GameDevelopers
Conference 2002

ATI TECHNOLOGIES INC.

Advanced Pixel Shading Techniques

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Outline

- DirectX 8.1 Pixel Shader Architecture (ps.1.4)
  - Inputs and Outputs
  - Unified Instruction set
  - Flexible dependent texture read
  - Projective Dependent Reads
- Gallery of Shaders
  - Image Processing
    - Popular new trend. The “lens flare” of 2002 - 2003?
    - Image-space outlining for NPR
  - Polynomial Texture Maps from HP
  - Refraction
  - Skin
  - Dynamic Fur – Doing physics with the rasterizer!
- Tools from ATI
  - FurGen
  - ShadeLab
- Looking Forward: DX9 ps.2.0

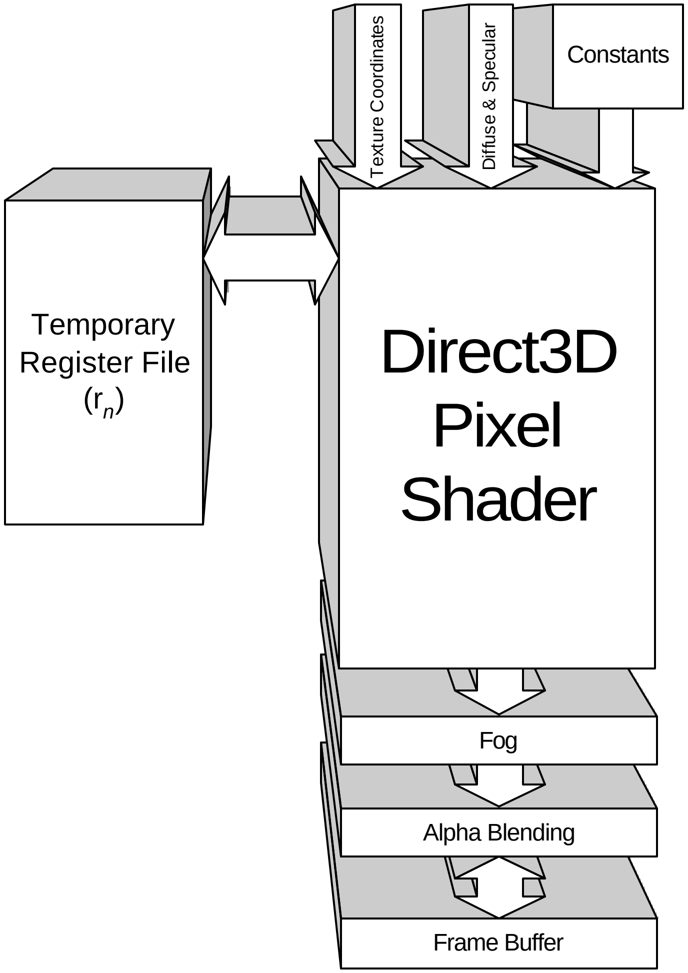
What about OpenGL?

- For this talk, we'll use Direct3D terminology to remain internally consistent. But we still love OpenGL!
- In fact, ATI is the newest permanent OpenGL Architectural Review Board (ARB) member
- Pixel shading operations of the RADEON™ 8500 are exposed via the `ATI_fragment_shader` extension.

What is a Pixel Shader?

- A pixel shader is a small program which processes pixels and executes on the Graphics Processing Unit.
- An application programmer writes pixel shaders in a specialized assembly language and downloads them onto the Graphics Processor during rendering.

Pixel Shader In’s and Out’s



- Inputs are texture coordinates, constants, diffuse and specular
- Several read-write temps
- Output color and alpha in r0.rgb and r0.a
- Output depth is in r5.r if you use texdepth (ps.1.4)
- No separate specular add when using a pixel shader
  - You have to code it up yourself in the shader
- Fixed-function fog is still there
- Followed by alpha blending

Pixel Shader Constants

- Eight read-only constants (c0..c7)
- Range -1 to +1
  - If you pass in anything outside of this range, it just gets clamped
- A given co-issue (rgb and a) instruction may only reference up to two constants
- Example constant definition syntax:

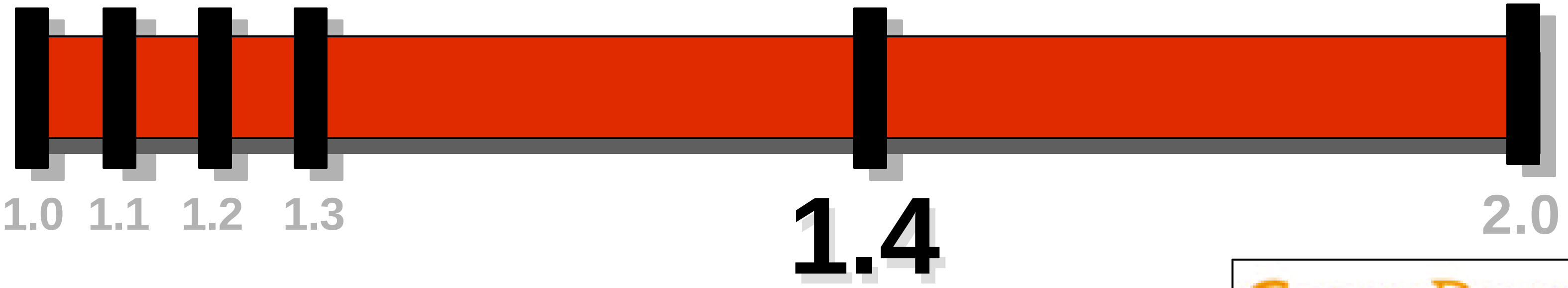
```
def c0, 1.0f, 0.5f, -0.3f, 1.0f
```

Interpolated Quantities

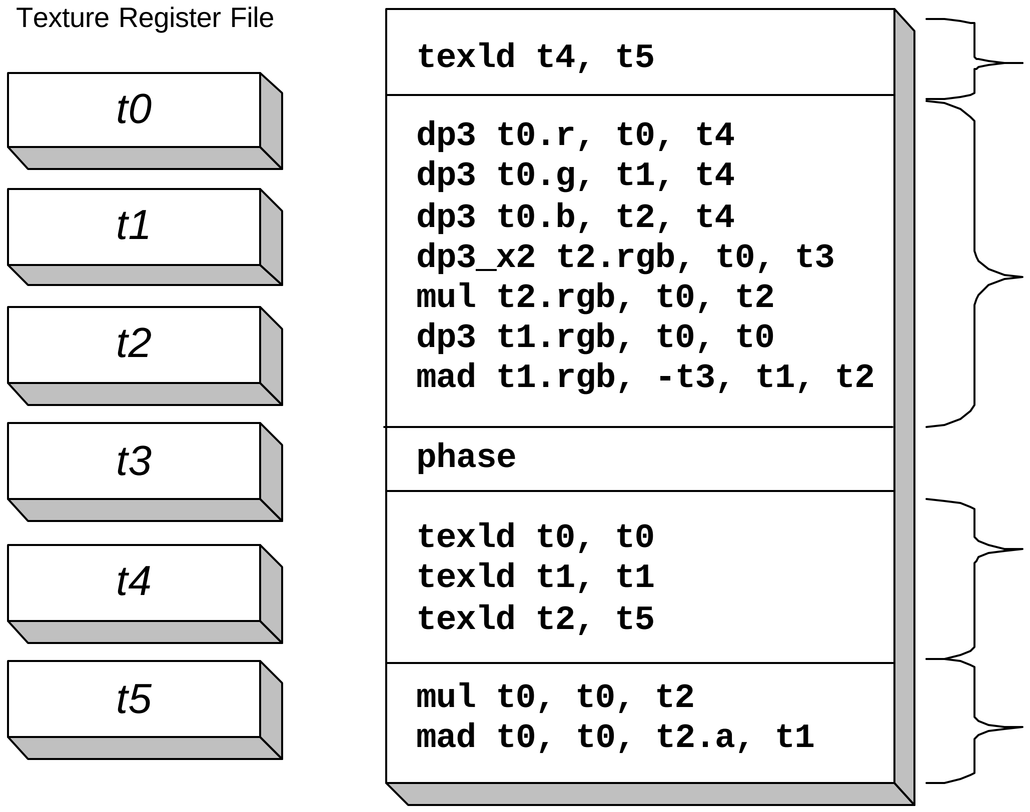
- Diffuse and Specular (v0 and v1)
  - Low precision and unsigned
  - In ps.1.1 through ps.1.3, available only in “color shader”
  - Not available before ps.1.4 *phase* marker
- Texture coordinates
  - High precision signed interpolators
  - Can be used as extra colors, signed vectors, matrix rows etc

ps.1.4 Model

- Flexible, unified instruction set
  - Think up your own math and just do it rather than try to wedge your ideas into a fixed set of modes
- Flexible dependent texture fetching
- More textures
- More instructions
- High Precision
- Range of at least -8 to +8
- Well along the road to ps.2.0



1.4 Pixel Shader Structure



Texture Register File

```
texld t4, t5

dp3 t0.r, t0, t4
dp3 t0.g, t1, t4
dp3 t0.b, t2, t4
dp3_x2 t2.rgb, t0, t3
mul t2.rgb, t0, t2
dp3 t1.rgb, t0, t0
mad t1.rgb, -t3, t1, t2

phase

texld t0, t0
texld t1, t1
texld t2, t5

mul t0, t0, t2
mad t0, t0, t2.a, t1
```

- Optional Sampling
  - Up to 6 textures
- Address Shader
  - Up to 8 instructions
- Optional Sampling
  - Up to 6 textures
  - Can be dependent reads
- Color Shader
  - Up to 8 instructions

1.4 Texture Instructions

Mostly just data routing. Not ALU operations per se

- texld
  - Samples data into a register from a texture
- texcrd
  - Moves high precision signed data into a temp register (r_n)
  - Higher precision than v0 or v1
- texkill
  - Kills pixels based on sign of register components
  - Fallback for chips that don't have clip planes
- texdepth
  - Substitute value for this pixel's z!

1.4 Pixel Shader ALU Instructions

```
• add   d, s0, s1        // sum
• sub   d, s0, s1        // difference
• mul   d, s0, s1        // modulate
• mad   d, s0, s1, s2    // s0 * s1 + s2
• lrp   d, s0, s1, s2    // s2 + s0*(s1-s2)
• mov   d, s0            // d = s0
• cnd   d, s0, s1, s2    // d = (s2 > 0.5) ? s0 : s1
• cmp   d, s0, s1, s2    // d = (s2 >= 0) ? s0 : s1
• dp3   d, s0, s1        // s0·s1 replicated to d.rgba
• dp4   d, s0, s1        // s0·s1 replicated to d.rgba
• bem   d, s0, s1, s2    // Macro similar to texbem
```

Argument Modifiers

- Negate $-r_n$
- Invert $1-r_n$
  - Unsigned value in source is required
- Bias (_bias)
  - Shifts value down by ½
- Scale by 2 (_x2)
  - Scales argument by 2
- Scale and bias (_bx2)
  - Equivalent to _bias followed by _x2
  - Shifts value down and scales data by 2 like the implicit behavior of `D3DTOP_DOTPRODUCT3` in `SetTSS()`
- Channel replication
  - r_n.r, r_n.g, r_n.b or r_n.a
  - Useful for extracting scalars out of registers
  - Not just in alpha instructions like the .b in ps.1.2

Instruction Modifiers

- _x2 - Multiply result by 2
- _x4 - Multiply result by 4
- _x8 - Multiply result by 8
- _d2 - Divide result by 2
- _d4 - Divide result by 4
- _d8 - Divide result by 8
- _sat - Saturate result to 0..1

- _sat may be used alone or combined with one of the other modifiers. i.e. mad_d8_sat

Write Masks

- Any channels of the destination register may be masked during the write of the result
- Useful for computing different components of a texture coordinate for a dependent read
- Example:

```
dp3 r0.r, t0, t4
mov r0.g, t0.a
```

Projective Textures

- You can do texture projection on any texld instruction.
- This includes projective *dependent* reads, which are fundamental to doing reflection and refraction mapping of things like water surfaces. This is used in the Nature and Rachel demos.
- Syntax looks like this:

```
 texld r3, r3_dz  or
 texld r3, r3_dw
```

- Useful for projective textures like the refraction map in the nature demo or just doing a divide.

