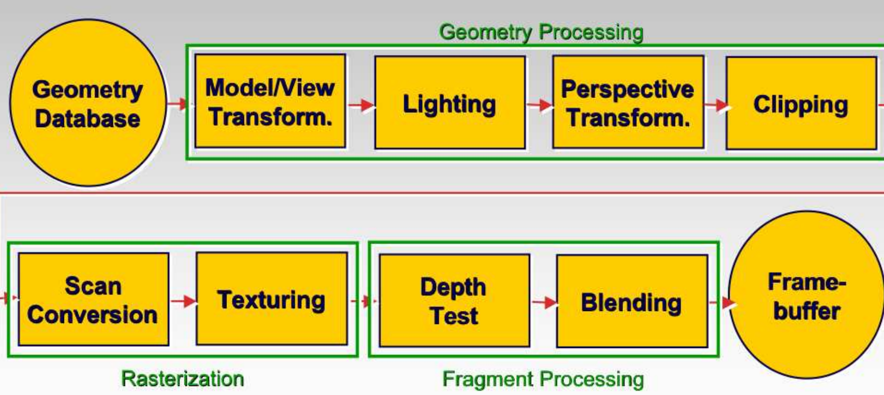
# Modern GPU Architectures

***CPSC 314***



## The Rendering Pipeline



## Rendering Pipeline

***So far:***

- Have discussed rendering pipeline as a specific set of stages with **fixed functionality**

***Modern graphics hardware is more flexible:***

- Programmable "vertex shaders" replace several geometry processing stages
- Programmable "fragment/pixel shaders" replace texture mapping stage
- Hardware with these features now called 'Graphics Processing Unit" (GPU)



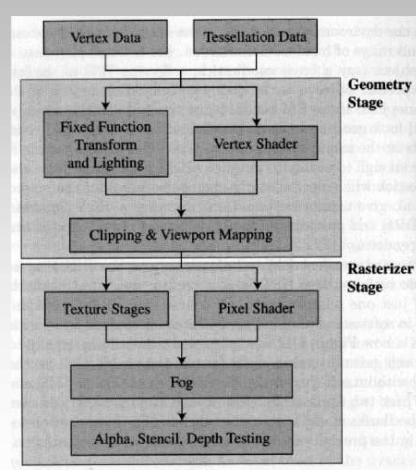
## Modified Pipeline

***Vertex shader***

- Replaces model/view, lighting, and perspective
- Have to implement these yourself
- But can also implement much more

***Fragment/pixel shader***

- Replaces texture mapping
- Fragment shader must do texturing
- But can do other things



## Vertex Shader Motivation

***Hardware "transform&lighting:***

- I.e. hardware geometry processing
- Was mandated by need for higher performance in the late 90s
- Previously, geometry processing was done on CPU, except for very high end machines
- Downside: now limited functionality due to fixed function hardware



## Vertex Shaders

***Programmability required for more complicated effects***

- The tasks that come before transformation vary widely
- Putting every possible lighting equation in hardware is impractical
- Implementing programmable hardware has advantages over CPU implementations
  - *Better performance due to massively parallel implementations*
  - *Lower bandwidth requirements (geometry can be cached on GPU)*

# Vertex Program Properties

***Run for every vertex, independently***

- Access to all per-vertex properties
  - *Position, color, normal, texture coords, other custom properties*
- Access to read/write registers for temporary results
  - *Value is reset for every vertex*
  - *I.e. cannot pass information from one vertex to the next*
- Access to read-only registers
  - *Global variables, like ligt position, transformation matrices*
- Write output to a specific register for the resulting color



