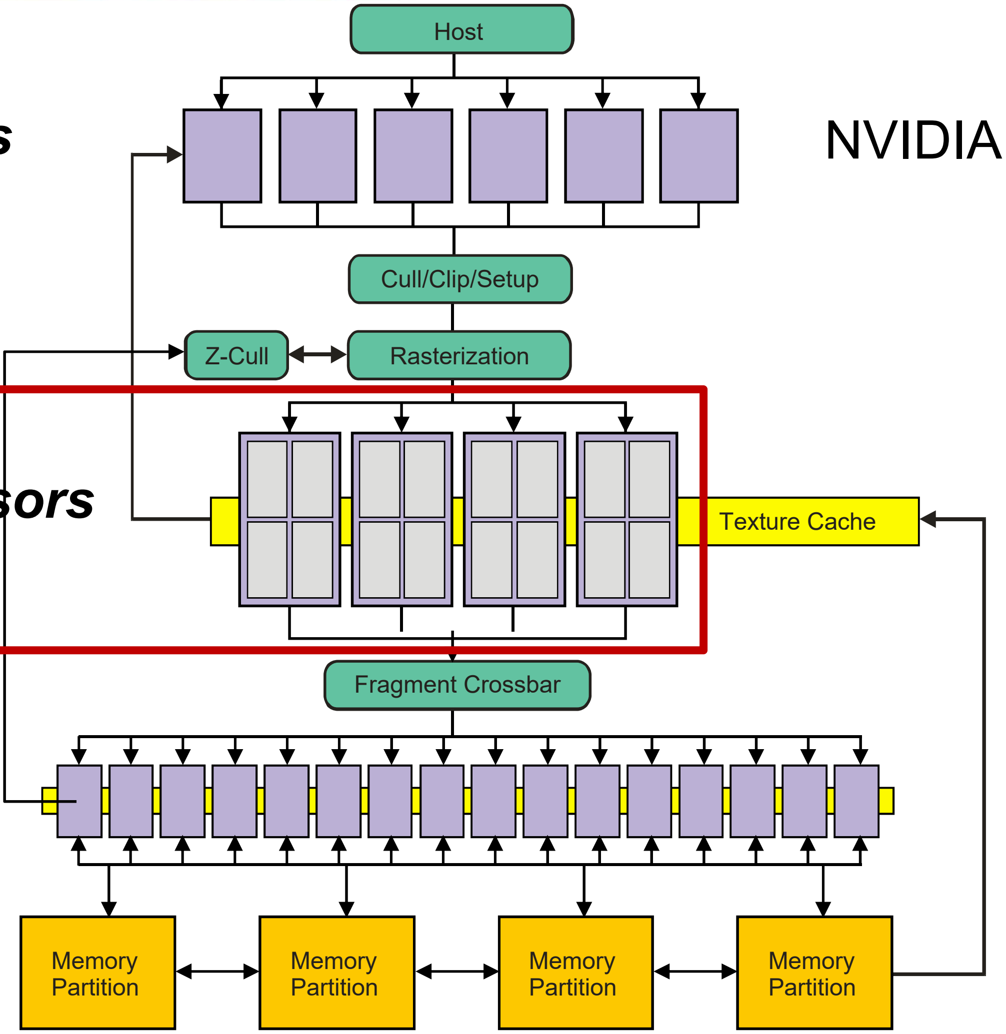
GPU Architecture

GPU Structure Before Unified Shaders

Vertex Processors

Fragment Processors

Memory Access
Z-Compare and
Blending (ROPs)



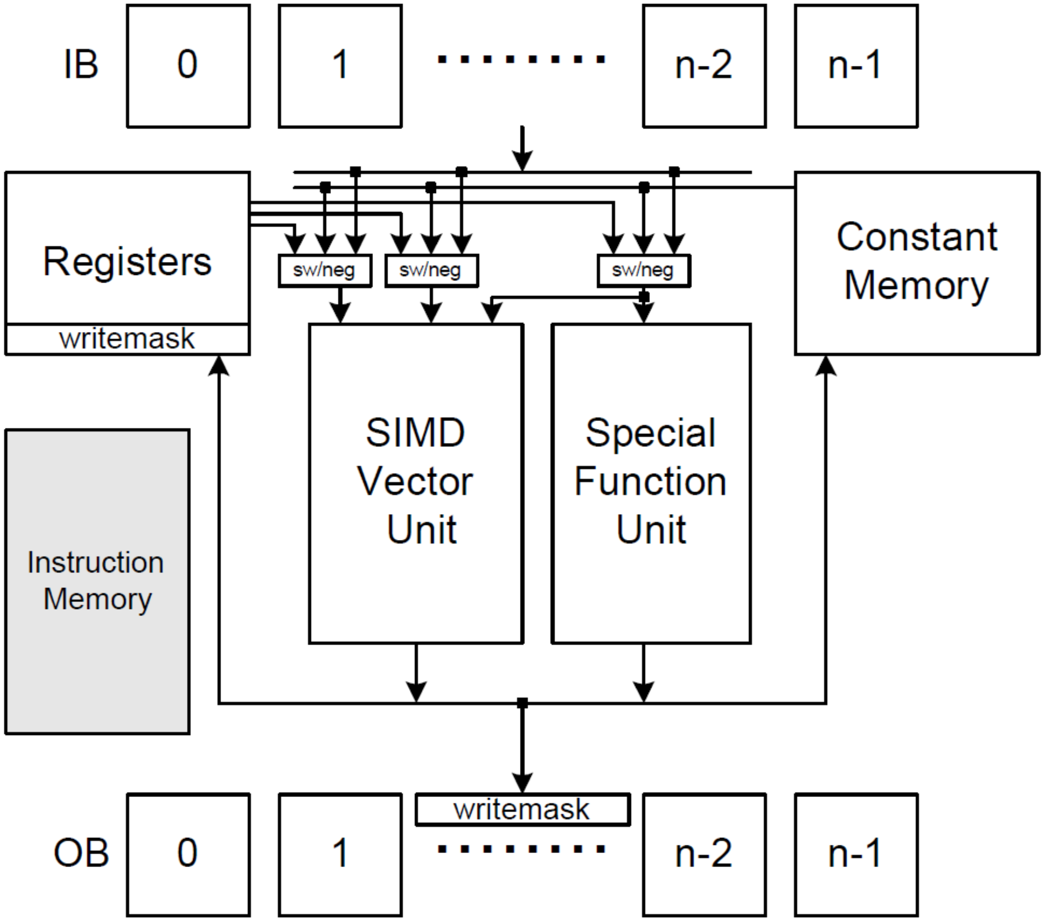
NVIDIA Geforce 6/7
(NV40)
2004, 2005

Legacy Vertex Shading Unit (1)