Frame Post Processing: Image Filters in Pixel Shaders

- Use on 2D images in general
- Use as post processing pass over 3D scenes
  - Opportunity for you to customize your look
  - Luminance filter for Black and White effect
    - The film *Thirteen Days* does a crossfade to black and white with this technique several times for dramatic effect
  - Edge filters for non-photorealistic rendering
  - Glare filters for soft look (see *Fiat Lux* by Debevec, *ICO* on PS2, Halo on XBox)
  - Refraction Mapping (see *Jak and Daxter* on PS2)
  - Check out the XBox game *Wreckless: The Yakuza Missions* for some extreme examples of 3D scene post-processing
- Rendering to textures is fundamental
- Becomes especially interesting when we get to high dynamic range (tone mapping)
- See Dan Baker's notes from the DX Dev Day

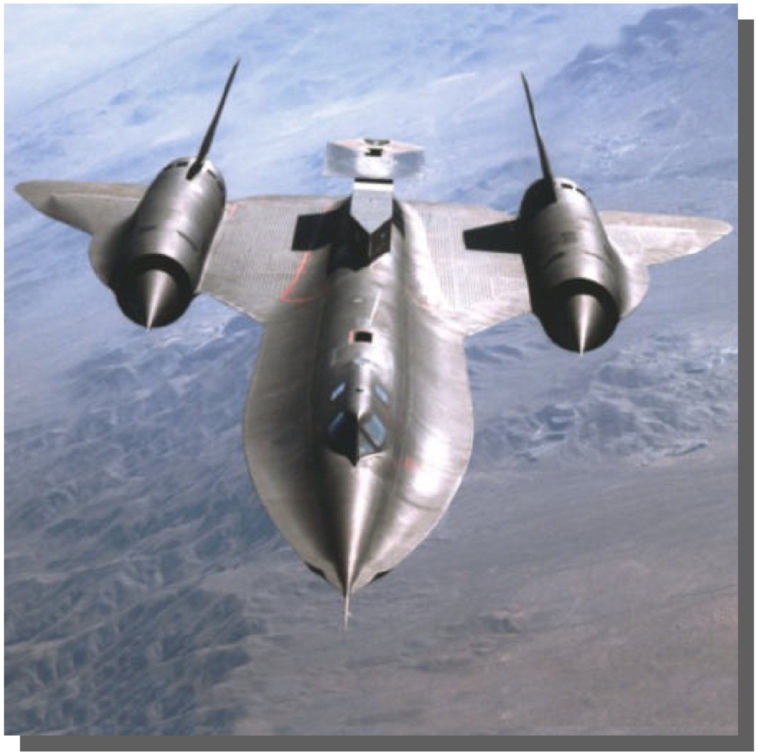
Luminance Filter

- Different RGB recipes give different looks
  - Black and White TV (*Pleasantville*)
  - Black and White film (*Thirteen Days*)
  - Sepia
  - Run through arbitrary transfer function using a dependent read for “heat signature”
- A common recipe is Lum = .3r + .59g + .11b

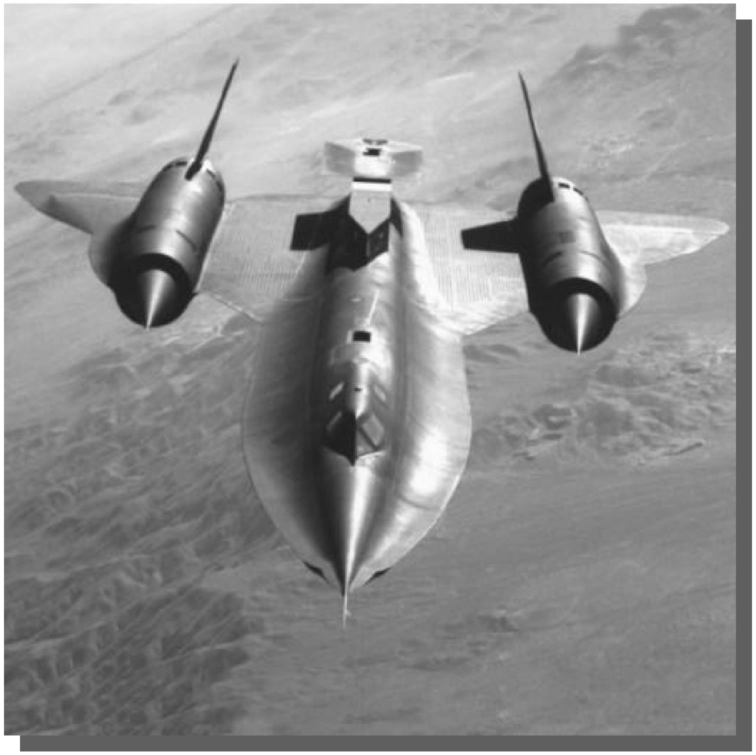
```
ps.1.4
def c0, 0.30f, 0.59f, 0.11f, 1.0f
texld r0, t0
dp3 r0, r0, c0
```

Luminance Filter

Original Image



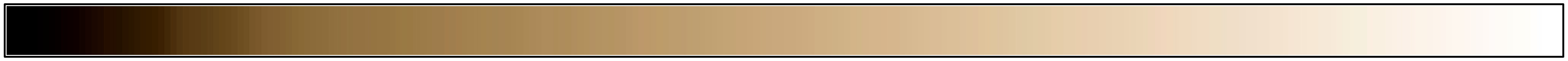
Luminance Image



Sepia Transfer Function

Dependent Read →

```
ps.1.4
def c0, 0.30f, 0.59f, 0.11f, 1.0f
texld r0, t0
dp3 r0, r0, c0  // Convert to Luminance
phase
texld r5, r0    // Dependent read from 1D Sepia map
mov r0, r5
```

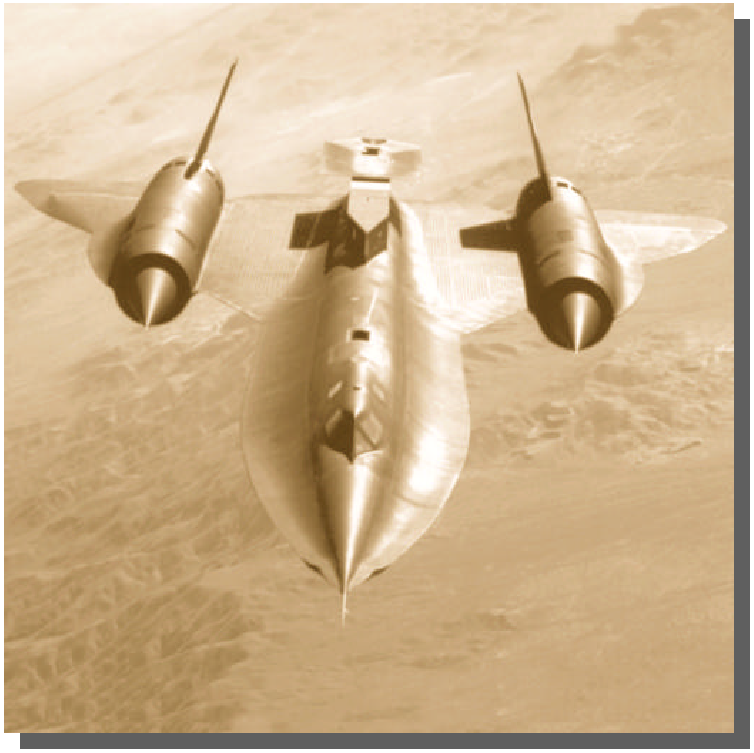


1D Luminance to Sepia map

Sepia Transfer Function

Original Image

Sepia Tone Image



Multitap Filters

- Effectively code filter kernels right into the pixel shader
- Pre offset taps with texture coordinates
  - For traditional image processing, offsets are a function of image/texture dimensions and point sampling is used
  - Or compose complex filter kernels from multiple bilinear kernels

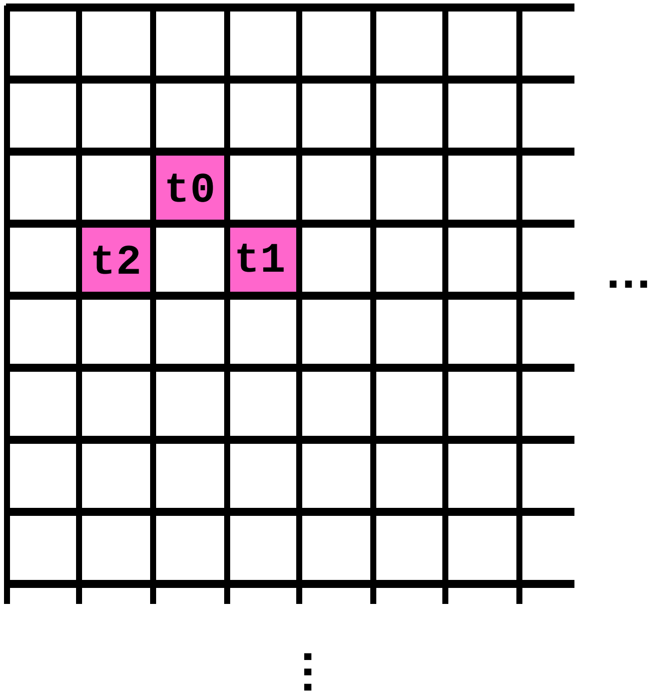
Edge Detection Filter

- Roberts Cross Gradient Filters

```
ps.1.4
texld r0, t0 // Center Tap
texld r1, t1 // Down & Right
texld r2, t2 // Down & Left
add r1, r0, -r1
add r2, r0, -r2
cmp r1, r1, r1, -r1
cmp r2, r2, r2, -r2
add_x8 r0, r1, r2
```