# IO for Vertex Shaders (Circa 2001)

- Newer hardware has more instructions, more memory

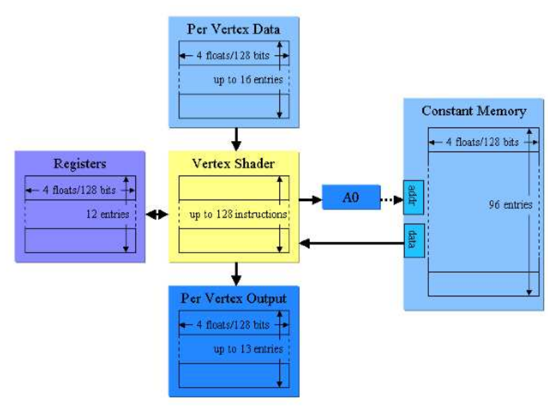



**Figure 2: The inputs and outputs of vertex shaders. Arrows indicate read-only, write-only, or read-write.**

## Vertex Shaders/Programs

***Concept:***

- Programmable pipeline stage
  - *Floating-point operations on 4 vectors*
    - Points, vectors, and colors!
- Replace all of
  - *Model/View Transformation*
  - *Lighting*
  - *Perspective projection*



## Vertex Shaders/Programs

***Concept:***

- A little assembly-style program is executed on every individual vertex
- It sees:
  - *Vertex attributes that change per vertex:*
    - position, color, texture coordinates…
  - *Registers that are constant for all vertices (changes are expensive):*
    - Matrices, light position and color, …
  - *Temporary registers*
  - *Output registers for position, color, tex coords…*

## Vertex Programs – Instruction Set

### *Arithmetic Operations on 4-vectors:*

- ADD, MUL, MAD, MIN, MAX, DP3, DP4

### *Operations on Scalars*

- RCP (1/x), RSQ (1/√x), EXP, LOG

### *Specialty Instructions*

- DST (distance: computes length of vector)
- LIT (quadratic falloff term for lighting)

### *Later generation:*

- Loops and conditional jumps



## Vertex Programs – Applications

### *What can they be used for?*

- Can implement all of the stages they replace, but can allocate resources more dynamically
  - *E.g. transforming a vector by a matrix requires 4 dot products*
  - *Enough memory for 24 matrices*
  - *Can arbitrarily deform objects*
    - Procedural freeform deformations
  - *Lots of other applications*
    - Shading
    - Refraction
    - …

## Vertex Programming Example

### *Example (from Stephen Cheney)*

- Morph between a cube and sphere while doing lighting with a directional light source (gray output)
- Cube position and normal in attributes (input) 0,1
- Sphere position and normal in attributes 2,3
- Blend factor in attribute 15
- Inverse transpose model/view matrix in constants 12-14
  - *Used to transform normal vectors into eye space*
- Composite matrix is in 4-7
  - *Used to convert from object to homogeneous screen space*
- Light dir in 20, half-angle vector in 22, specular power, ambient, diffuse and specular coefficients all in 21



## Vertex Program Example

**#blend normal and position**

**# v= $\alpha v_1+(1-\alpha)v_2 = \alpha(v_1-v_2)+ v_2$**

```
MOV R3, v[3] ;
MOV R5, v[2] ;
ADD R8, v[1], -R3 ;
ADD R6, v[0], -R5 ;
MAD R8, v[15].x, R8, R3
MAD R6, v[15].x, R6, R5 ;
```

**# transform normal to eye space**

```
DP3 R9.x, R8, c[12] ;
DP3 R9.y, R8, c[13] ;
DP3 R9.z, R8, c[14] ;
```

**# transform position and output**

```
DP4 o[HPOS].x, R6, c[4] ;
DP4 o[HPOS].y, R6, c[5] ;
DP4 o[HPOS].z, R6, c[6] ;
DP4 o[HPOS].w, R6, c[7] ;
```

**# normalize normal**

```
DP3 R9.w, R9, R9 ;
RSQ R9.w, R9.w ;
MUL R9, R9.w, R9 ;
```

**# apply lighting and output color**

```
DP3 R0.x, R9, c[20] ;
DP3 R0.y, R9, c[22] ;
MOV R0.zw, c[21] ;
LIT R1, R0 ;
DP3 o[COL0], c[21], R1 ;
```