Geforce 3 (NV20), 2001

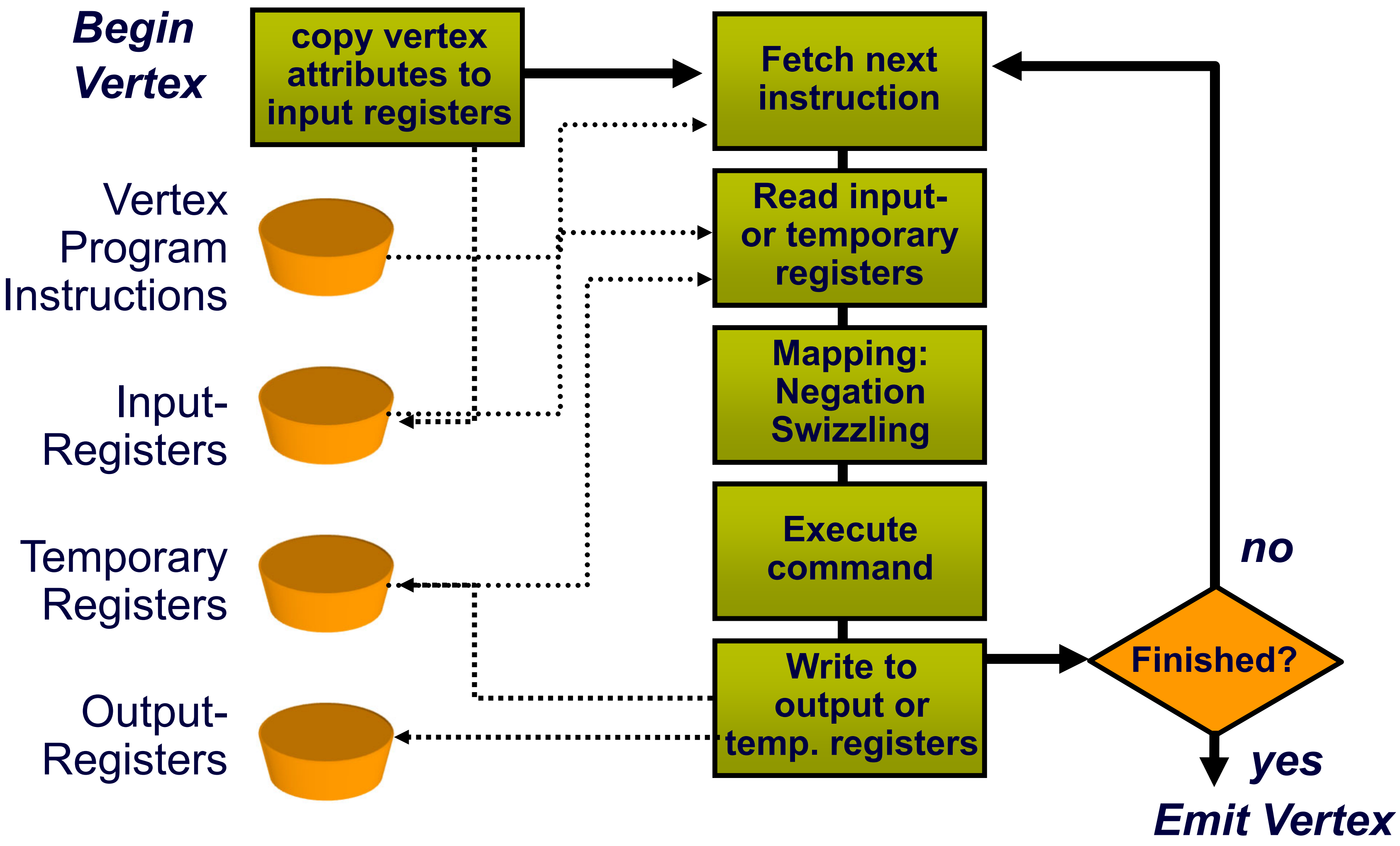
- floating point 4-vector vertex engine

- still very instructive for understanding GPUs in general



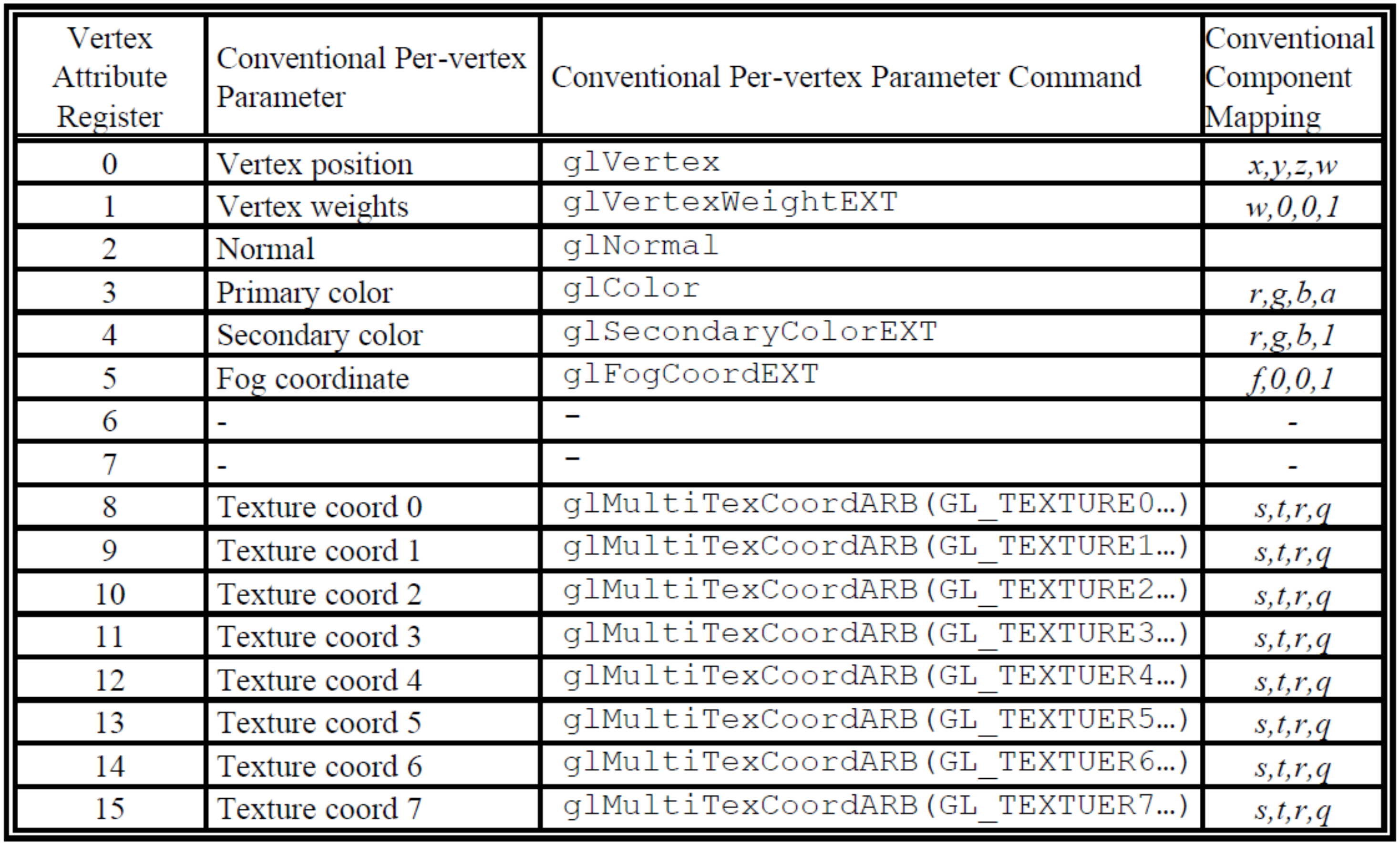
Lindholm et al., A User-Programmable Vertex Engine, SIGGRAPH 2001

Vertex Processor



Legacy Vertex Shading Unit (2)

Input attributes



Vertex Attribute Register	Conventional Per-vertex Parameter	Conventional Per-vertex Parameter Command	Conventional Component Mapping
0	Vertex position	`glVertex`	*x,y,z,w*
1	Vertex weights	`glVertexWeightEXT`	*w,0,0,1*
2	Normal	`glNormal`	
3	Primary color	`glColor`	*r,g,b,a*
4	Secondary color	`glSecondaryColorEXT`	*r,g,b,1*
5	Fog coordinate	`glFogCoordEXT`	*f,0,0,1*
6	-	–	-
7	-	–	-
8	Texture coord 0	`glMultiTexCoordARB(GL_TEXTURE0…)`	*s,t,r,q*
9	Texture coord 1	`glMultiTexCoordARB(GL_TEXTURE1…)`	*s,t,r,q*
10	Texture coord 2	`glMultiTexCoordARB(GL_TEXTURE2…)`	*s,t,r,q*
11	Texture coord 3	`glMultiTexCoordARB(GL_TEXTURE3…)`	*s,t,r,q*
12	Texture coord 4	`glMultiTexCoordARB(GL_TEXTUER4…)`	*s,t,r,q*
13	Texture coord 5	`glMultiTexCoordARB(GL_TEXTUER5…)`	*s,t,r,q*
14	Texture coord 6	`glMultiTexCoordARB(GL_TEXTUER6…)`	*s,t,r,q*
15	Texture coord 7	`glMultiTexCoordARB(GL_TEXTUER7…)`	*s,t,r,q*

Code examples

```
DP4 o[HPOS].x, c[0], v[OPOS];
```

```
MUL R1, R0.zxyw, R2.yzxw ;
MAD R1, R0.yzxw, R2.zxyw, -R1;
```

swizzling!

Legacy Vertex Shading Unit (3)

