Implementing Bump-Mapping using Register Combiners

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Overview

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  - Required GPU Features
- Overview of Bump-Mapping Technique
  - Lighting Equation
  - Rendering Strategy
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  - Relationship to Texture Space
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  - Light and Half-angle Vector Calculations
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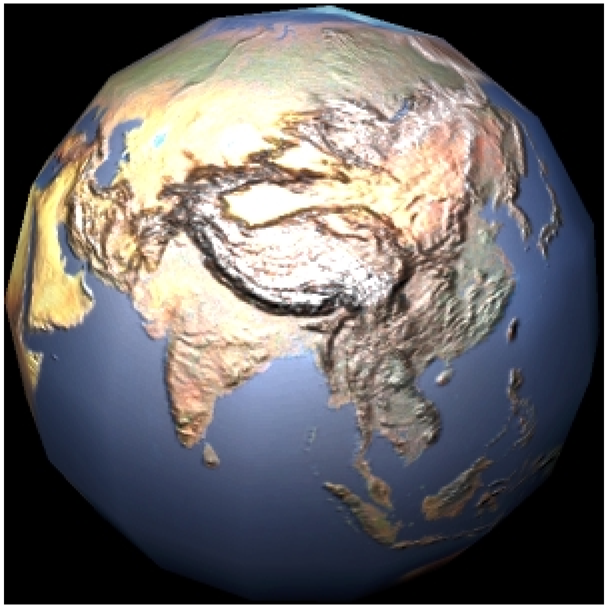
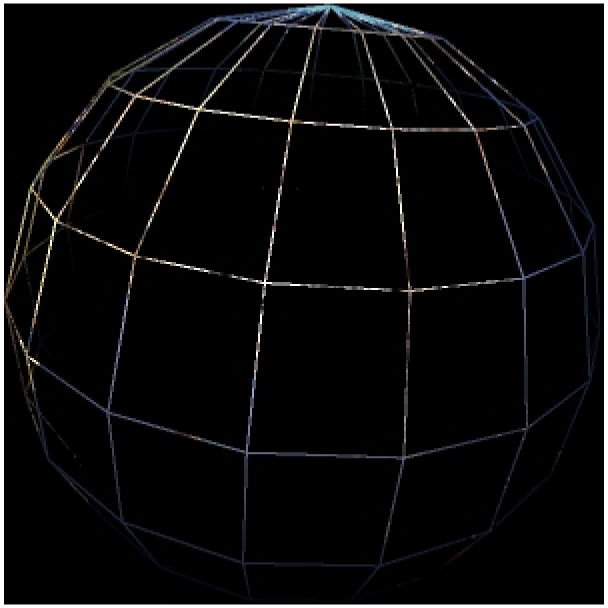
Why Bump-Mapping?

- Offers Accurate Lighting at the Pixel Level
- Provides Increased Realism
  - Surface detail
  - Surface irregularities
- Simulates Complex Geometry
  - Reduces geometric complexity required to capture a certain level of detail
    - Memory and Performance benefits
  - Form of lossy geometry compression
- Looks Great!

Why Bump-Mapping?

- **Simulate surface detail on an object by computing accurate lighting on a per-pixel basis.**





- **Vertex lighting would require significantly more polygons to capture same amount of detail.**

Why Bump-Mapping?

- **Particularly compelling in dynamic scenes**
  - **Moving objects with respect to light(s)**
  - **Animated characters**

- **Demo…**

What GPU features required?

- **Register Combiners – for per-pixel dot-products and additional lighting equation math**
  - **NV_register_combiners**

  ARB_texture_env_dot3 can be used instead, but with substantially less flexibility in the lighting equation

- **Dual or Quad Texture – for normal map, diffuse map, gloss map, normalization cube-map, etc.**
  - **ARB_multitexture**
- **Cube Maps – (optional) for per-pixel normalization**
  - **ARB_texture_cube_map**
- **Vertex Program – (optional) for offloading per-vertex setup code**
  - **NV_vertex_program**

Overview of Bump-Mapping Technique

- **Basic Idea:**
  - **Start with a model.**
  - **Provide per-pixel normals.**
  - **Provide other required per-pixel lighting parameters (light vector, half-angle vector, etc.).**
  - **For each pixel:**

    Evaluate "some" lighting model using per-pixel normal and other lighting parameters.