## Skinning

***Example was one case of general problem:***

- Want to have natural looking joints on human and animal limbs
- Requires deforming geometry, e.g.
  - *Single triangle mesh modeling both upper and lower arm*
  - *If arm is bent, upper and lower arm remain more or less in the same shape, but transition zone at elbow joint needs to deform*



## Skinning

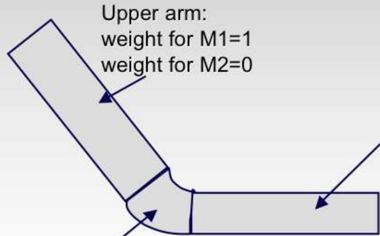
***Approach:***

- Multiple transformation matrices
  - *There is more than one model/view matrix stack, e.g.*
    - one for model/view matrix for lower arm, and
    - one for model/view matrix for upper arm
  - *Every vertex is transformed by both matrices*
    - Yields 2 different transformed vertex positions!
  - *Use per-vertex blending weights to interpolate between the two positions*

# Skinning

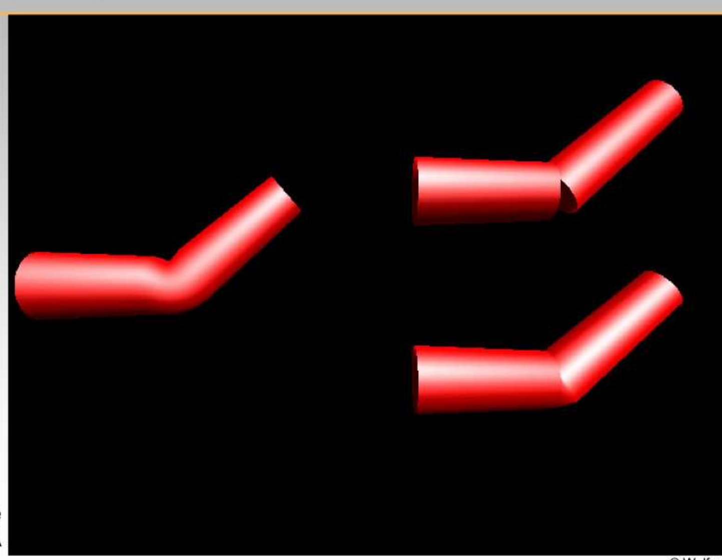
***Arm Example:***

- M1: matrix for upper arm
- M2: matrix for lower arm






# Skinning



Example by NVIDIA

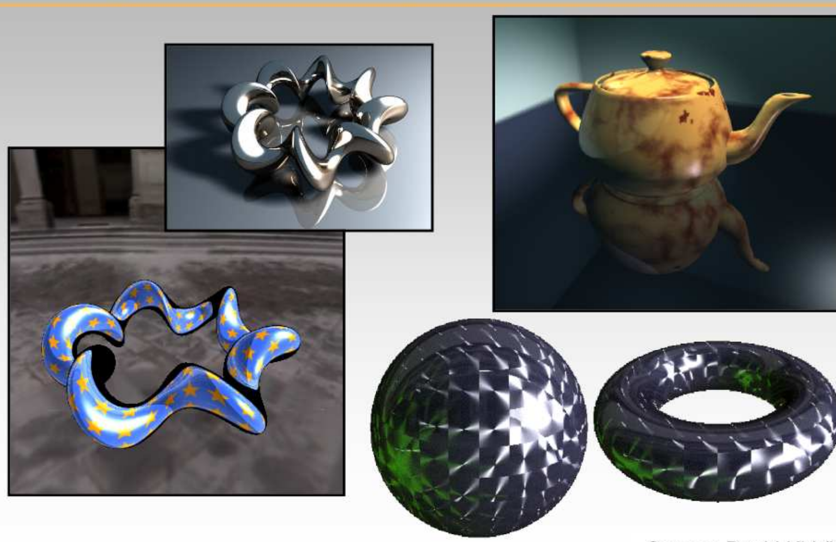
## Skinning

***In general:***

- Many different matrices make sense!
  - *EA facial animations: up to 70 different matrices ("bones")*
  - *Hardware supported:*
    - Number of transformations limited by available registers and max. instruction count of vertex programs
    - But dozens are possible today