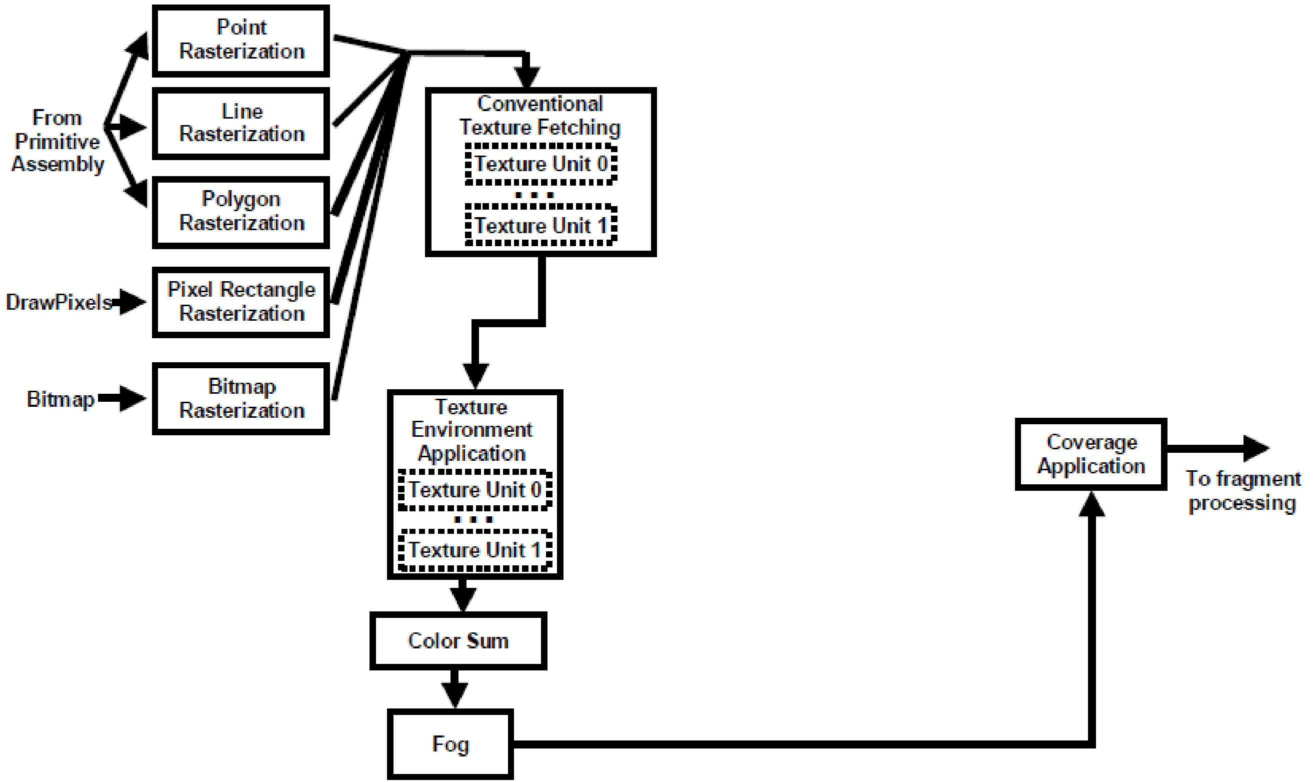
Vector instruction set, very few instructions; **no branching** yet!

OpCode	Full Name	Description
MOV	Move	vector -> vector
MUL	Multiply	vector -> vector
ADD	Add	vector -> vector
MAD	Multiply and add	vector -> vector
DST	Distance	vector -> vector
MIN	Minimum	vector -> vector
MAX	Maximum	vector -> vector
SLT	Set on less than	vector -> vector
SGE	Set on greater or equal	vector -> vector
RCP	Reciprocal	scalar-> replicated scalar
RSQ	Reciprocal square root	scalar-> replicated scalar
DP3	3 term dot product	vector-> replicated scalar
DP4	4 term dot product	vector-> replicated scalar
LOG	Log base 2	miscellaneous
EXP	Exp base 2	miscellaneous
LIT	Phong lighting	miscellaneous
ARL	Address register load	miscellaneous