Typically use a variant of Blinn's version of the Phong lighting model:

$$out_{col} = diffuse_{col} * (N \bullet L) + spec_{col} * (N \bullet H)^{m}$$

Overview of Bump-Mapping Technique

- **How this is done in real-time:**
  - **Encode normals into a texture.**
  - **Map the “normal map” texture onto a model using standard 2D texture mapping.**
  - **Compute L and/or H vectors on a per-vertex basis and interpolate these across a triangle.**
  - **Compute the necessary dot-products using texture combining hardware (ex. register combiners)**

Requires custom vertex processing AND some pixel processing – ideal for GeForce-class GPUs.

Overview of Bump-Mapping Technique

- **Other lighting models possible but we'll focus on Blinn-Phong for simplicity :**

  $$out_{col} = diffuse_{col} * (N' \bullet L) + spec_{col} * (N' \bullet H)^m$$

- **Ignore (for now)**
  - **ambient, spotlighting, shadowing, distance atten.**

"Key" in implementing bump-mapping is understanding:

1. **How to provide the GPU with the per-pixel parameters (vectors N', L, and H)**
2. **How to compute the per-pixel dot-products**

Providing Per-Pixel Parameters: The Normal Map

- Per-pixel normal vectors specified using a "Normal Map"
- Normal Map
  - 2D texture map that encodes (x,y,z) unit-length normal vectors.
  - GL_RGB:

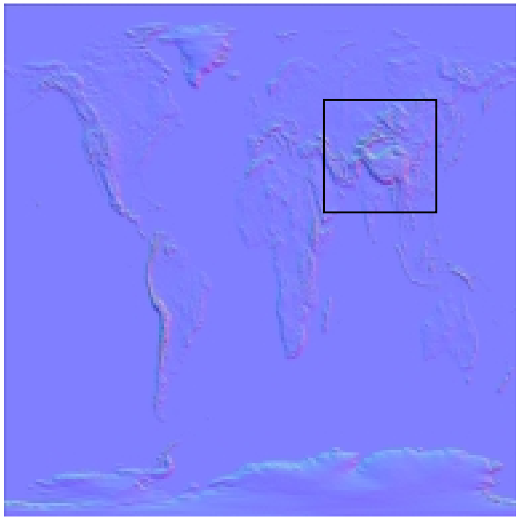
Signed	(R,G,B) = (x,y,z)
Unsigned	(R,G,B) = .5 * (x,y,z) + (.5, .5, .5)

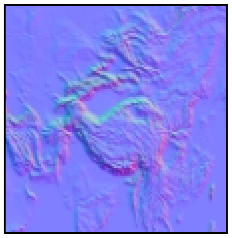
  - GL_HILO_NV:

Signed	(HI,LO) = (x,y)
Unsigned	N/A

Providing Per-Pixel Parameters: The Normal Map

- **Normal Map constructed from a Height Map**
  - **Convert height-field to normal map using finite differencing (di/ds, di/dt, scale)**



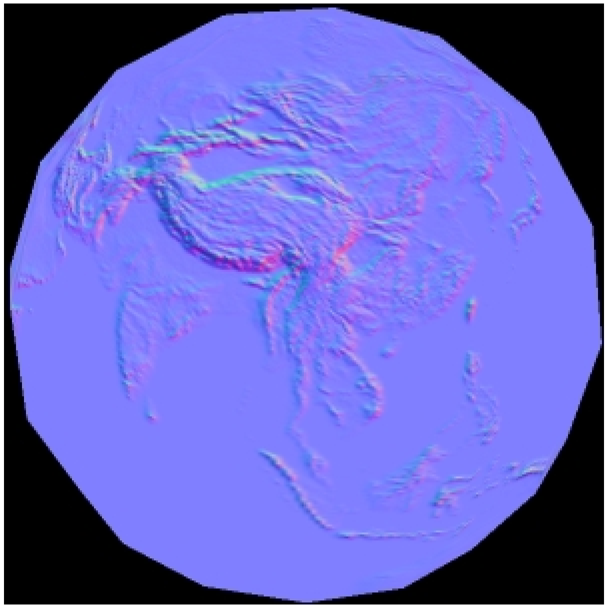


Here, normals in the [-1..1] range are compressed to the [0..1] range

The mostly chalk blue appearance is because the "straight up" normal is [0.5 0.5 1.0]