## GeForce FX Fragment/Pixel Program Examples



Source: David Kirk/NVIDIA

## Fragment Shader Motivation

***The idea of per-fragment shaders have been around for a long time***

- Renderman is the best example, but not at all real time

***In a traditional pipeline, the only major per-pixel operation is texture mapping***

- All lighting, etc. is done in the vertex processing, *before* primitive assembly and rasterization
- In fact, a fragment is *only* screen position, color, and tex-coords

***What kind of shading interpolation does this restrict you to?***



## Fragment Shader Generic Structure

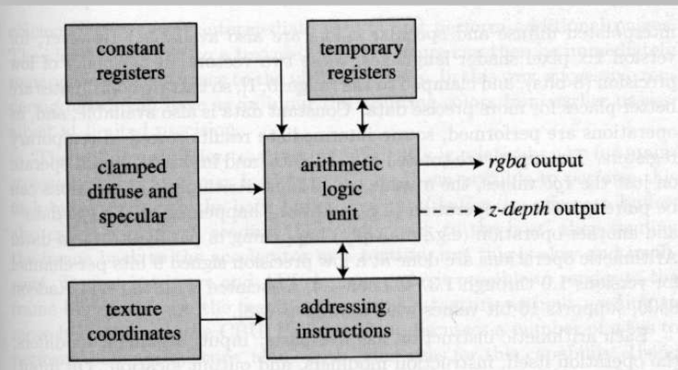



Figure 6.20. Generalized pixel shader. Variants in the pixel shader language primarily affect the way texture address instructions work, where temporary results can be stored, and whether the z-depth can be modified and output.

## Fragment Shaders

- *Fragment shaders* operate on fragments in place of the texturing hardware
  - *After rasterization, before any fragment tests or blending*
- Input: The fragment, with screen position, depth, color, and a set of texture coordinates
- Access to textures and some constant data and registers
- Compute RGBA values for the fragment, and depth
  - *Can also "kill "a fragment, that is throw it away*
- Two types of fragment shaders: register combiners (GeForce4) and fully programmable (GeForceFX, Radeon 9700)



## Fragment Shader Functionality

***At a minimum, we want to be able to do Phong interpolation***

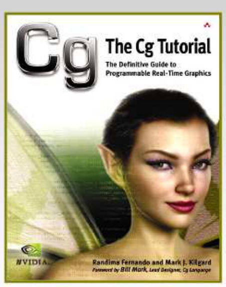
- How do you get normal vector info?
- How do you get the light?
- How do you get the specular color?
- How do you get the world position?

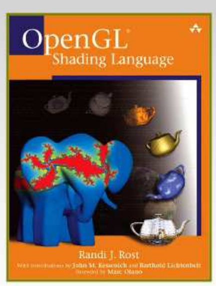
## Shading Languages

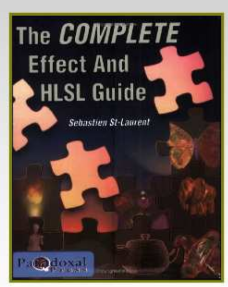
- Programming shading hardware is still a difficult process
  - *Akin to writing assembly language programs*
- Shading languages and accompanying compilers allow users to write shaders in high level languages
- Two examples: Microsoft's HLSL (part of DirectX 9) and Nvidia's Cg (compatable with HLSL)
- Renderman is the ultimate example, but it's not real time



## Shading Languages



## Cg

***Cg is a high-level language develped by NVIDIA***

- It looks like C or C++
- Actually a language and a runtime environment
  - *Can compile ahead of time, or compile on the fly*
  - *Why compile on the fly?*
- What it can do is tightly tied to the hardware
  - *How does it know which hardware, and how to use it?*



## Vertex Program Example

```
void C5E2v_fragmentLighting(float4 position : POSITION,
                            float3 normal   : NORMAL,

                        out float4 oPosition : POSITION,
                        out float3 objectPos : TEXCOORD0,
                        out float3 oNormal   : TEXCOORD1,

                    uniform float4x4 modelViewProj)
{
  oPosition = mul(modelViewProj, position);
  objectPos = position.xyz;
  oNormal = normal;
}
```