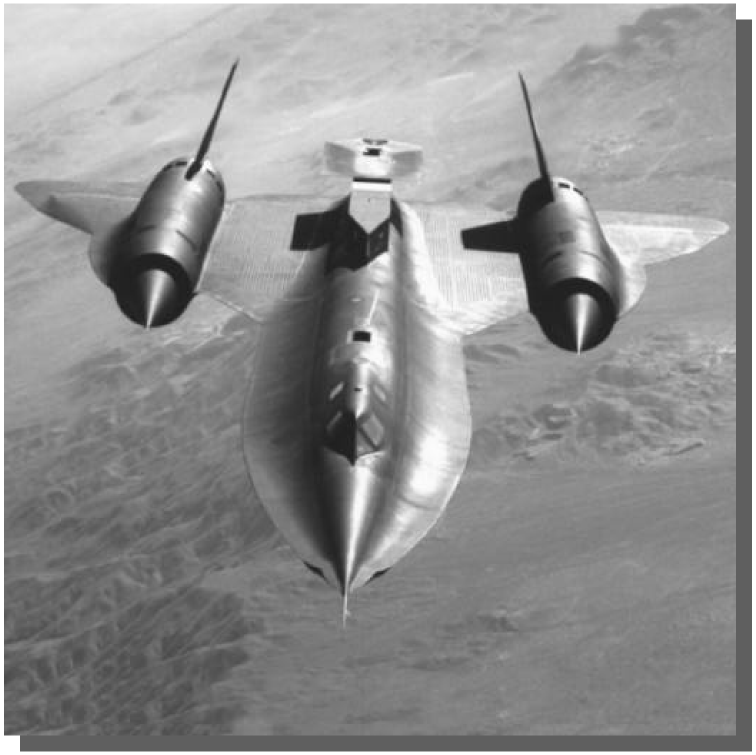
1	0
0	-1

0	1
-1	0

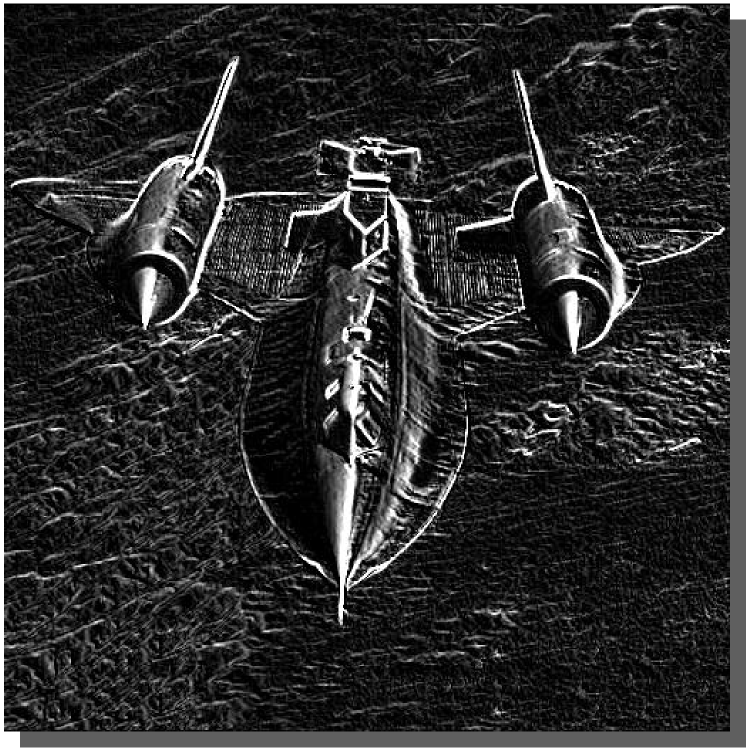


Gradient Filter

Original Image

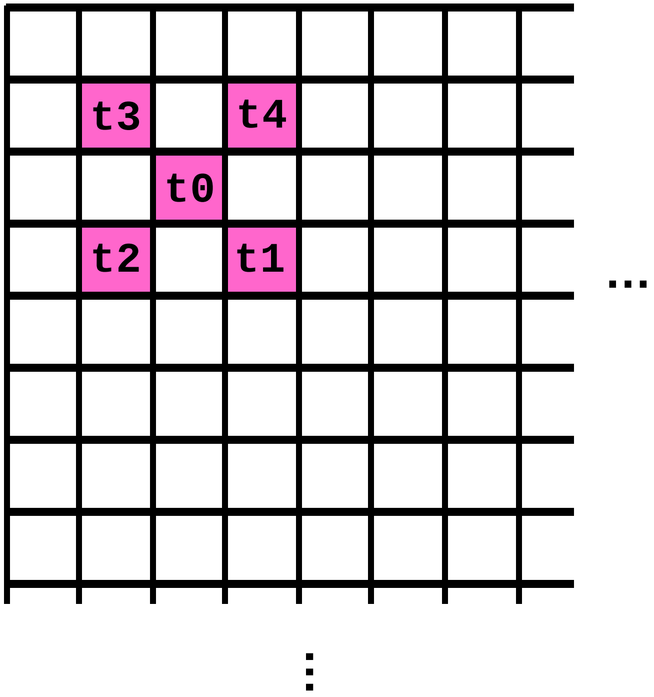


8 x Gradient Magnitude



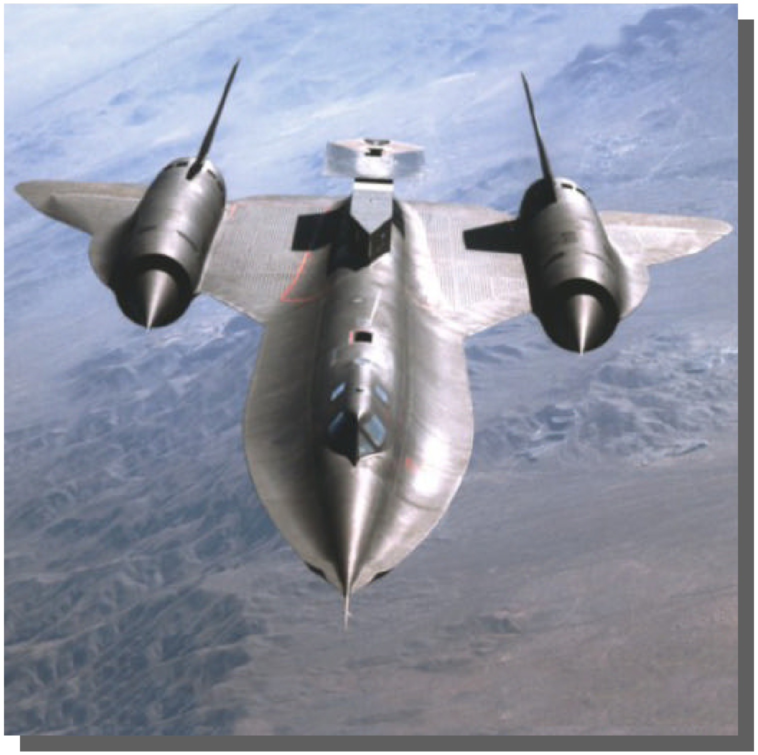
Five Tap Blur Filter

```
ps.1.4
def c0, 0.2f, 0.2f, 0.2f, 1.0f
texld r0, t0 // Center Tap
texld r1, t1 // Down & Right
texld r2, t2 // Down & Left
texld r3, t3 // Up & Left
texld r4, t4 // Up & Right
add r0, r0, r1
add r2, r2, r3
add r0, r0, r2
add r0, r0, r4
mul r0, r0, c0
```



Five Tap Blur Filter

Original Image



Blurred Image

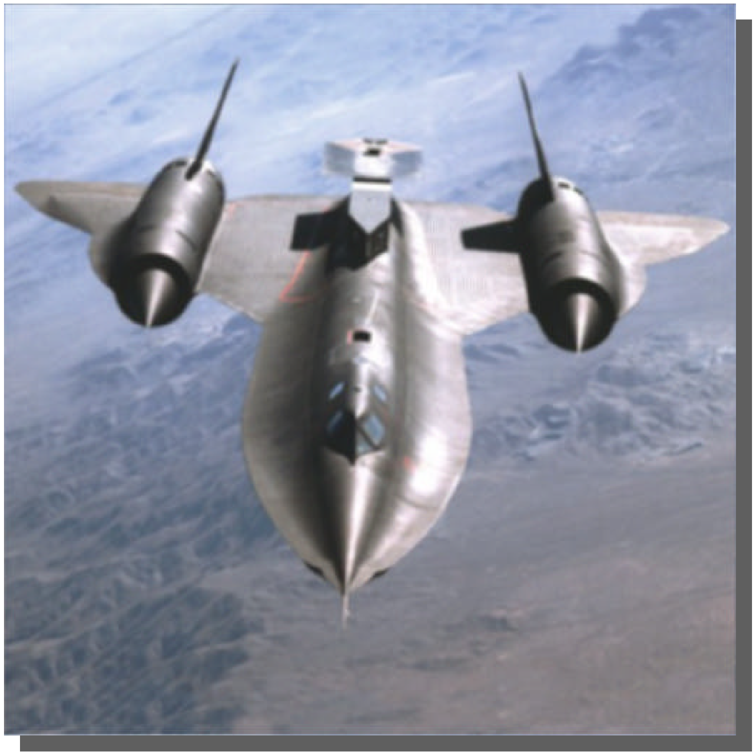
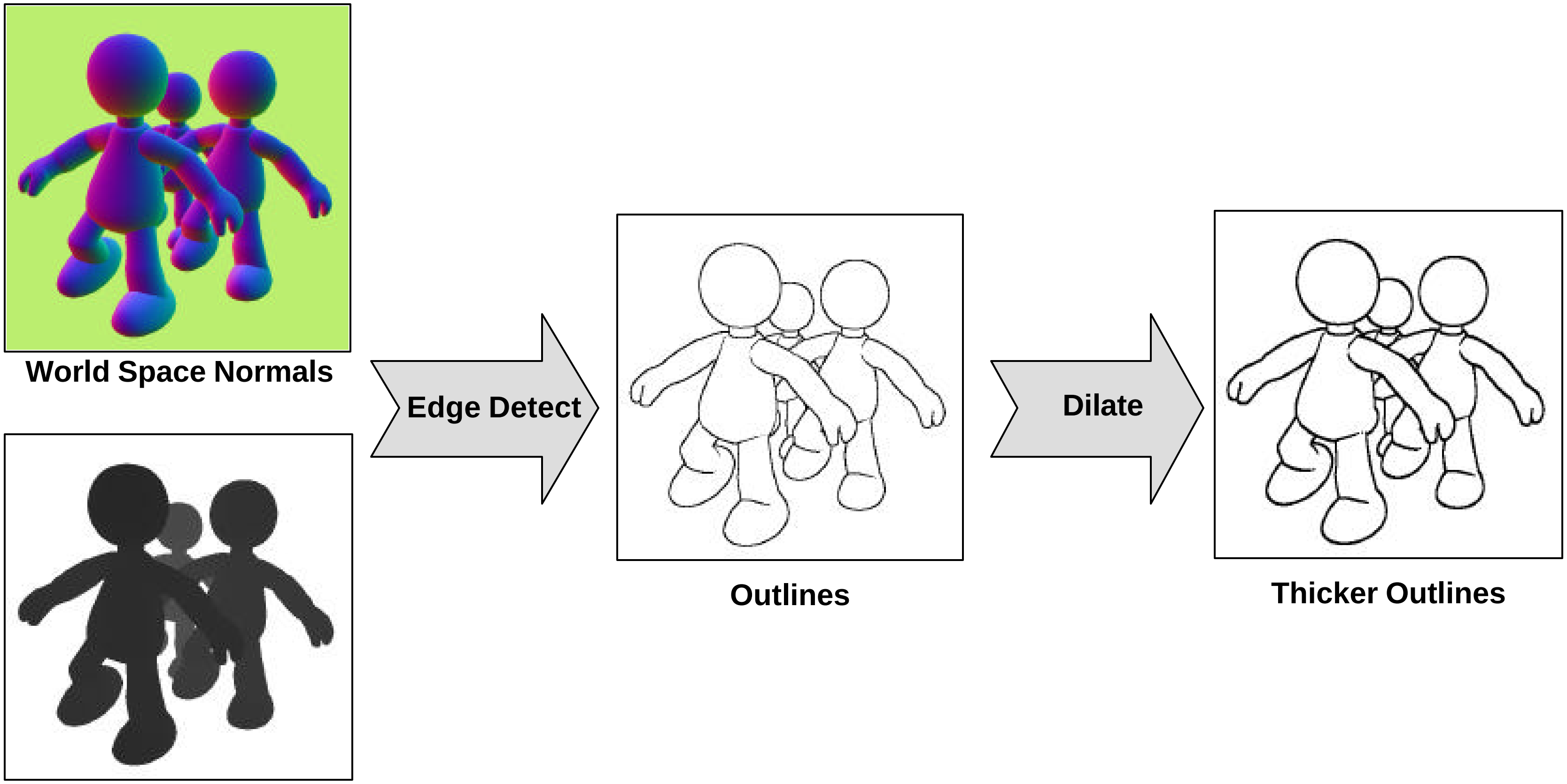


Image Space Outlining for NPR

- Outlines of objects are an important element of Non Photorealistic Rendering (NPR)
- Geometric approaches require some access to the model geometry and don't necessarily scale well as a result. *Jet Set Radio Future*, for example, appears to use a geometric approach to outlining and you can see how low-poly their characters are.
- Image space approaches scale better and work well with higher-order surfaces