Providing Per-Pixel Parameters: The Normal Map

- **Texture the model with the Normal Map**



Normal Map applied to sphere model.

… Per-pixel normals

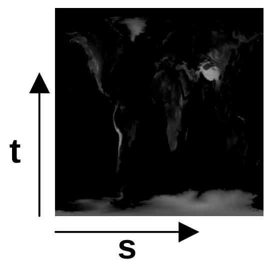
In order to compute meaningful per-pixel dot-products, the L, H, and N' vectors must be defined in the *same* coordinate space:

- **World space**
- **Eye space**
- **Any other space**

Must understand what space the per-pixel normals are in…

Understanding the Normal Map

- **Recall how we constructed the normal map**
- **Finite differencing**



(di/ds, di/dt, scale) = (1, 0, -di/ds) x (0, 1, -di/dt)

di/ds = change in height when moving along s axis

di/dt = change in height when moving along t axis

In a local region of constant height

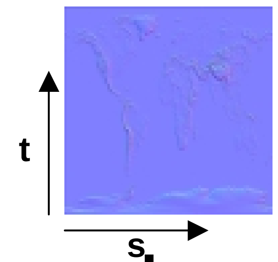
(0, 0, scale) = (1, 0, 0) x (0, 1, 0)

and the normal points “straight up (or down)”

Understanding the Normal Map

- **Finite differencing**

  (di/ds, di/dt, scale) = (1, 0, -di/ds) x (0, 1, -di/dt)



- **When mapped onto a model in 3-space, di/ds and di/dt correspond to the change in height when moving along S and T *direction vectors* defined in 3-space.**
  - **S and T indicate the direction in which the texture is mapped or “wrapped” onto the model.**
  - **S, T, and SxT form a basis called “Texture Space” – this is the space per-pixel normals are defined in**

Understanding the Normal Map

- **So…**

  Normals in the normal map are defined in Texture Space (S,T, SxT)

  AND

  Texture Space is defined by how a 2D texture is mapped onto a 3D model (more on this later)

- **For correct per-pixel lighting we must either:**
  - **Compute dot-products in Texture Space**
  - **Compute dot products in some other space**
    - **Would require transforming each N’ to the correct space before using it**

Providing Per-Pixel Parameters: The Light and Halfangle Vectors

- In order to compute lighting, we need to specify per-pixel L and H vectors.
- Since N' is already in texture space, it's convenient to provide vectors in the same space

- Overview
  - Compute vectors at each vertex of the model
  - Interpolate (and renormalize) across a poly
    - Unit-length vectors per-pixel

- Specifying L and H vectors is pretty much the same
  - For simplicity, we'll just consider L…

Providing Per-Pixel Parameters: The Light and Halfangle Vectors

- **For each vertex…**
  - **compute unit-length L vector**
  - **transform into Texture Space**

- **Specify the Texture Space L vector as a vertex parameter and allow it to be interpolated**

Two ways:

1. **Specify L as an RGB color**
   - **Colors clamped to [0,1] so must "range compress" the L vector (i.e. glColor3f(.5(L_x+1), .5(L_y+1), .5(L_z+1)))**
   - **Each R, G, B component interpolated independently**
     - **Renormalize using the register combiners**
2. **Specify L as (s,t,r) texture coordinates and use a "Normalization" Cube-Map to produce unit-length vectors**