Fast Forward to Programm. Fragment Shading

Core OpenGL Fragment Texturing & Coloring

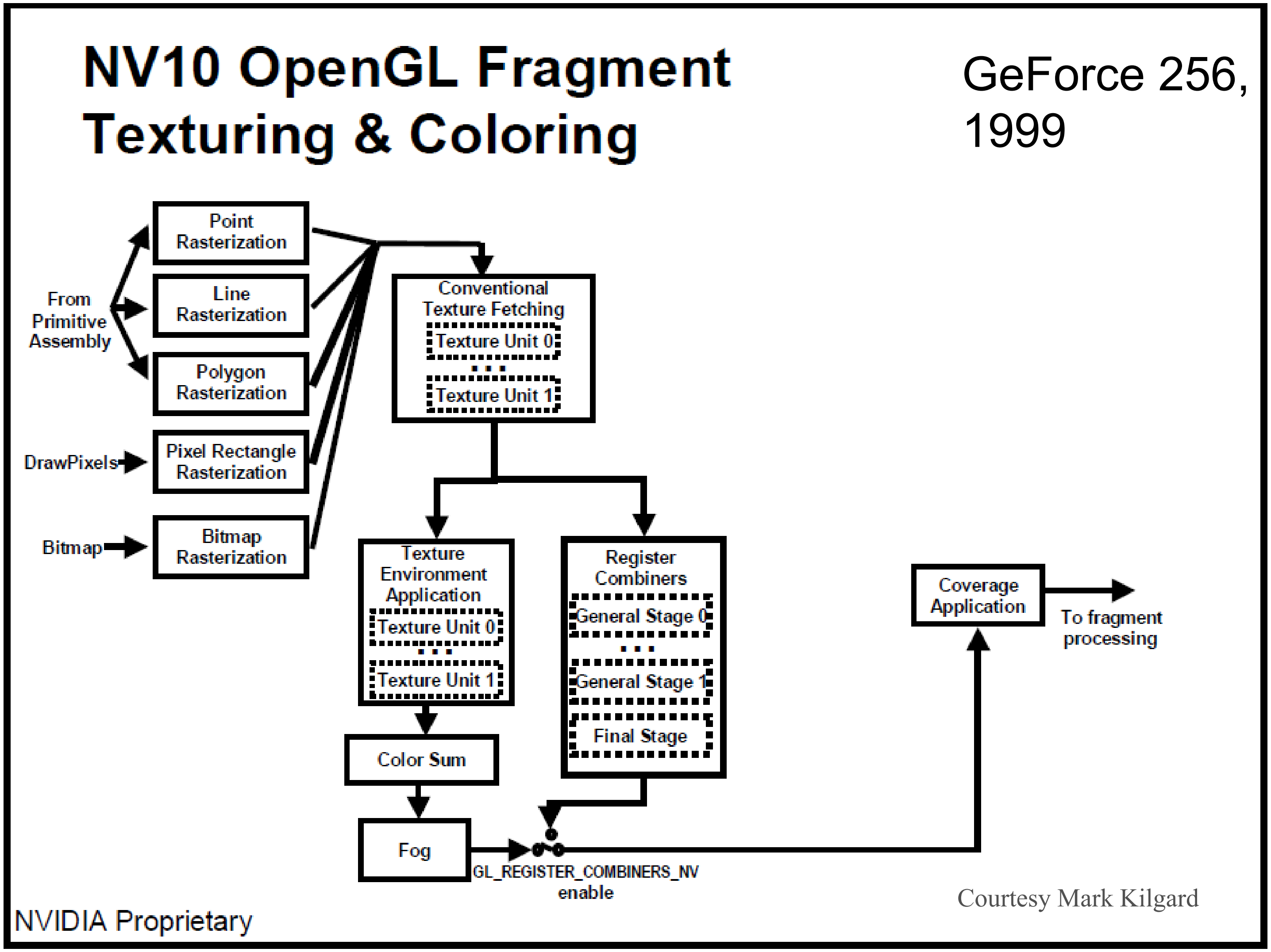
< 1999



Courtesy Mark Kilgard

NVIDIA Proprietary

Fast Forward to Programm. Fragment Shading



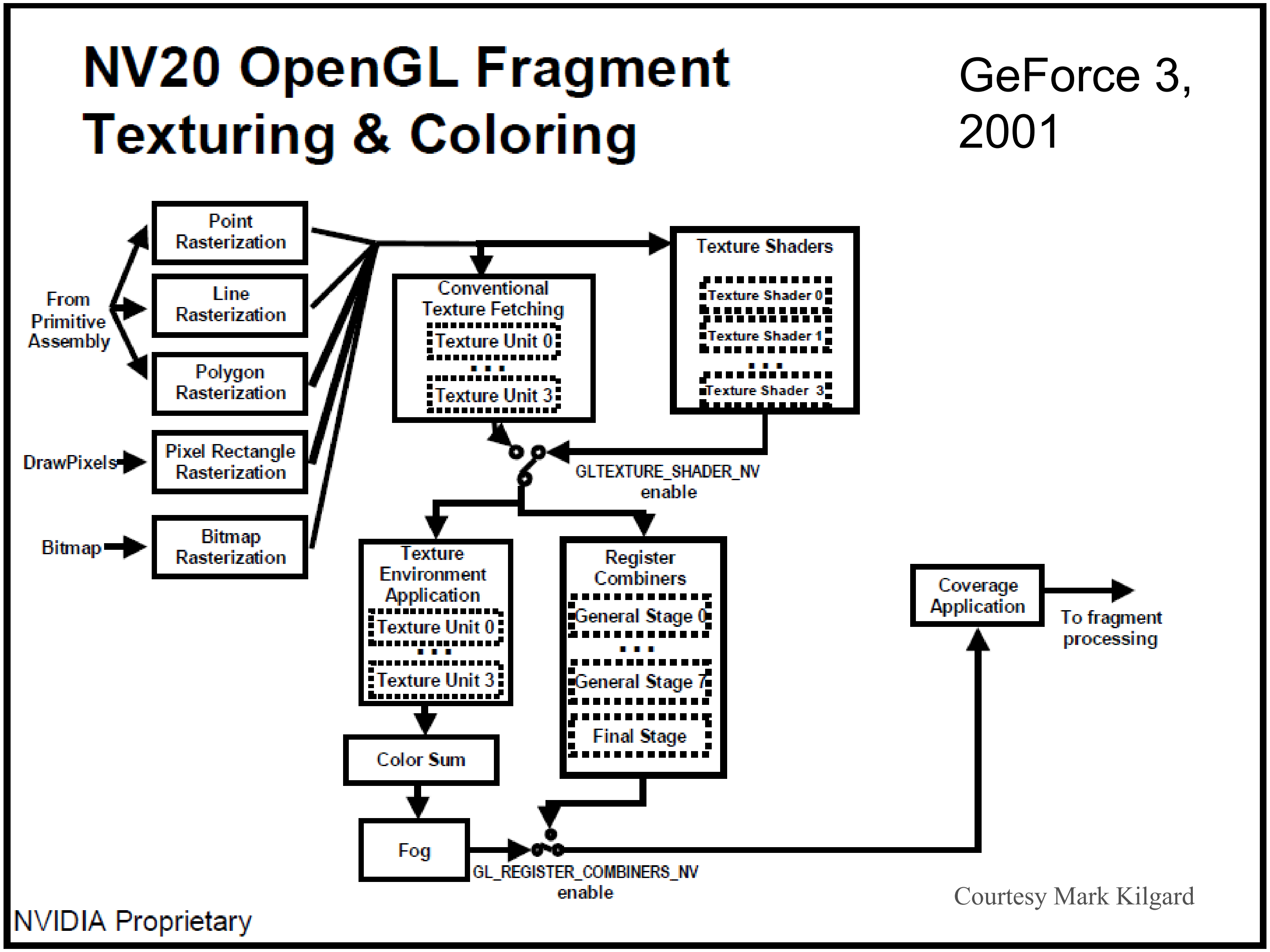
NV10 OpenGL Fragment Texturing & Coloring