Image Space Outlining for NPR



World Space Normals

Eye Space Depth

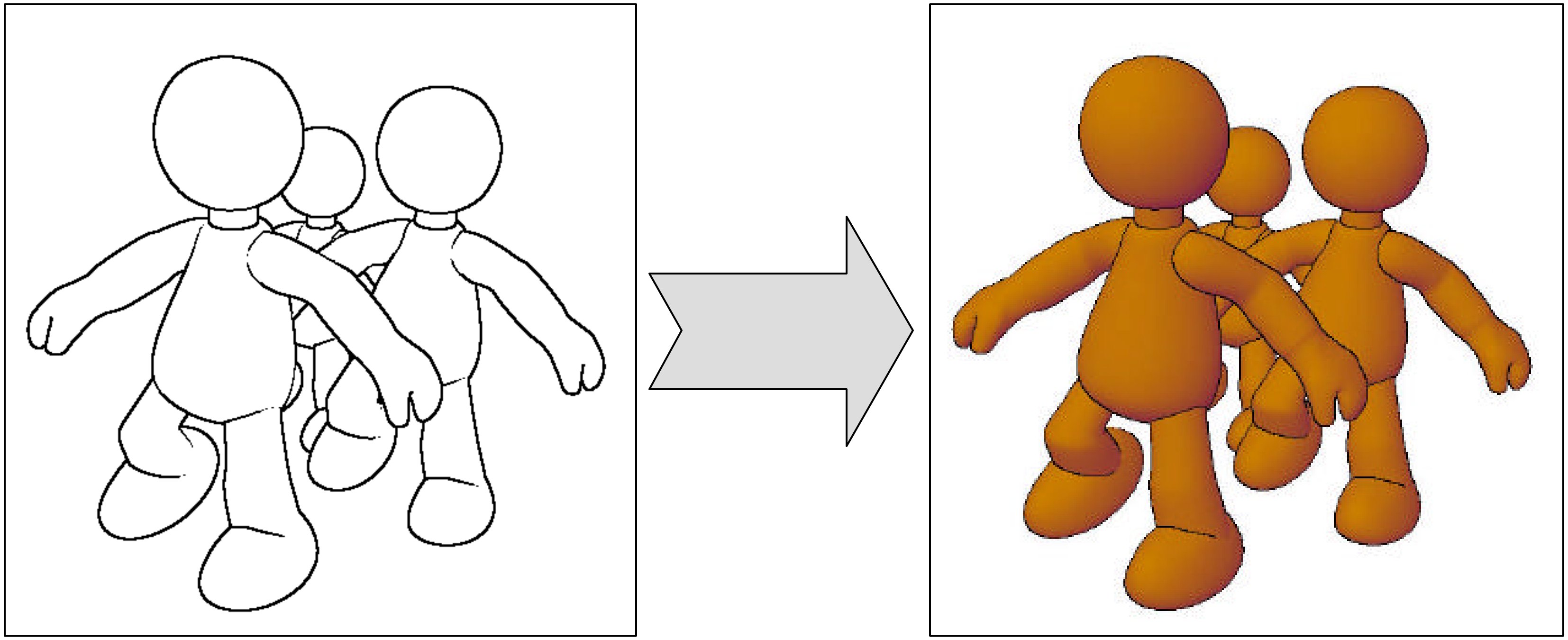
Edge Detect

Outlines

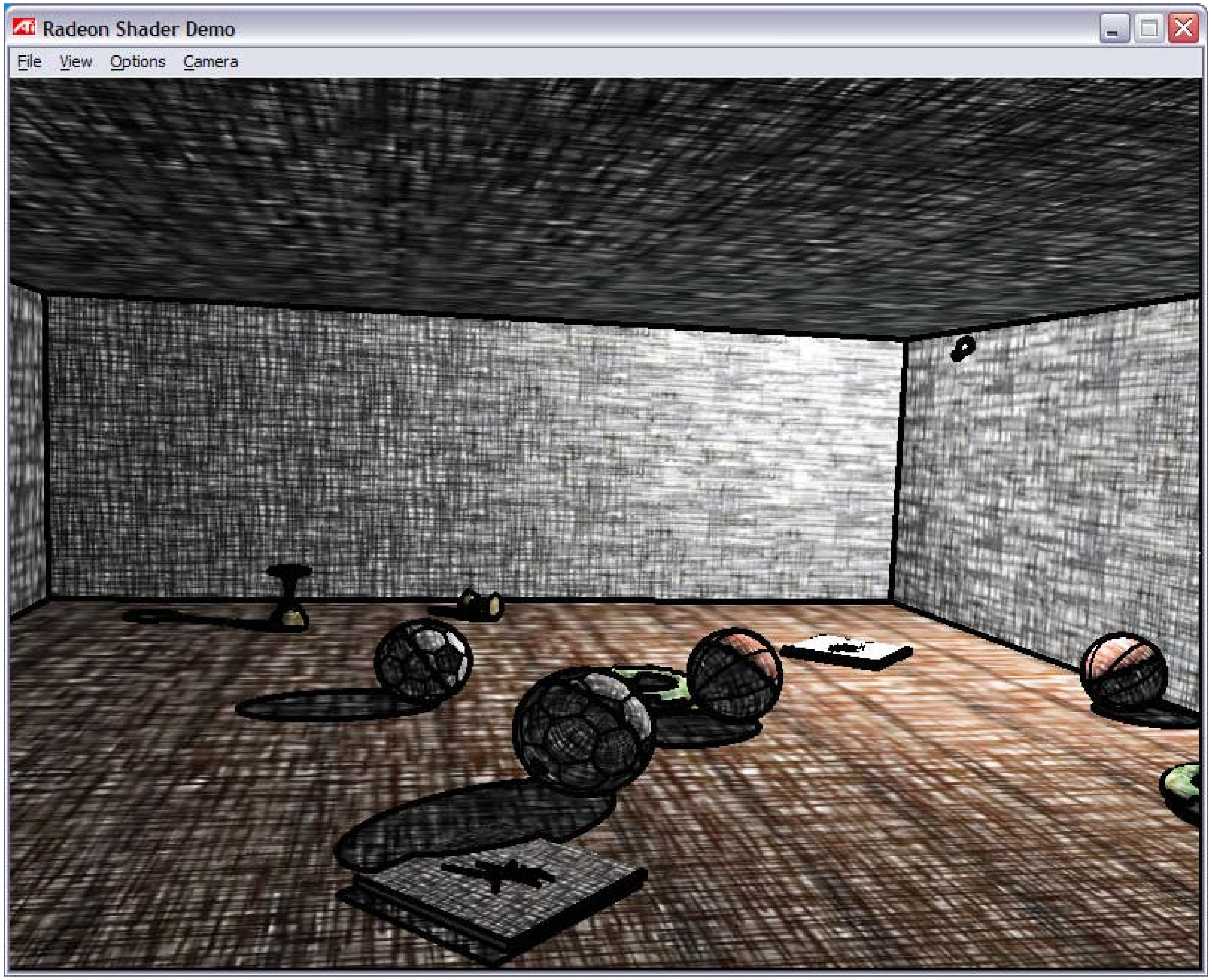
Dilate

Thicker Outlines

Composite Outlines over Shaded Scene

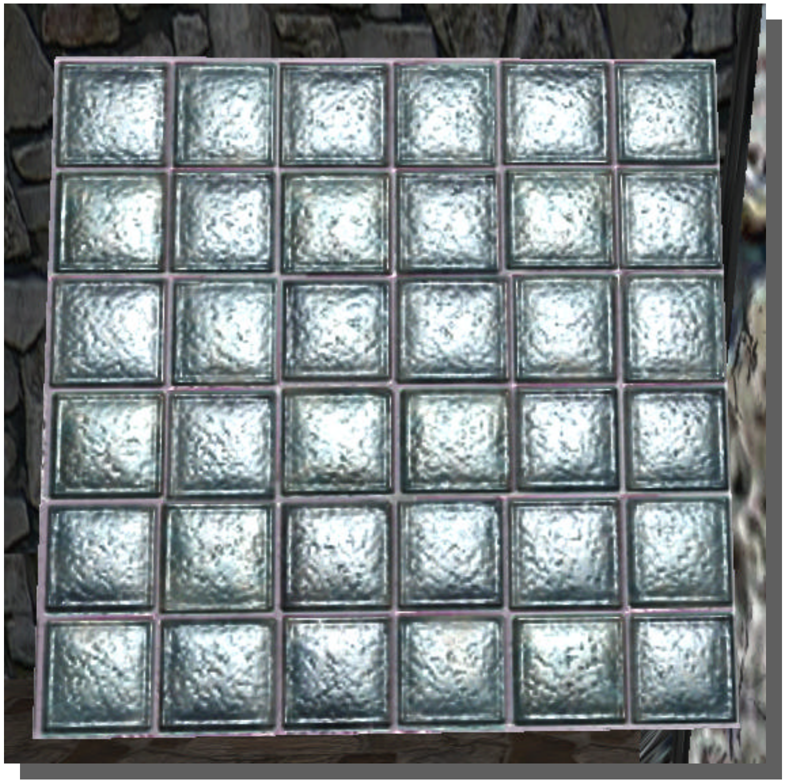


Composite Outlines over Shaded Scene

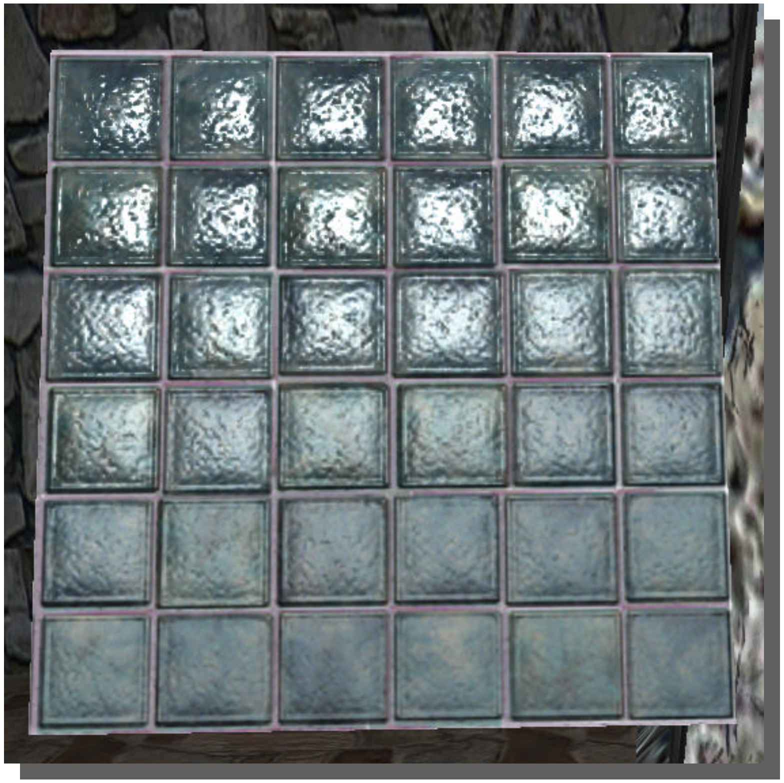


Variable Specular Power

Constant specular power

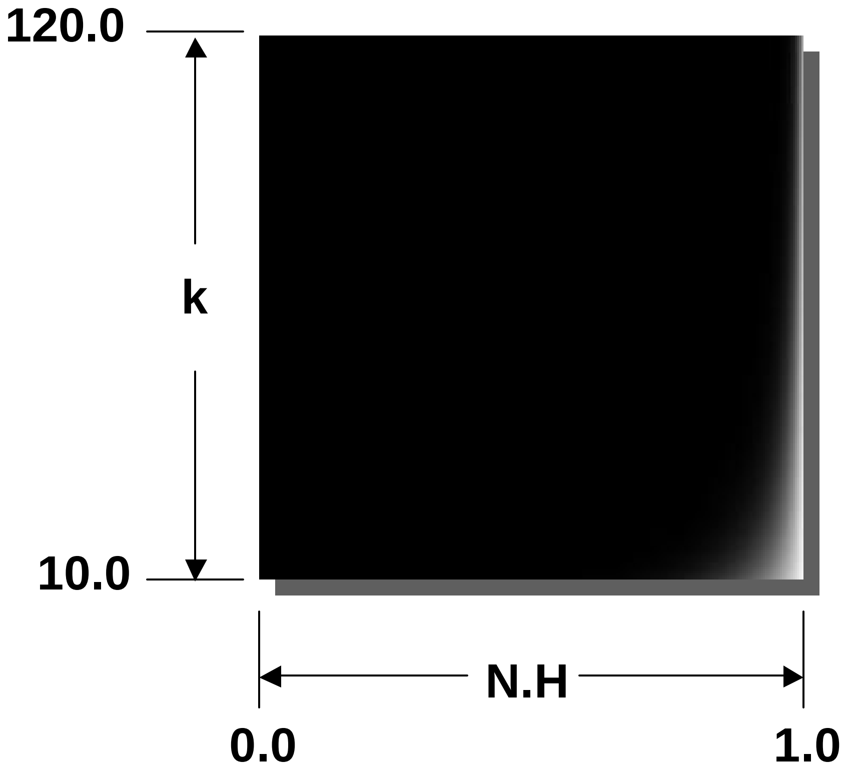


Variable specular power



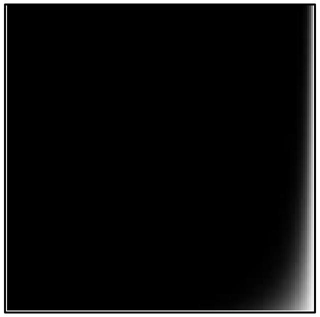
Variable Specular Power

Per-pixel $(N\cdot H)^k$ with per-pixel variation of k

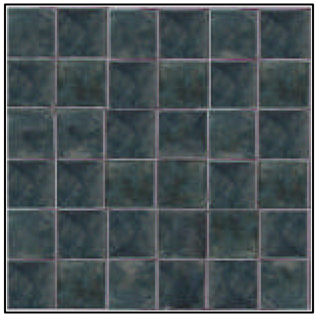


- Base map with albedo in RGB and gloss in alpha
- Normal map with xyz in RGB and k in alpha
- N·H ´ k map