Providing Per-Pixel Parameters: The Normalization Cube-Map

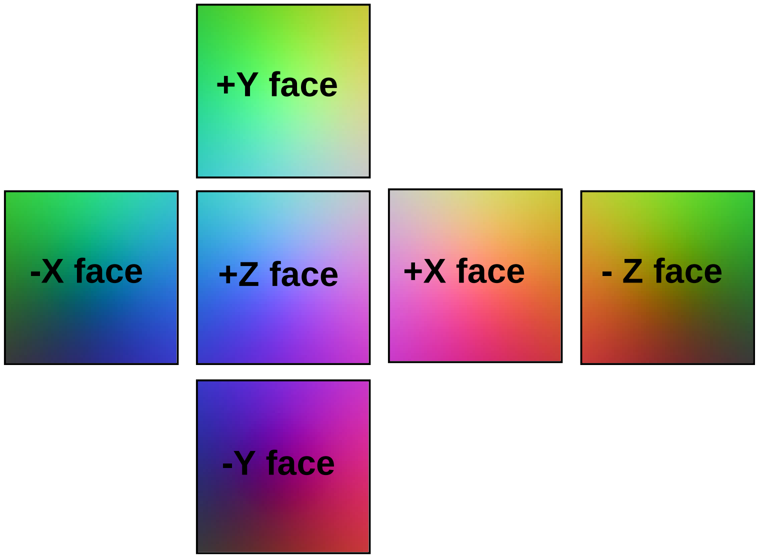
- **Cube-Maps not only useful for Environment Mapping**
- **Useful for looking up ANY function of direction.**

  Think: Cube-Map = F(V) where V is a direction vector

- **Normalization Cube-Map encodes the function:**
  F(V) = normalize(V)
  - **Each texel of cube-map stores RGB representing range-compressed normalized vector from origin to the texel**
  - **Magnitude does not alter cube-map texture fetch**
    - **Valid way to get normalized version of (s,t,r)**
    - **32x32x6 often sufficient (GL_NEAREST filtering)**