# Pixel Program Example

```
void C5E3f_basicLight(float4 position   : TEXCOORD0,
                      float3 normal     : TEXCOORD1,

                  out float4 color      : COLOR,

              uniform float3 globalAmbient,
              uniform float3 lightColor,
              uniform float3 lightPosition,
              uniform float3 eyePosition,
              uniform float3 Ke,
              uniform float3 Ka,
              uniform float3 Kd,
              uniform float3 Ks,
              uniform float  shininess)
{
  float3 P = position.xyz;
  float3 N = normalize(normal);

  // Compute the emissive term
  float3 emissive = Ke;

  // Compute the ambient term
  float3 ambient = Ka * globalAmbient;

  // Compute the diffuse term
  float3 L = normalize(lightPosition - P);
  float diffuseLight = max(dot(N, L), 0);
  float3 diffuse = Kd * lightColor * diffuseLight;

  // Compute the specular term
  float3 V = normalize(eyePosition - P);
  float3 H = normalize(L + V);
  float specularLight = pow(max(dot(N, H), 0),
                            shininess);
  if (diffuseLight <= 0) specularLight = 0;
  float3 specular = Ks * lightColor * specularLight;

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



# Cg Runtime

- There is a sequence of commands to get your Cg program onto the hardware

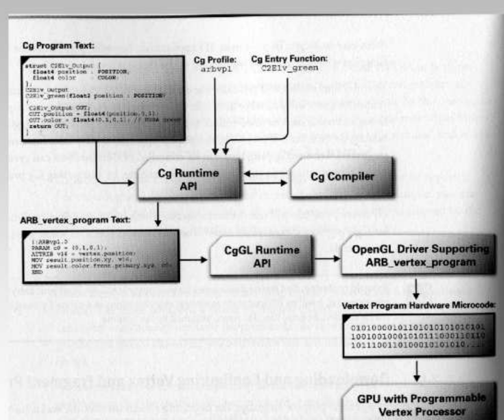



Figure 2-2. Compiling and Loading a Cg Program into the GPU

## Bump/Normal Mapping

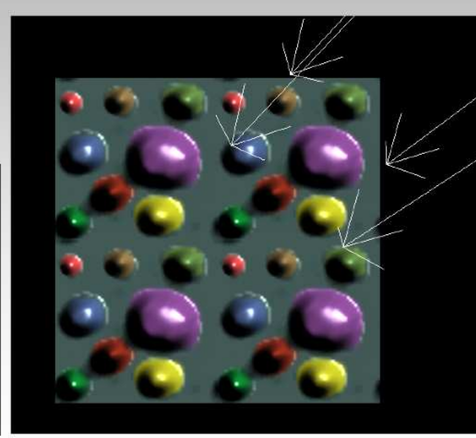
### *Normal Mapping Approach:*

- Directly encode the normal into the texture map
  - *(R,G,B)= (x,y,z), appropriately scaled*
- Then only need to perform illumination computation
  - *Interpolate world-space light and viewing direction from the vertices of the primitive*
    - Can be computed for every vertex in a vertex shader
    - Get interpolated automatically for each pixel
  - *In the fragment shader:*
    - Transform normal into world coordinates
    - Evaluate the lighting model



## Bump Mapping

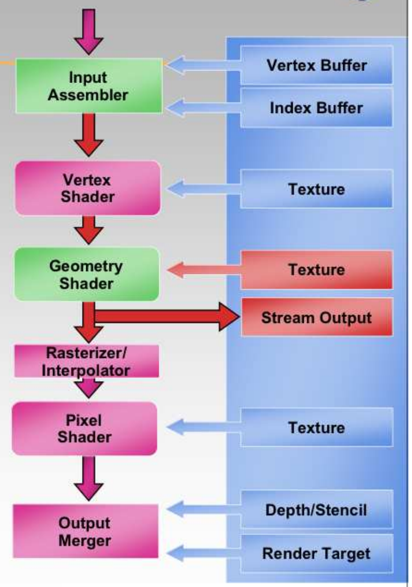
### *Examples*

# Latest Developments: Geometry Shaders

## "Direct X 10" Hardware

- Geometry shaders
- …




Source: Glassenberg/Microsoft