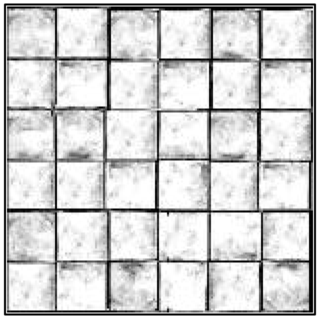
Maps for per-pixel variation of k shader



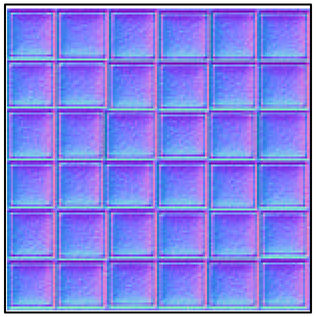
N·H ´ k map



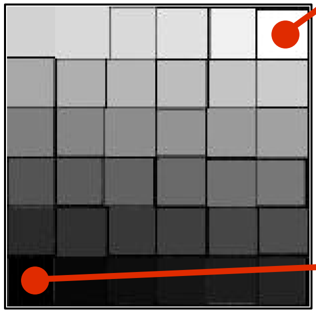
Albedo in RGB



Gloss in alpha



Normals in RGB



k = 120

k = 10

k in alpha

Variable Specular Power

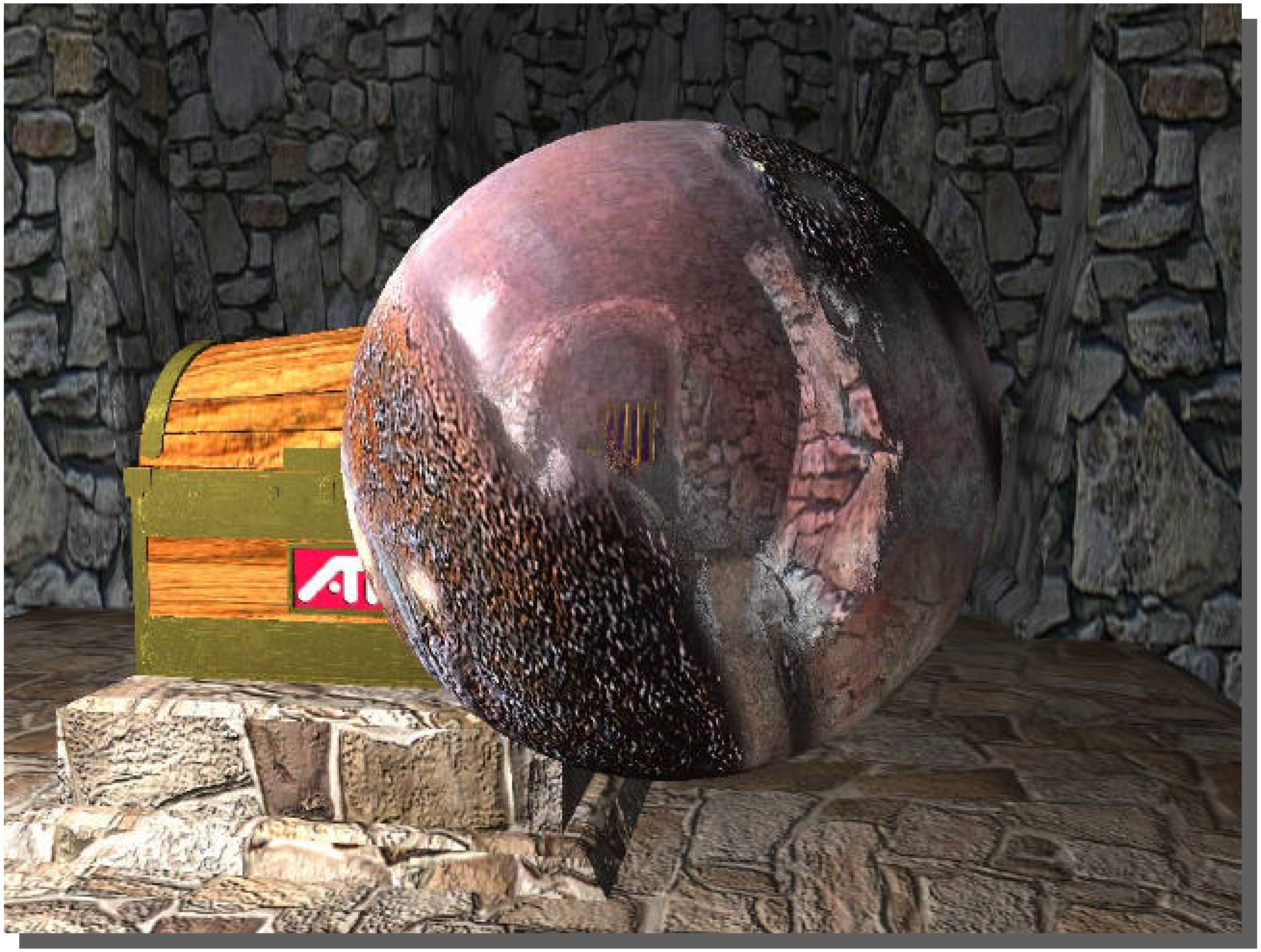
```
 ps.1.4
 texld  r1, t0      ; Normal
 texld  r2, t1      ; Normalized Tangent Space L vector
 texcrd r3.rgb, t2  ; Tangent Space Halfangle vector

 dp3_sat r5.xyz, r1_bx2, r2_bx2 ; N·L
 dp3_sat r2.xyz, r1_bx2, r3     ; N·H
 mov     r2.y, r1.a             ; K = Specular Exponent
 phase
 texld  r0, t0                  ; Base
 texld  r3, r2                  ; Specular NH×K map
 add       r4.rgb, r5, c7       ; += ambient
 mul       r0.rgb, r0, r4       ; base * (ambient + N·L))
+mul_x2    r0.a, r0.a, r3.a     ; Gloss map * specular
 add       r0.rgb, r0, r0.a     ; (base*(ambient + N·L)) +
                                ; (Gloss*Highlight)
```

Dependent Read →

Bumped Cubic Environment Mapping

- Interpolate a 3x3 matrix which represents a transformation from tangent space to cube map space
- Sample normal and transform it by 3x3 matrix
- Sample diffuse map with transformed normal
- Reflect the eye vector through the normal and sample a specular and/or env map
- Do both
- Blend with a per-pixel Fresnel Term!

Bumpy Environment Mapping

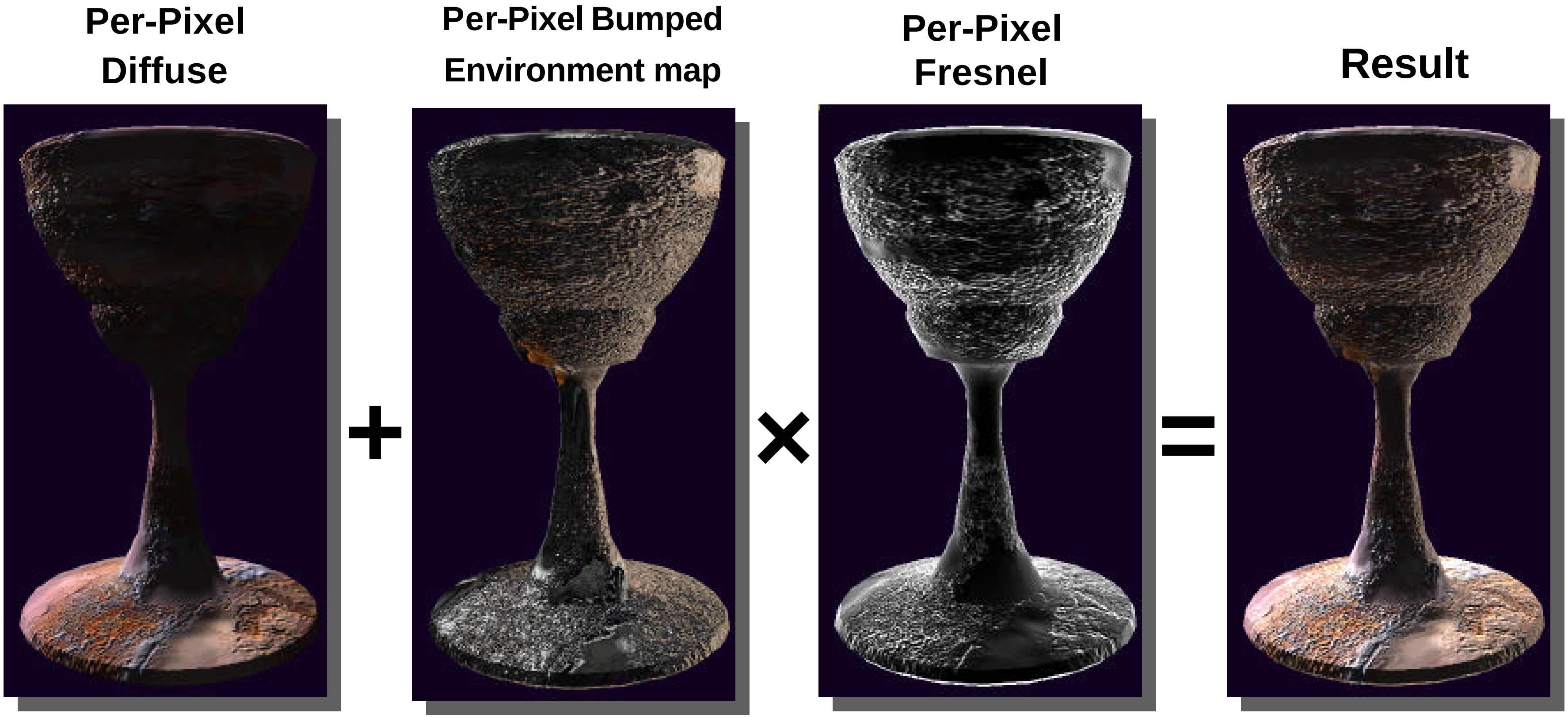


Bumpy Environment Mapping

Dependent Reads

```
texld   r0, t0              ; Look up normal map
texld   r1, t4              ; Eye vector through normalizer cube map
texcrd  r4.rgb, t1          ; 1st row of environment matrix
texcrd  r2.rgb, t2          ; 2st row of environment matrix
texcrd  r3.rgb, t3          ; 3rd row of environment matrix
texcrd  r5.rgb, t5          ; World space L (Unit length is light's range)

dp3     r4.r, r4, r0_bx2        ; 1st row of matrix multiply
dp3     r4.g, r2, r0_bx2        ; 2nd row of matrix multiply
dp3     r4.b, r3, r0_bx2        ; 3rd row of matrix multiply
dp3_x2  r3.rgb, r4, r1_bx2      ; 2(N·Eye)
mul     r3.rgb, r4, r3          ; 2N(N·Eye)
dp3     r2.rgb, r4, r4          ; N·N
mad     r2.rgb, -r1_bx2, r2, r3 ; 2N(N·Eye) - Eye(N·N)
phase
texld   r2, r2                  ; Sample cubic reflection map
texld   r3, t0                  ; Sample base map
texld   r4, r4                  ; Sample cubic diffuse map
texld   r5, t0                  ; Sample gloss map

mul     r1.rgb, r5, r2          ; Specular = Gloss * Reflection
mad     r0.rgb, r3, r4_x2, r1   ; Base * Diffuse + Specular
```

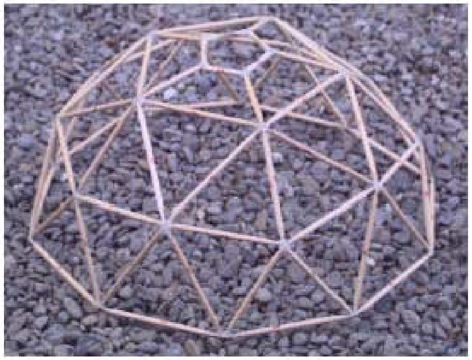
Per-Pixel Fresnel

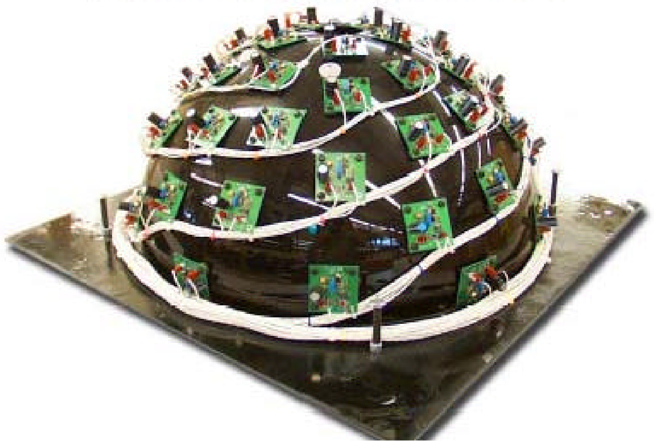


Per-Pixel Diffuse + Per-Pixel Bumped Environment map × Per-Pixel Fresnel = Result

Polynomial Texture Maps

- Published at SIGGRAPH 2001
- Images of surface are acquired from one position using various lighting directions
- Can be applied to virtual surfaces using the same tools.