GeForce 256, 1999

NVIDIA Proprietary

Courtesy Mark Kilgard

Fast Forward to Programm. Fragment Shading



NV20 OpenGL Fragment Texturing & Coloring

GeForce 3, 2001

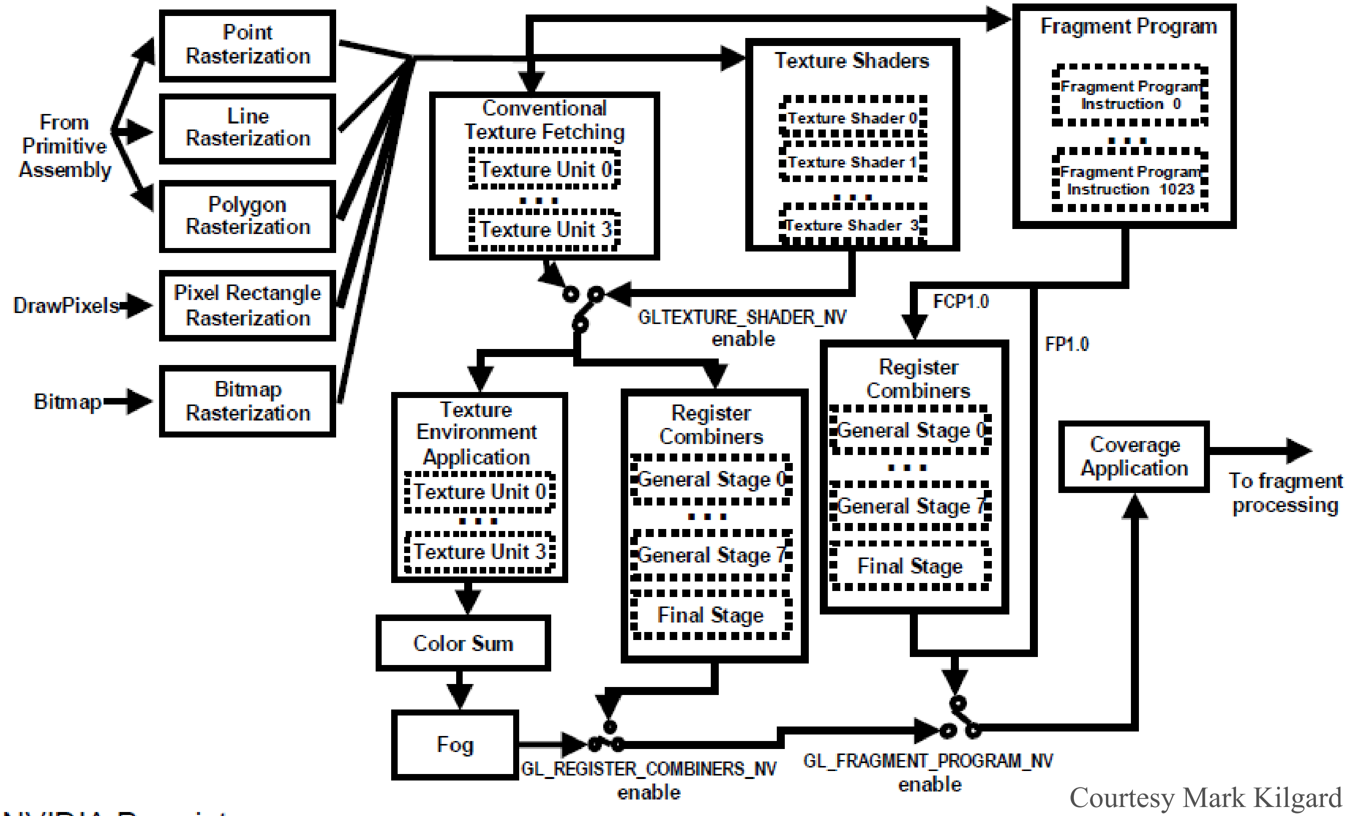
NVIDIA Proprietary

Courtesy Mark Kilgard

Fast Forward to Programm. Fragment Shading

NV30 OpenGL Fragment Texturing & Coloring

GeForce FX (5), 2003



Courtesy Mark Kilgard

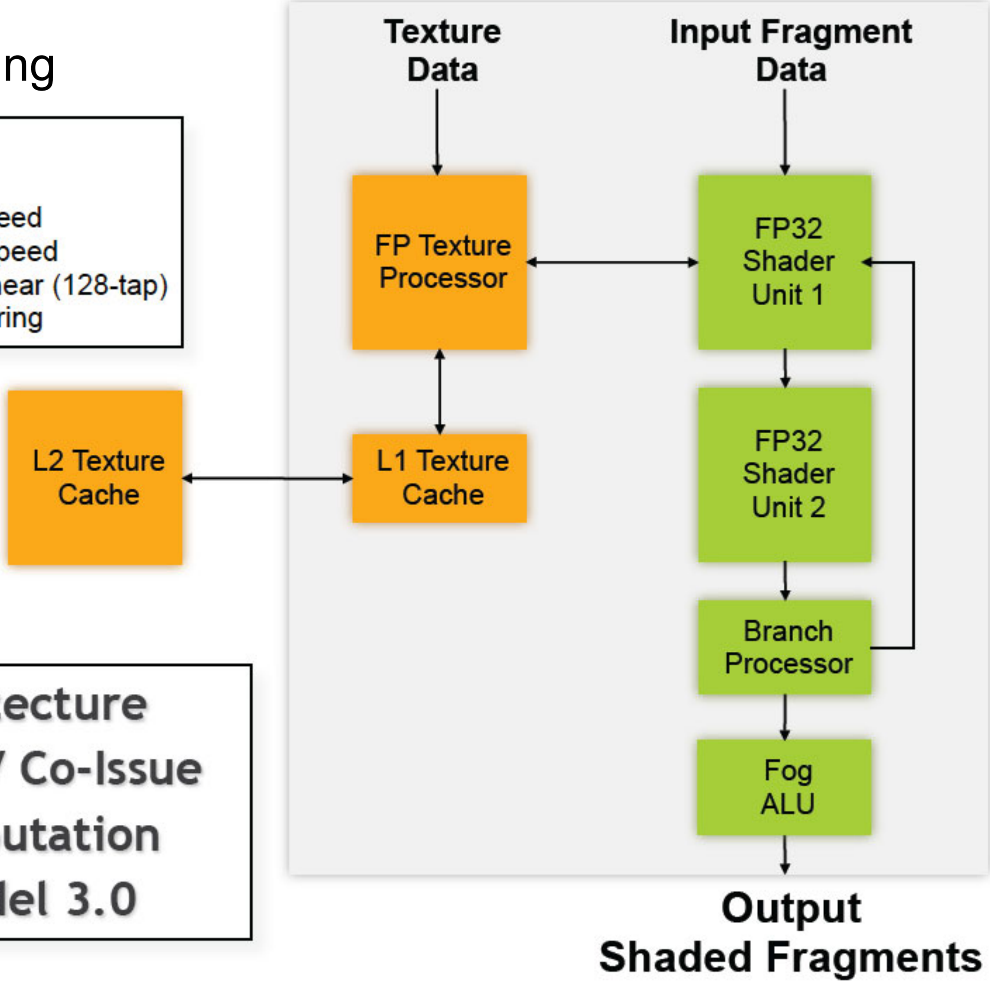
NVIDIA Proprietary

Legacy Fragment Shading Unit (1)

GeForce 6 (NV40), 2004

- dynamic branching

Texture Filter
Bi / Tri / Aniso
1 texture @ full speed
4-tap filter @ full speed
16:1 Aniso w/ Trilinear (128-tap)
FP16 Texture Filtering



Shader Unit 1
4 FP Ops / pixel
Dual/Co-Issue
Texture Address Calc
Free fp16 normalize
+ mini ALU

Shader Unit 2
4 FP Ops / pixel