Providing Per-Pixel Parameters: The Normalization Cube-Map

- **Normalization Cube-Map (unsigned RGB)**

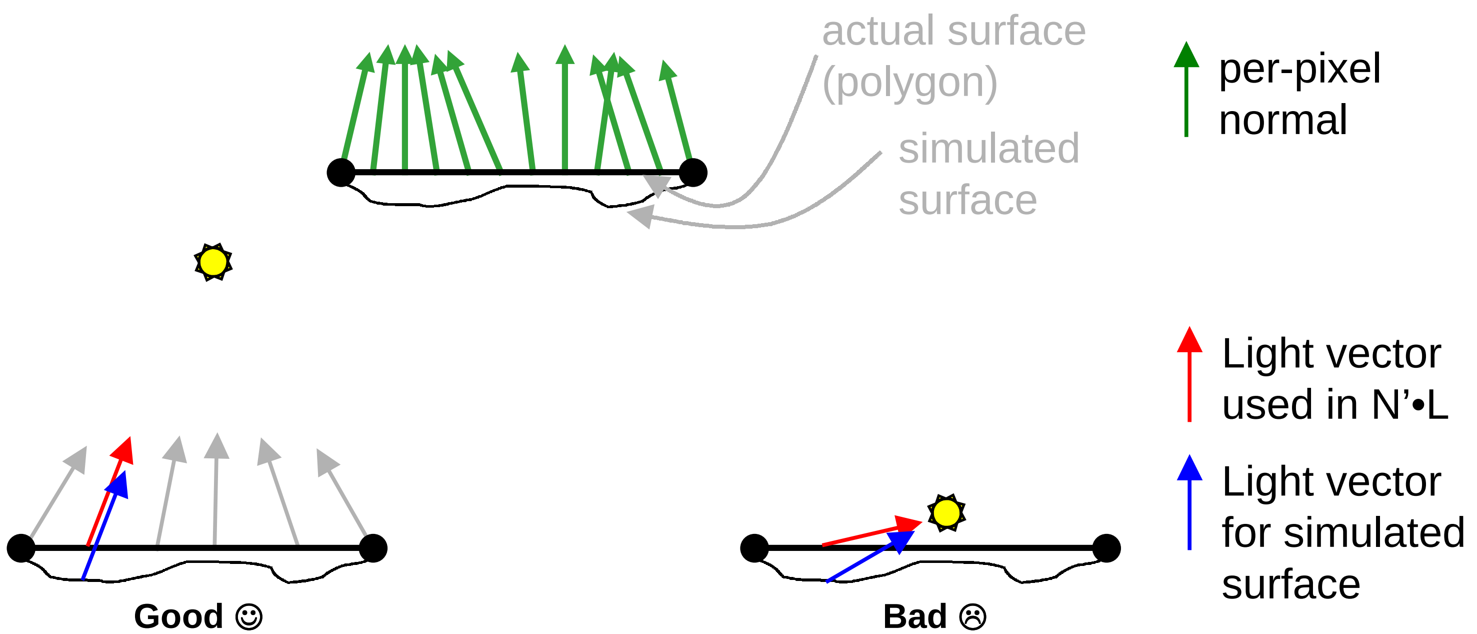


- **What happens if you don't re-normalize? (highlights lost across poly!)**

Why Interpolation Works…

- **Bump-Mapping based on an assumption:**

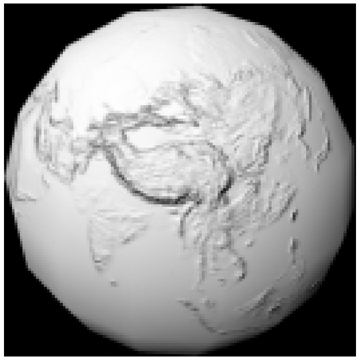
  distance from actual surface to light >>
  distance from simulated surface to actual surface



- **This is a reasonable assumption for small scale detail.**

Computing Dot-Products using the Combiners

Diffuse Lighting



tex0: normal map (N')

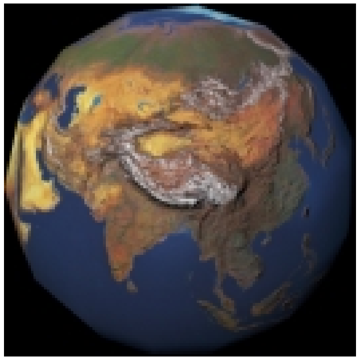
tex1: normalization cube-map (L)

```
!!RC1.0
{
   rgb {
        spare0 = expand(tex0) . expand(tex1);   // NdotL
   }
}
out.rgb = spare0;                         // auto clamped to [0,1]
```

"expand" mapping assumes tex0 and tex1 are unsigned RGB
- not required for signed RGB formats

Computing Dot-Products using the Combiners

Diffuse w/ Decal Modulation



tex0: normal map (N')

tex1: normalization cube-map (L)

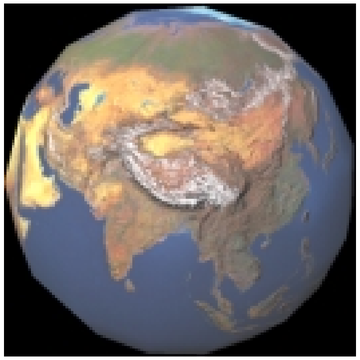
tex2: decal texture

```
!!RC1.0
{
   rgb {
        spare0 = expand(tex0) . expand(tex1);   // NdotL
   }
}
out.rgb = spare0 * tex2;
```

Single pass on GeForce3 (Two-pass on GeForce)

Computing Dot-Products using the Combiners

Add Ambient w/ const. color



tex0: normal map (N')

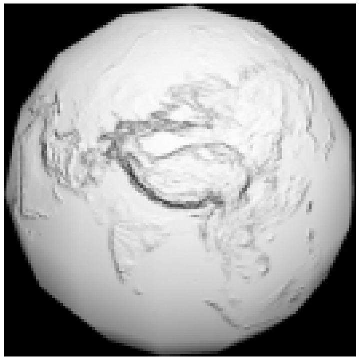
tex1: normalization cube-map (L)

tex2: decal texture

```
!!RC1.0
const0 = ( 0.2, 0.2, 0.2, 0 );                  // Ambient
{
   rgb {
        spare0 = expand(tex0) . expand(tex1);   // NdotL
   }
}
out.rgb = spare0 * tex2 + const0;
```