PTM algorithms provided courtesy of Hewlett-Packard. HP retains all rights to the algorithms and code.

Polynomial Texture Maps

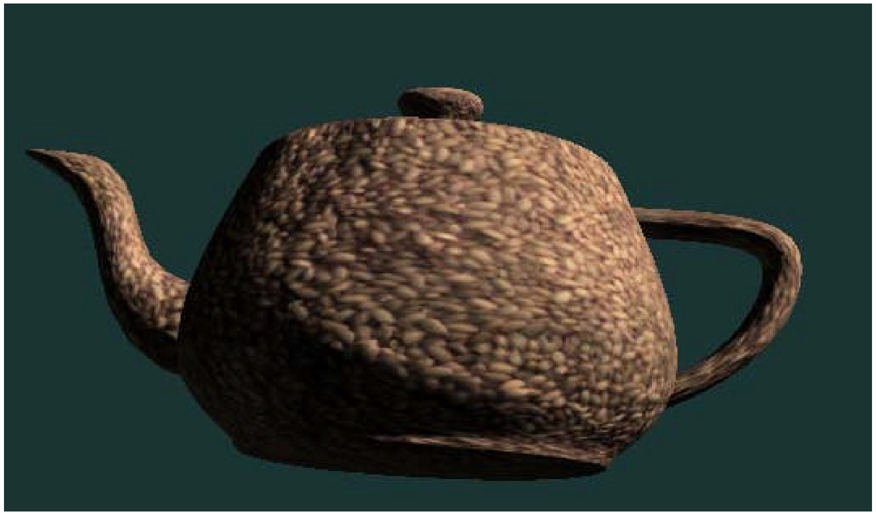
- $L(u,v{:}l_u l_v) = a_0(u,v)l_u^2 + a_1(u,v)l_v^2 + a_2(u,v)\, l_u\, l_v + a_3(u,v)\, l_u + a_4(u,v)\, l_v + a_5(u,v)$

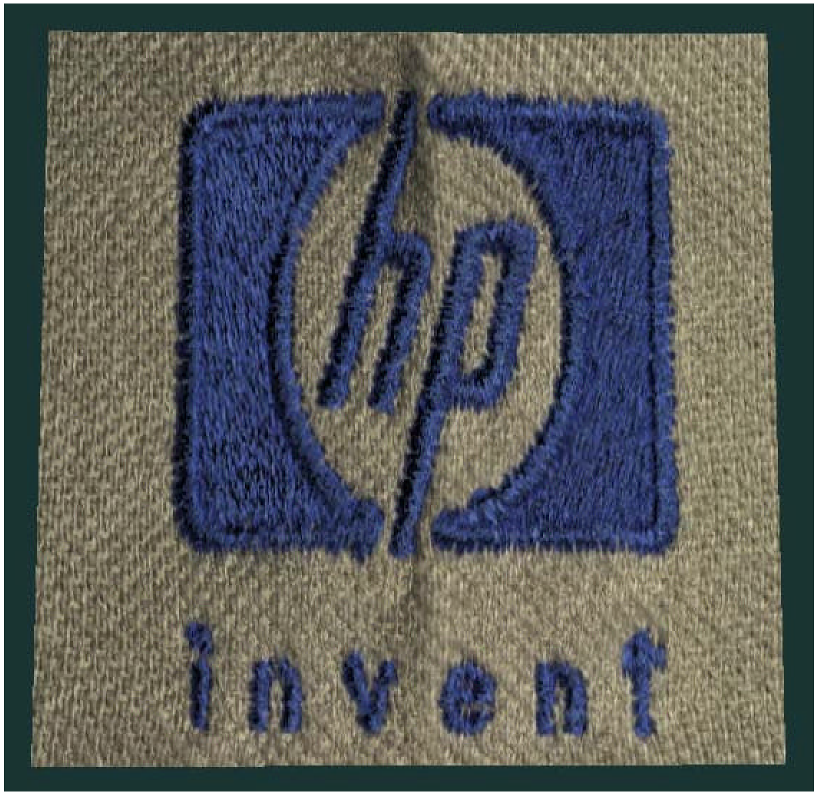
  where (l_u,l_v) are projections of the normalized light vector into the local texture coordinate system *(u,v)* and *L* is the resultant surface luminance at that coordinate.
- a_0-a_5 are fit to the (real or virtual) photographic data and are stored in the PTM

PTM algorithms provided courtesy of Hewlett-Packard. HP retains all rights to the algorithms and code.

Polynomial Texture Maps

- Accurate filtering
  - Unlike normal maps
- Self-shadowing





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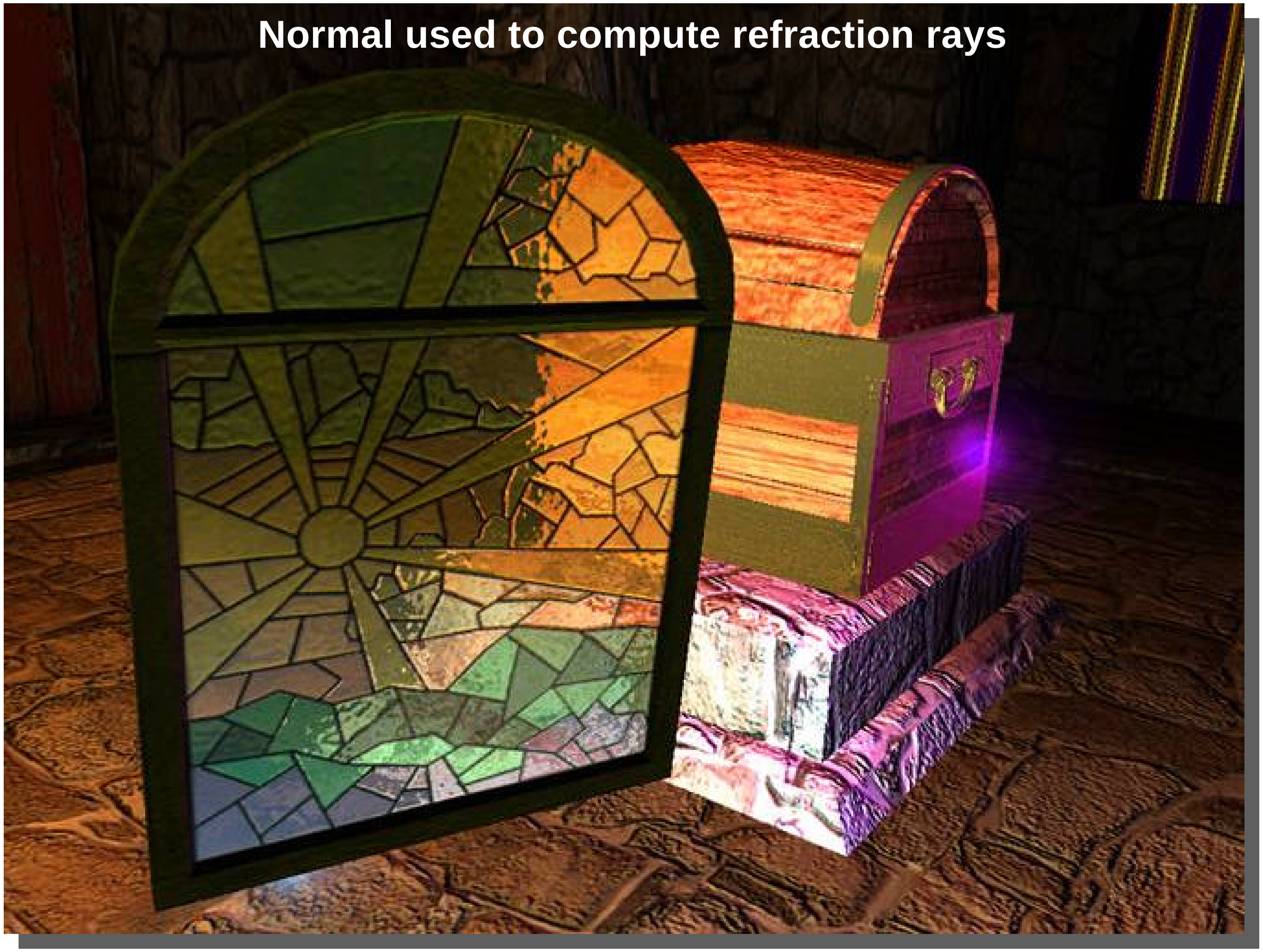
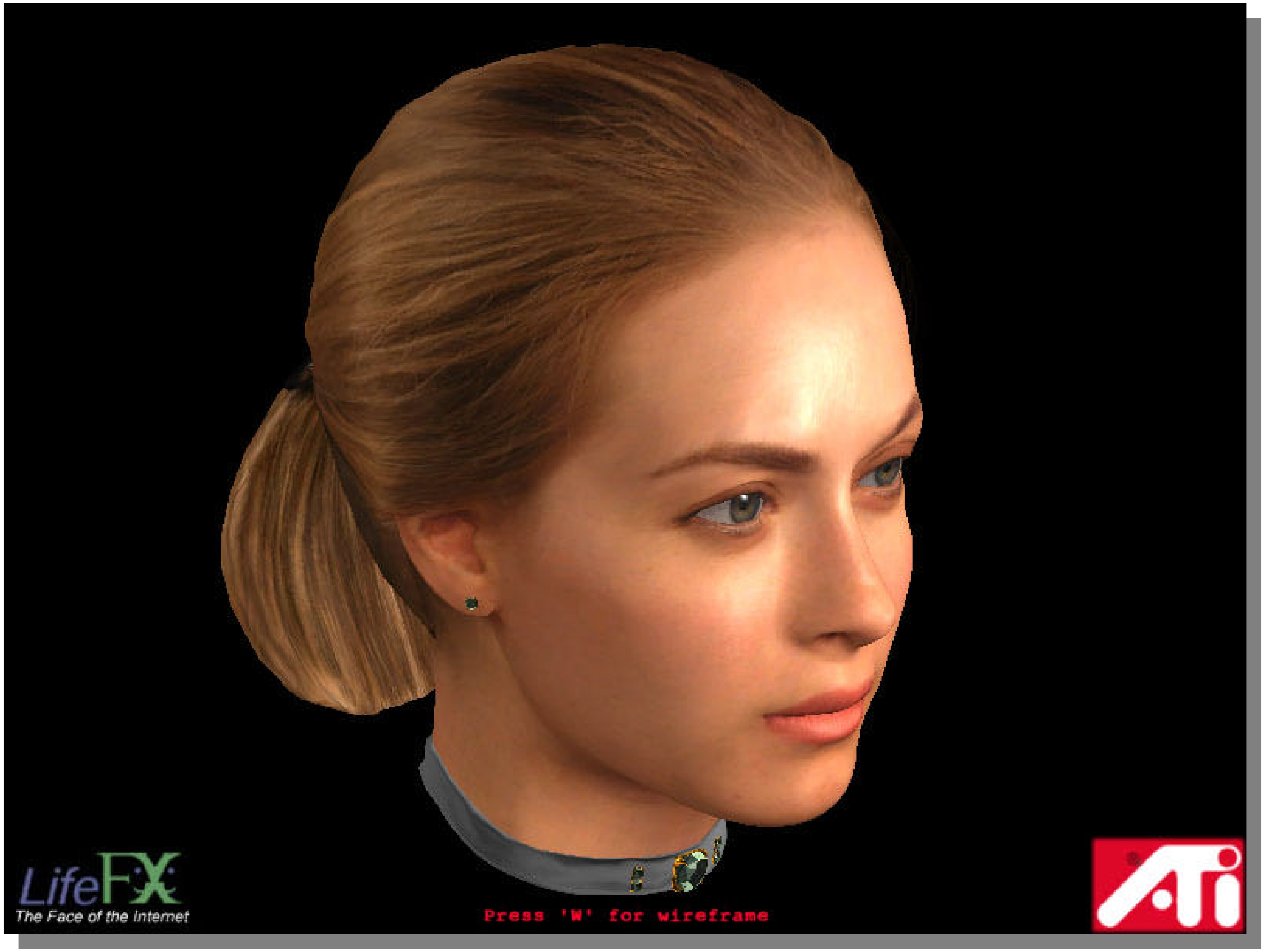
Refractive Stained Glass