Dual/Co-Issue
+ mini ALU

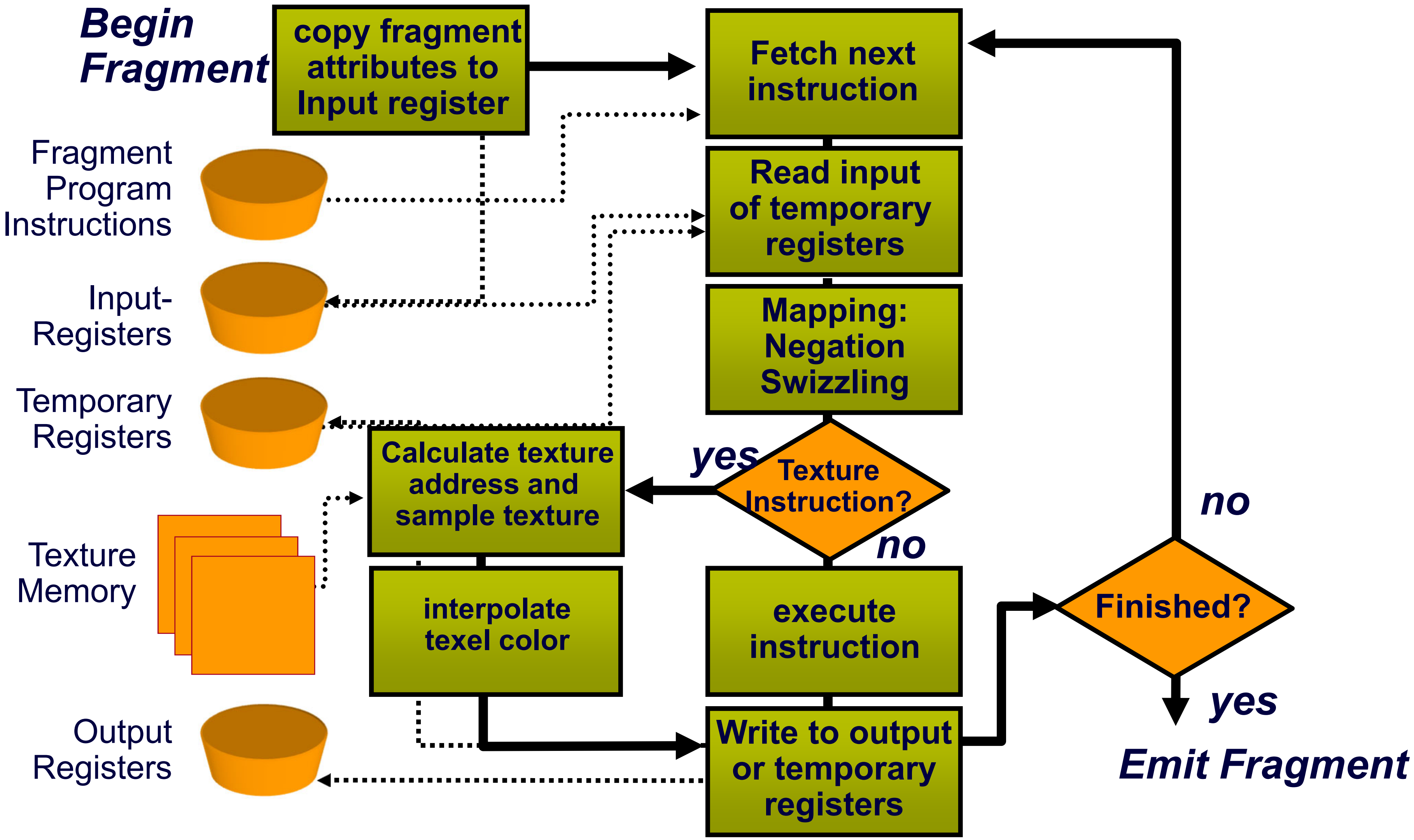
SIMD Architecture
Dual Issue / Co-Issue
FP32 Computation
Shader Model 3.0

Legacy Fragment Shading Unit (2)

Example code

```
!!ARBfp1.0

ATTRIB unit_tc = fragment.texcoord[ 0 ];
PARAM  mvp_inv[]  = { state.matrix.mvp.inverse };
PARAM  constants  = {0, 0.999, 1, 2};

TEMP pos_win, temp;

TEX pos_win.z, unit_tc, texture[ 1 ], 2D;

ADD pos_win.w, constants.y, -pos_win.z;
KIL pos_win.w;

MOV result.color.w, pos_win.z;

MOV pos_win.xyw, unit_tc;
MAD pos_win.xyz, pos_win, constants.a, -constants.b;

DP4 temp.w, mvp_inv[ 3 ], pos_win;
RCP temp.w, temp.w;

MUL pos_win, pos_win, temp.w;

DP4 result.color.x, mvp_inv[ 0 ], pos_win;
DP4 result.color.y, mvp_inv[ 1 ], pos_win;
DP4 result.color.z, mvp_inv[ 2 ], pos_win;

END
```