Computing Dot-Products using the Combiners

Specular Lighting (N'•H)



tex0: normal map (N')

tex1: normalization cube-map (H)

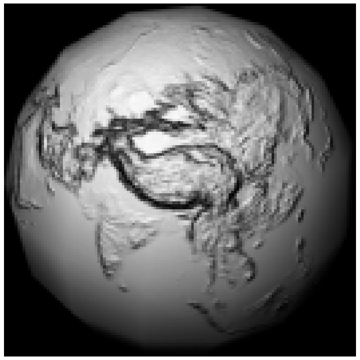
```
!!RC1.0
{
   rgb {
        spare0 = expand(tex0) . expand(tex1);   // NdotH
   }
}
out.rgb = spare0;
```

Modulate w/ a constant for specular color

$(N•H)^m$ where m = 1
What about higher powers of m?

Computing Dot-Products using the Combiners

Specular Lighting (N'•H)^4

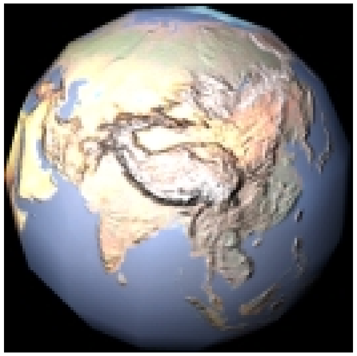


```
!!RC1.0
{
   rgb {
        spare0 = expand(tex0) . expand(tex1);   // NdotH
   }
}
{
   rgb {
        spare0 = unsigned(spare0) * unsigned(spare0);
   }
}
final_product = spare0 * spare0;
out.rgb = final_product;
```

Clamp to [0,1] before squaring

Computing Dot-Products using the Combiners

Diffuse + Specular



$decal_{col} * (N' \bullet L) + spec_{col} * (N' \bullet H)^4$

tex0: normal map (N')

tex1: normalization cube-map (L)

tex2: normalization cube-map (H)

tex3: decal texture

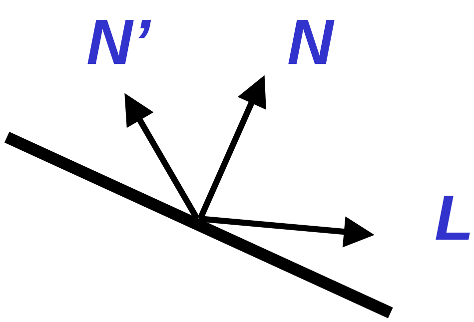
Computing Dot-Products using the Combiners

Diffuse + Specular: $decal_{col} * (N' \bullet L) + spec_{col} * (N' \bullet H)^4$

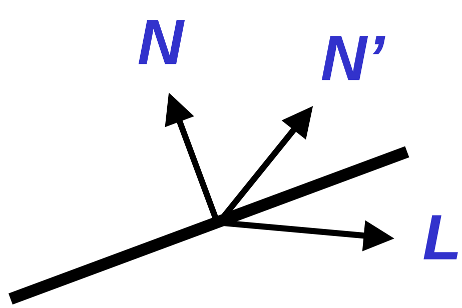
```
!!RC1.0
const0 = ( 0.2, 0.2, 0.2, 0 );                      // Spec. color
{
   rgb {
        spare0 = expand(tex0) . expand(tex1);   // NdotL
        spare1 = expand(tex0) . expand(tex2);   // NdotH
   }
}
{
   rgb {
        spare0 = tex3 * unsigned(spare0);       // decal*NdotL
        spare1 = unsigned(spare1) * spare1;     // NdotH 2
   }
}
final_product = spare1 * spare1;                   // NdotH 4
out.rgb = const0 * final_product + spare0;
```