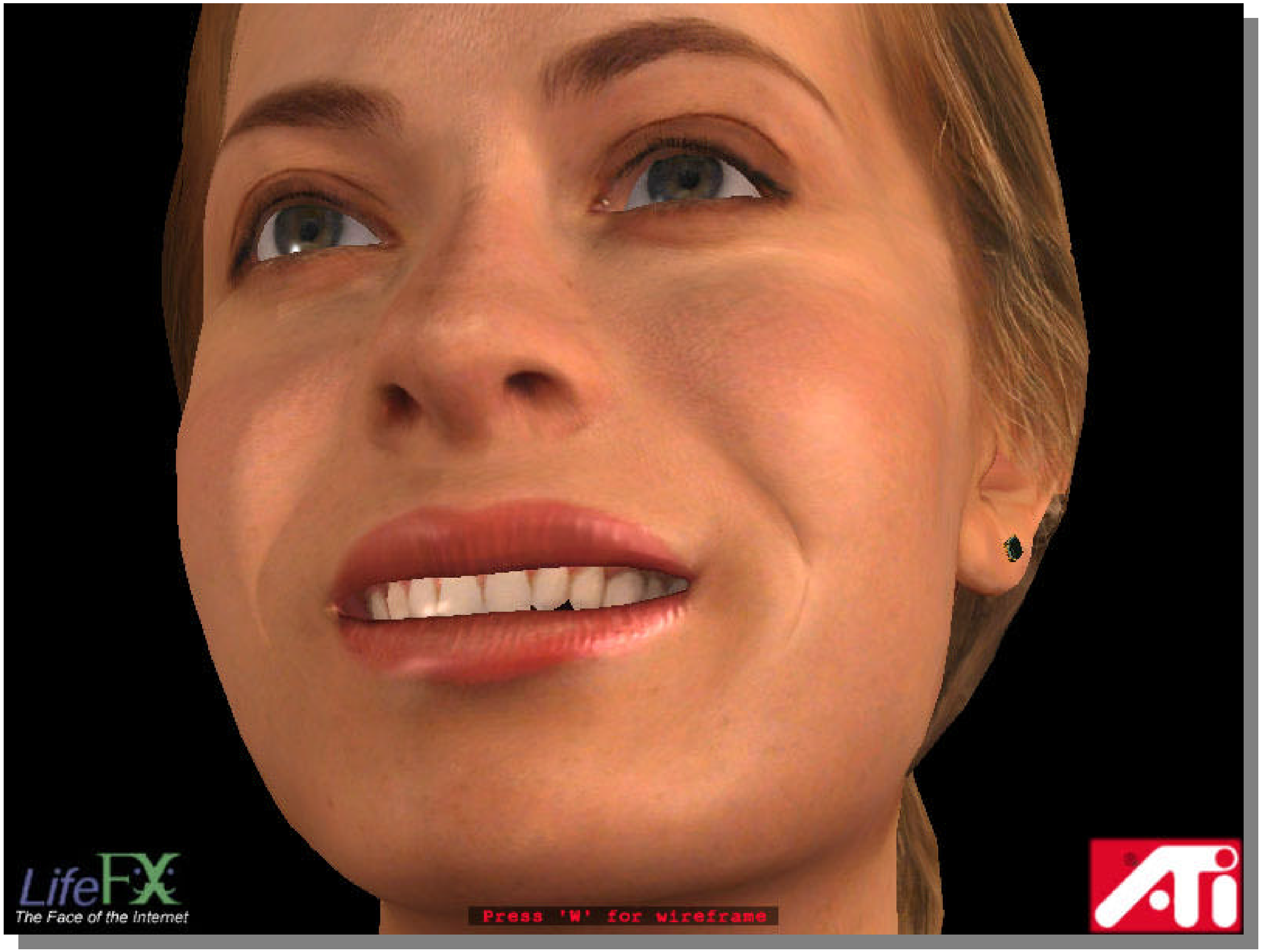


Normal used to compute refraction rays

Rachel



Rachel



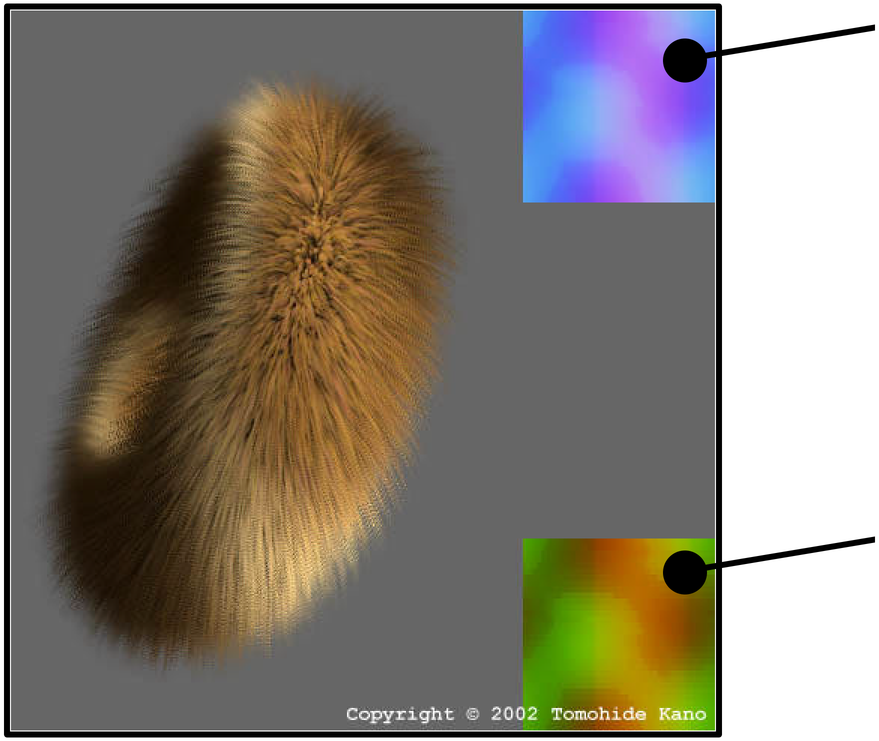
Rachel Skin Pixel Shader

```
 ps.1.4
 texld r0, t0
 texcrd r1.xyz, t3              // tangent space H0
 texcrd r2.xyz, t5              // tangent space H1
 dp3_sat r4.r, r0_bx2, r1       // (N.H0)
 dp3_sat r4.b, r1, r1           // (H0.H0)
 mul_sat r4.g, r4.b, c0.a       // c0.a*(H0.H0)
 mul r4.r, r4.r, r4.r           // (N.H0)^2
 dp3_sat r5.r, r0_bx2, r2       // (N.H1)
 dp3_sat r5.b, r2, r2           // (H1.H1)
 mul_sat r5.g, r5.b, c0.a       // c0.a*(H1.H1)
 mul r5.r, r5.r, r5.r           // (N.H1)^2
 phase
 texld r0, t0                   // fetch a second time to get spec map to use as gloss map
 texld r1, t0                   // base map
 texld r2, t2                   // tangent space L0
 texld r3, t4                   // tangent space L1
 texld  r4, r4_dz               // ((N.H)^2 /(H.H)) ^k @= |N.H|^k
 texld  r5, r5_dz               // ((N.H)^2 /(H.H)) ^k @= |N.H|^k
 dp3_sat r2.r, r2_bx2, r0_bx2   // (N.L0)
+mul r2.a, r0.a, r4.r           // f(k) * |N.H0|^k   <- Gloss specular highlight 0
 dp3_sat r3.r, r3_bx2, r0_bx2   // (N.L1)
+mul r3.a, r0.a, r5.r           // f(k) * |N.H1|^k   <- Gloss specular highlight 1
 mul r0.rgb, r2.a, c2           // Id0*f(k)*|N.H0|^k
 mad_x2 r0.rgb, r3.a, c3, r0    // Id0*f(k)*|N.H0|^k + Id1*f(k)*|N.H1|^k
 mad r2.rgb, r2.r, c2, c1       // Ia + Id0*(N.L)
 mad r2.rgb, r3.r, c3, r2       // Ia + Id0*(N.L) + Id1*(N.L)
 mul r0.rgb, r0, c4             // spec strength * (Id0*f(k)*|N.H0|^k + Id1*f(k)*|N.H1|^k)
 mad_x2_sat r0.rgb, r2, r1, r0  // base(Ia + Id0*(N.L) + Id1*(N.L))
                                //                   + Id0*f(k)*|N.H0|^k + Id1*f(k)*|N.H1|^k

+mov r0.a, c0.z
```

Using Pixel Shaders to Perform Physics during Fur Rendering

- Maps normal and force textures onto object
- Render to/from these textures to perform physics using pixel shader

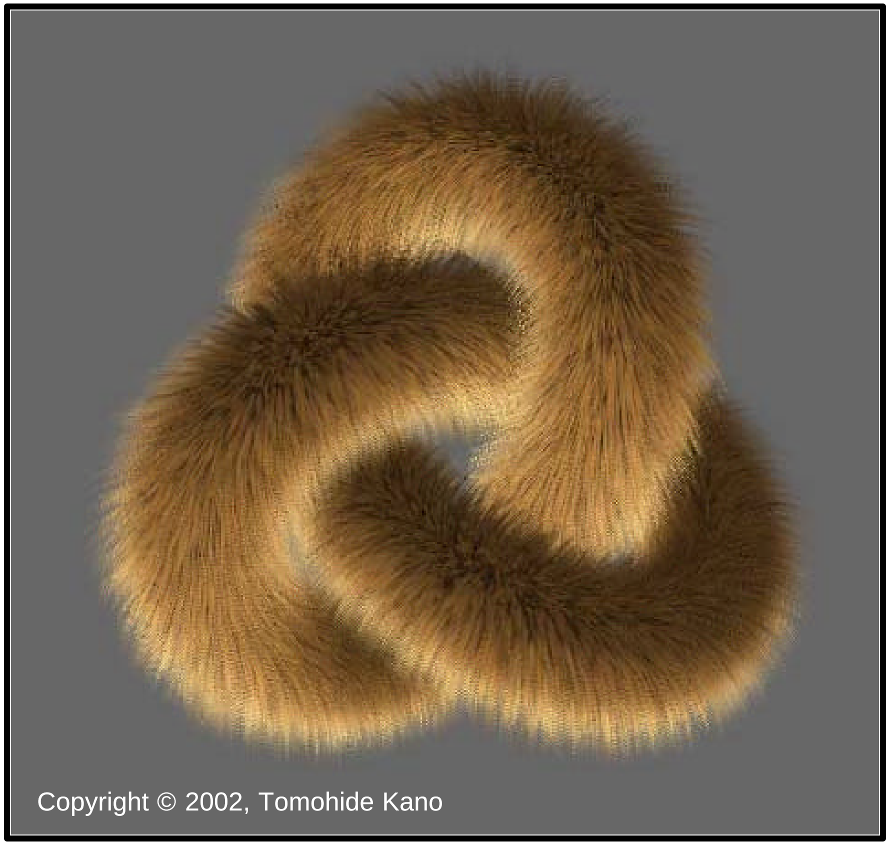


Normal Texture

Force Texture

ATI RADEON™ 8500 Fur Demo by Tomohide Kano

- Models effect of gravity and inertia on fur using math done in a pixel shader
- Drawn entirely with “shells”
- OpenGL Demo, with source code, available on ATI Developer Relations Website: www.ati.com/developer