Fragment Processor



A diffuse reflectance shader

```
sampler mySamp;
Texture2D<float3> myTex;
float3 lightDir;

float4 diffuseShader(float3 norm, float2 uv)
{
  float3 kd;
  kd = myTex.Sample(mySamp, uv);
  kd *= clamp( dot(lightDir, norm), 0.0, 1.0);
  return float4(kd, 1.0);
}
```

Independent, but no explicit parallelism

Compile shader

1 unshaded fragment input record

```
sampler mySamp;
Texture2D<float3> myTex;
float3 lightDir;

float4 diffuseShader(float3 norm, float2 uv)
{
  float3 kd;
  kd = myTex.Sample(mySamp, uv);
  kd *= clamp ( dot(lightDir, norm), 0.0, 1.0);
  return float4(kd, 1.0);
}
```

```
<diffuseShader>:
sample r0, v4, t0, s0
mul  r3, v0, cb0[0]
madd r3, v1, cb0[1], r3
madd r3, v2, cb0[2], r3
clmp r3, r3, l(0.0), l(1.0)
mul  o0, r0, r3
mul  o1, r1, r3
mul  o2, r2, r3
mov  o3, l(1.0)
```

1 shaded fragment output record

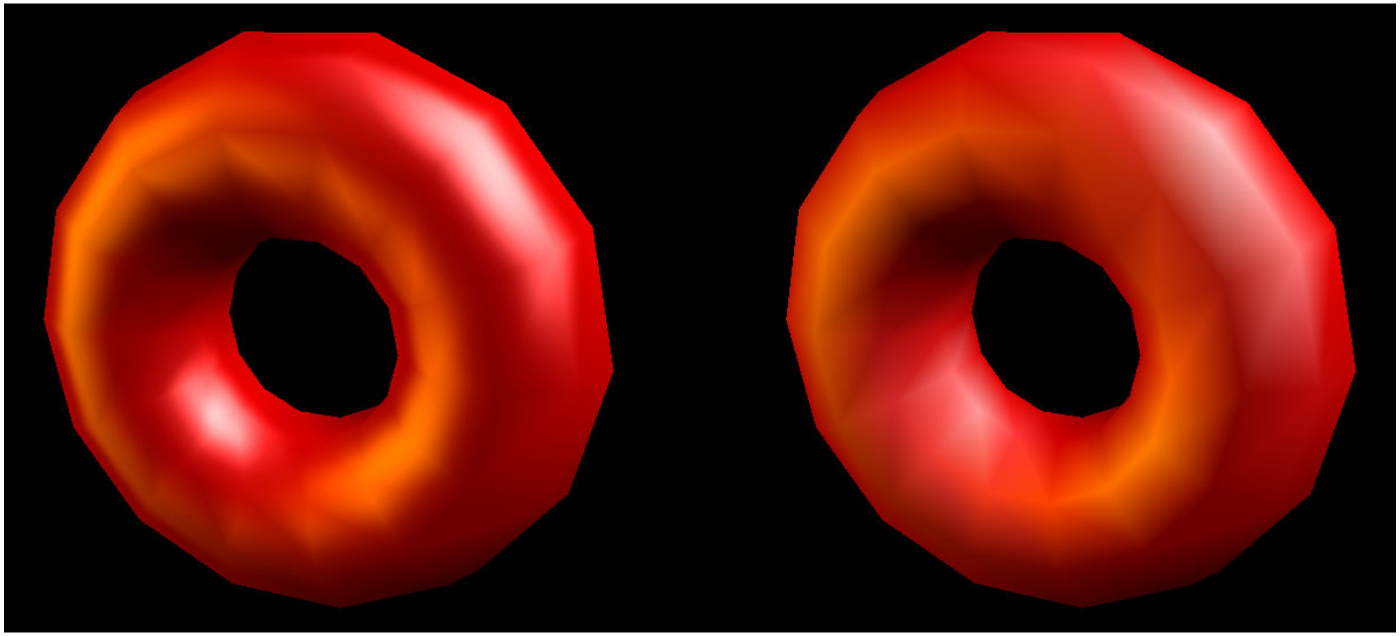
Per-Pixel(Fragment) Lighting

Simulating smooth surfaces by calculating illumination for each fragment

Example: specular highlights (Phong illumination/shading)

Phong shading:
per-fragment evaluation

Gouraud shading:
linear interpolation from vertices



Per-Pixel Phong Lighting (Cg)

```
void main(float4 position   : TEXCOORD0,
          float3 normal     : TEXCOORD1,

      out float4 oColor      : COLOR,

  uniform float3 ambientCol,
  uniform float3 lightCol,
  uniform float3 lightPos,
  uniform float3 eyePos,
  uniform float3 Ka,
  uniform float3 Kd,
  uniform float3 Ks,
  uniform float   shiny)
{
```

Per-Pixel Phong Lighting (Cg)

```
  float3 P = position.xyz;
  float3 N = normal;
  float3 V = normalize(eyePosition - P);
  float3 H = normalize(L + V);

  float3 ambient = Ka * ambientCol;

  float3 L         = normalize(lightPos - P);
  float  diffLight = max(dot(L, N), 0);
  float3 diffuse   = Kd * lightCol * diffLight;

  float specLight = pow(max(dot(H, N), 0), shiny);
  float3 specular = Ks * lightCol * specLight;

  oColor.xyz = ambient + diffuse + specular;
  oColor.w = 1;
}
```

Thank you.