# Direct3D 10

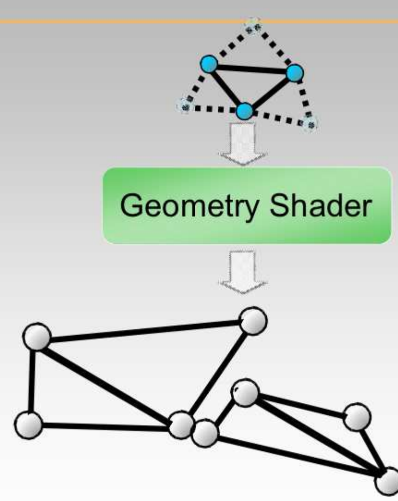
## Geometry Shader Applications

***Full control over the whole triangle***

- All-GPU Material Systems
- Better materials
  - *Hi-quality interpolation and derivatives*
  - *Wrinkle models*
  - *Cartoon and falloff effects*

***Geometry/data amplification***

- Fur/Fins
- Procedural geometry/detailing
- All-GPU Particle Systems
- Data visualization techniques
- Wide lines and strokes
- …




Source: Glassenberg/Microsoft

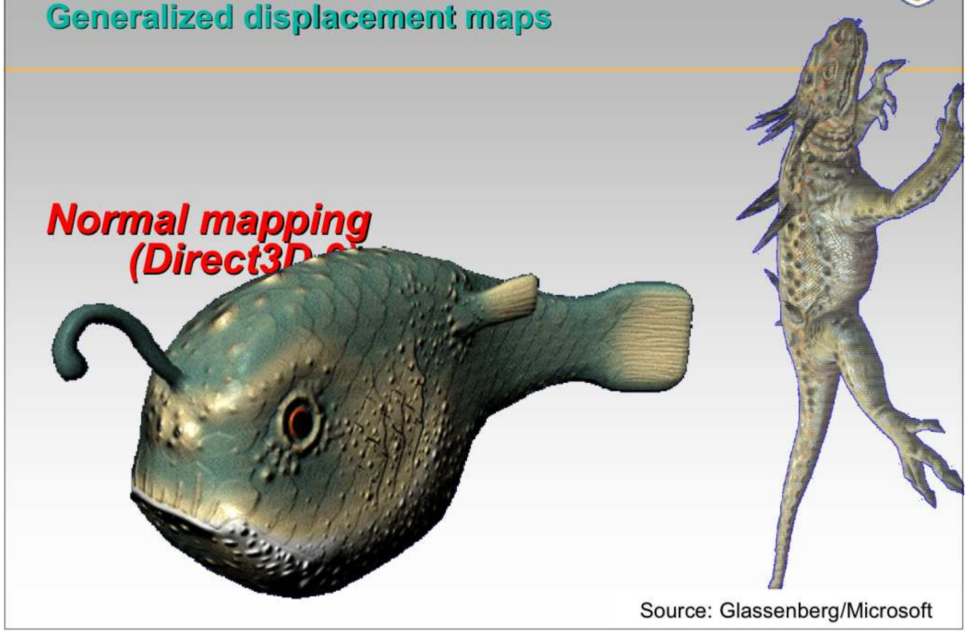
## Geometry Shader Example

### Shadow volume generation

Source: Glassenberg/Microsoft

## Geometry Shader Example

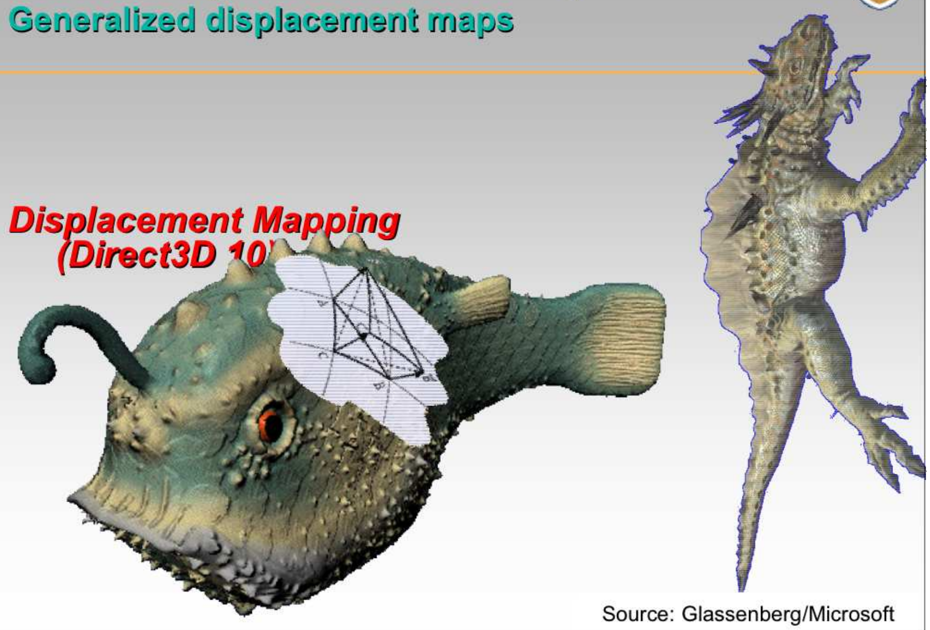
### Generalized displacement maps




Source: Glassenberg/Microsoft

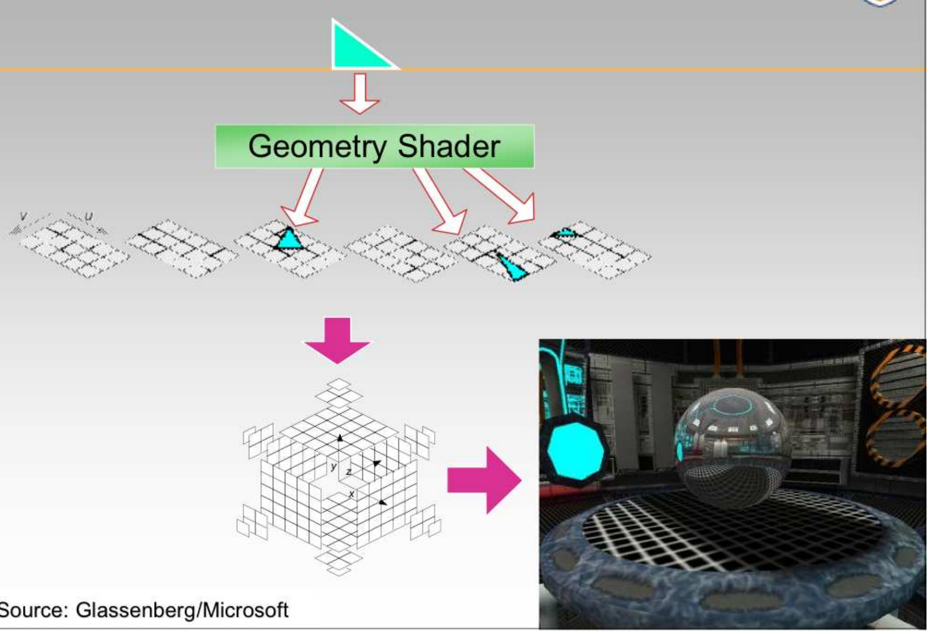
## Geometry Shader Example

### Generalized displacement maps




Source: Glassenberg/Microsoft

## Single Pass Render-To-Cubemap




Source: Glassenberg/Microsoft

## Single Pass Render-To-Cubemap

Source: Glassenberg/Microsoft

## Coming Up…

***Thursday:***

- Shadows

***Tuesday:***

- Color