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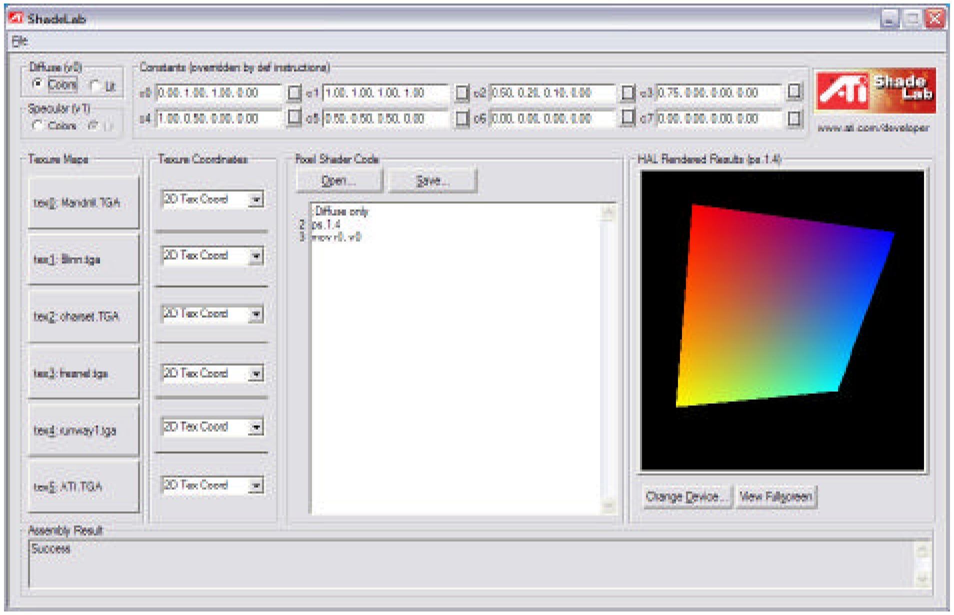
Tools from ATI

- ShadeLab
  - Pixel shader editor
  - Quickly experiment with ideas and check syntax
- FurGen
  - Fur rendering tool with a wide variety of customization parameters
  - Dynamically generates textures necessary for rendering fur according to user settings

ShadeLab

- Pixel shader editor
- Quickly experiment with and debug shaders
- Check syntax
- Choose from a variety of texture coordinate options



Diffuse (v0): ● Colors ○ Lit

Specular (v1): ○ Colors ● Lit

Constants (overridden by def instructions)

c0	0.00, 1.00, 1.00, 0.00	c1	1.00, 1.00, 1.00, 1.00	c2	0.50, 0.25, 0.10, 0.00	c3	0.75, 0.00, 0.00, 0.00
c4	1.00, 0.50, 0.00, 0.00	c5	0.50, 0.50, 0.50, 0.00	c6	0.00, 0.00, 0.00, 0.00	c7	0.00, 0.00, 0.00, 0.00

Texture Maps	Texture Coordinates
tex0: Mandrill.TGA	2D Tex Coord
tex1: Blinn.tga	2D Tex Coord
tex2: charset.TGA	2D Tex Coord
tex3: fresnel.tga	2D Tex Coord
tex4: runway1.tga	2D Tex Coord
tex5: ATI.TGA	2D Tex Coord

Pixel Shader Code

```
; Diffuse only
ps.1.4
mov r0, v0
```

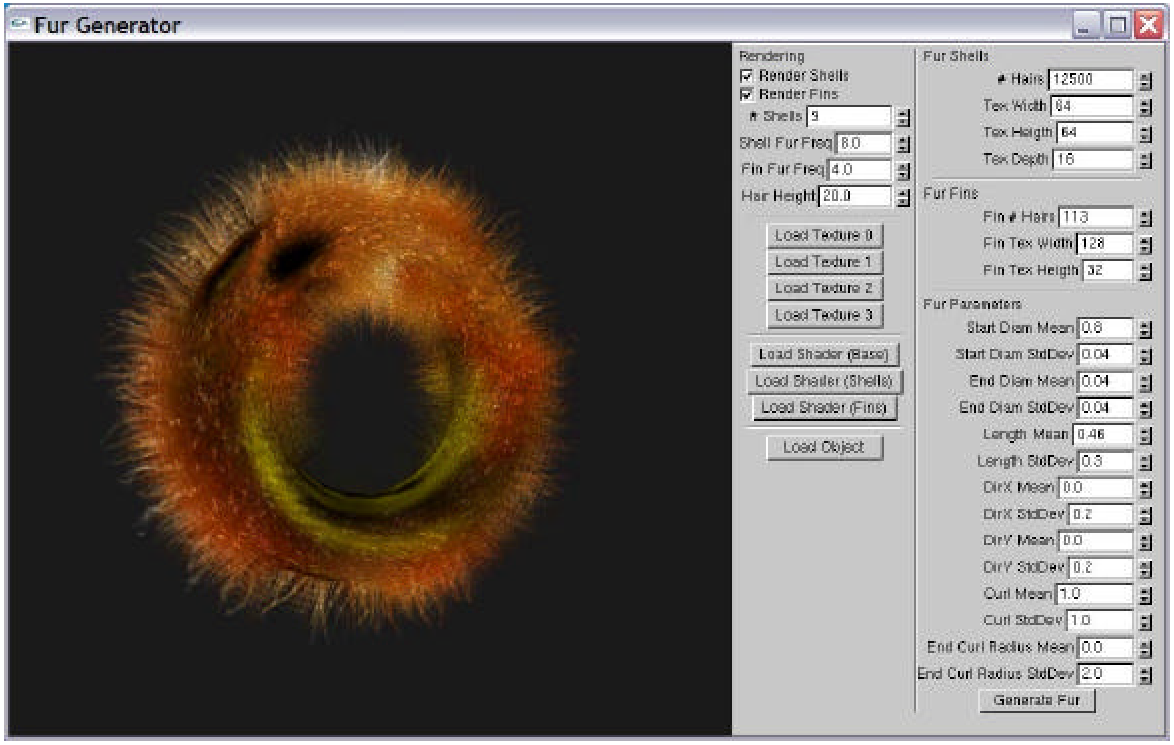
HAL Rendered Results (ps.1.4)

Assembly Result

Success

FurGen Fur Generation Utility

- User can tweak fur parameters such as length, curliness, color etc.
- Renders shells and fins
- Tangent map specifies tangent direction for anisotropic lighting
- Uses 1.4 Pixel Shaders for rendering



Rendering

☑ Render Shells

☑ Render Fins

# Shells 9

Shell Fur Freq 8.0

Fin Fur Freq 4.0

Hair Height 20.0

Fur Shells

# Hairs 12500

Tex Width 64

Tex Heigth 64

Tex Depth 16

Fur Fins

Fin # Hairs 113

Fin Tex Width 128

Fin Tex Heigth 32

Fur Parameters

Start Diam Mean 0.8

Start Diam StdDev 0.04

End Diam Mean 0.04

End Diam StdDev 0.04

Length Mean 0.46

Length StdDev 0.3

DirX Mean 0.0

DirX StdDev 0.2

DirY Mean 0.0

DirY StdDev 0.2

Curl Mean 1.0

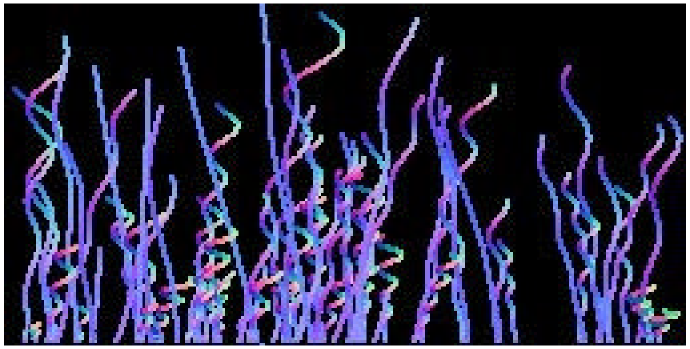
Curl StdDev 1.0

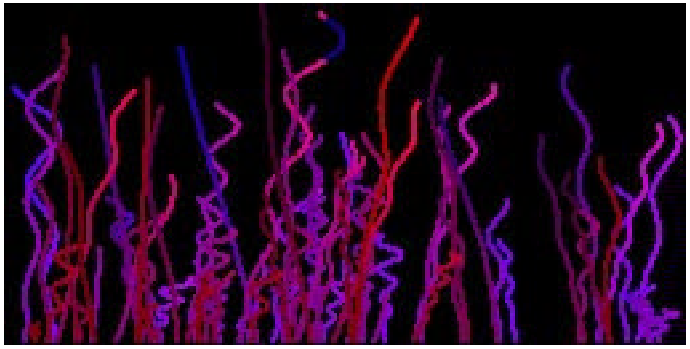
End Curl Radius Mean 0.0

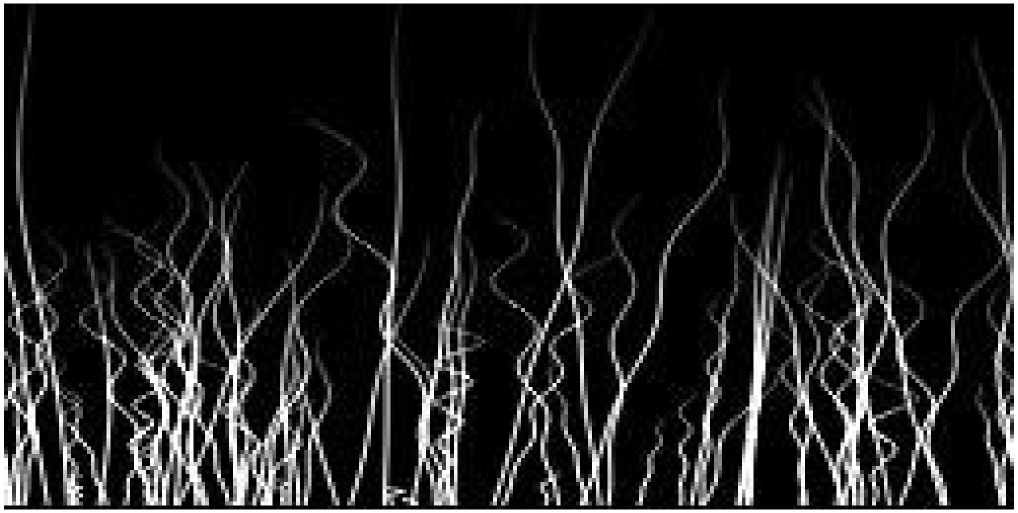
End Curl Radius StdDev 2.0

FurGen Fur Generation Utility

- Tangent Map
- Density Channel
- Bald-spots with albedo alpha







The Road to ps.2.0

- ps.1.4 is a good preparation for how to think about ps.2.0 pixel shaders
  - Unified instruction set
  - Floating point pixel pipeline
    - Think vectors, not colors
    - rcp, rsq etc
  - 16 textures
  - 64 ALU ops, 32 texture ops
  - Flexible dependent texture reads
    - Up to four levels of dependency

Summary

- DirectX 8.1 Pixel Shader Architecture (ps.1.4)
  - Inputs and Outputs
  - Unified Instruction set
  - Flexible dependent texture read
  - Projective Dependent Reads
- Gallery of Shaders
  - Image Processing
    - Popular new trend. The “lens flare” of 2002 - 2003?
    - Image-space outlining for NPR
  - Polynomial Texture Maps from HP
  - Refraction
  - Skin
  - Dynamic Fur – Doing physics with the rasterizer!
- Tools from ATI
  - ShadeLab
  - FurGen
- Looking Forward: DX9 ps.2.0

References

- DirectX 8.1 SDK
- ATI DevRel Website www.ati.com/developer
- T. Malzbender, D. Gelb, and H. Wolters, “Polynomial Texture Maps,” Computer Graphics, Proceedings of ACM SIGGRAPH 2001. www.hpl.hp.com/ptm
- New book coming out in the Spring:

  “Vertex and Pixel Shader Programming Tips and Tricks,” Wolfgang Engel, ed. Wordware, 2002

ATI @ GDC

- Alex Vlachos - Designing a Game's Shader Library for Current & Next Generation Hardware
  - Today at 4pm
- Arcot Preetham Nathaniel Hoffman - Rendering Outdoor Light Scattering in Real-Time
  - Today at 4pm
- Come by the booth!

Questions