Surface Self-Shadowing

- **Previous examples do not self-shadow correctly**
- **Two kinds of self-shadowing**
  - **max(0, L•N’) based on the perturbed normal**
  - **Also should clamp when L•N goes negative!**



Surface <u>should self-shadow</u> due to *perturbed* normal (i.e. L • N’ < 0)



Surface <u>should self-shadow</u> due to *unperturbed* normal (i.e. L • N < 0)

Self-Shadowing Computation

- Modulate specular and diffuse by: $(L_z < 0)\ ?\ 0 : 1$
  - Use mux() in the combiners
  - Simple, but may result in “hard” shadow boundary
    - Possible winking and popping of highlights.
  - Requires alpha portions of two combiners

```
{ alpha {
   spare0 = tex1.b; // spare0.a = Lz (unexpanded);
}}
{ alpha {
   discard = zero;
   discard = one;
   spare0 = mux(); // spare0.a = (Lz < 0) ? 0 : 1
}}
out.rgb = ... * spare0.a;
```

Self-Shadowing Computation

- Better, modulate by min(8*max(L_z,0), 1)
  - Steep ramp eliminates popping
  - Requires alpha portion of only one combiner

```
{ alpha {
   discard = expand(tex1.b);
   discard = expand(tex1.b);
   spare0 = sum();
   scale_by_four(); // spare0.a = 8 * Lz
}}
out.rgb = ... * unsigned(spare0.a);
```

- In either case, illumination does not appear on geometric “back side”.

Normalization in the Combiners

- **Previous examples used Normalization Cube-Map**
  - **Not necessary on GeForce3**

- **By using an approximation technique, can normalize in the combiners**

- **It can be shown (by numerical means) that…**

$$\text{Normalize}(V) \cong V/2 * (3 - V \bullet V) \quad \text{when}$$

1. **V is a vector derived from the interpolation of unit-length vectors across a polygon AND**
2. **The angle between all pairs of the original per-vertex vectors is no more than 40º (or so).**

For models of reasonable tesselation (and/or reasonable distance to the light and viewer) #2 holds

Normalization in the Combiners

- **Simplifying the approx.**

$$\begin{aligned} V/2 * (3 - V\bullet V) &= \quad 1.5V \quad - \; 0.5V * (V\bullet V) \\ &= V + 0.5V - \; 0.5V * (V\bullet V) \\ &= V + 0.5V * (\, 1 - (V\bullet V)\,) \end{aligned}$$

- **Compute simplified approx. in 2 general combiner stages…**

Normalization in the Combiners

Suppose col0 contains interpolated (de-normalized) vector compressed into [0..1] range

```
{ // normalize V (step 1.)
   rgb {
        spare0 = expand(col0) . expand(col0);   // VdotV
   }
}
{ // normalize V (step 2.)
   rgb {
        discard = expand(col0);                           // V in [-1..1]
        discard = half_bias(col0) * unsigned_invert(spare0);
        col0 = sum();
   }
}
```

V in [-0.5..0.5] ≡ 0.5V

1 – V•V

col0 = V + 0.5V(1 – V•V)

Normalization in the Combiners

- **Normalization of one vector requires 2 general combiners, but two vectors can be normalized in 3**
- **Combiner normalization FASTER than using cube-maps!**

For More Information…

- **NVIDIA OpenGL SDK**
  - **Technical Demos**
  - **Bump-Mapping Lab Exercises**
    - **Vertex Programming of Setup Code**
    - **Register combiner configuration**
- **Additional Bump-Mapping Presentations**
  - **Per-Pixel Lighting Mathematical background**
  - **Texture Space**
  - **Register Combiners**
  - **Bump-Mapping of Animated Models**
- **Available at NVIDIA Developer Website:**

  http://www.nvidia.com/developer

Acknowledgements

- **Scott Cutler**
  - **Newton-Raphson fast "combiner normalization" technique.**
- **Cass Everitt**
  - **Earth demo.**
- **Mark Kilgard**
  - **Slide content.**
  - **"A Practical and Robust Bump-mapping Technique for Today's GPUs" white paper.**

Questions, comments, feedback

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- www.nvidia.com/developer