AGDC Per-Pixel Shading

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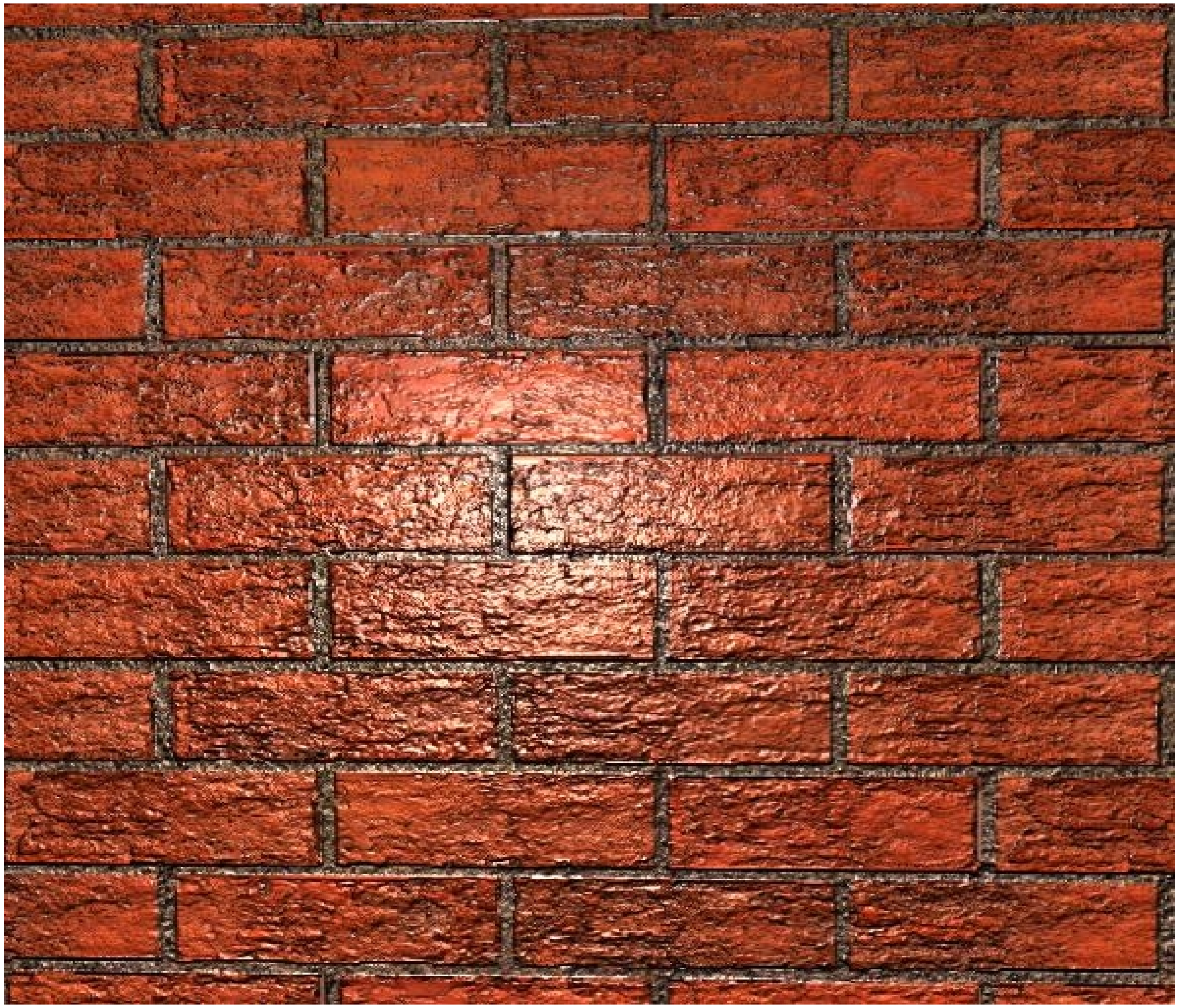
Goal Of This Talk

- The new features of Dx8 and the next generation of HW make huge strides in the area of Per-Pixel Shading
- Most developers have yet to adopt Per-Pixel Shading techniques, and rely on simple multi-texturing
- The goal of this talk is to introduce you to Per-Pixel Shading concepts necessary to understand and implement these techniques in your app

What is Per-Pixel Shading?

- Dynamic Shading computed on a per-pixel basis
- Per Pixel shading includes a variety of dynamic shading techniques
  - Bump Mapping
  - Per-Pixel Directional Lights
  - Per-Pixel Spot Lights
  - Per-Pixel Point Lights

A Single Quad Lit Per-Pixel



What this Talk will Cover

- Bump Mapping Overview
  - EMBM, Embossing, DOT3
  - Bump Mapping as Per-Pixel Shading
- Texture Space
  - A Vertex-Local Coordinate System
  - Animation And Per-Pixel Shading
- Per-Pixel
  - Directional Lights
  - Point Lights
    - Distance Attenuation
  - Spot Lights

What This Talk Will Cover

- DX8 Pixel Shaders
  - How they improve upon Dx7-Style Per-Pixel Shading
  - Integrating Pixel Shaders

Bump Mapping Overview

- Bump Mapping is a subset of Per-Pixel Lighting
- Bump Mapping examples such as Embossing simulate diffuse directional lighting
- Dx6 Environmental Bump Mapping (EMBM) simulates planar specular reflections
- However, DOT3 Per Pixel Lighting can be used to achieve diffuse and/or specular point lights, spotlights and volumetric lights as well

DOT3 Overview

- **This talk will primarily cover D3DTOP_DOTPRODUCT3, or DOT3 effects**
- **DOT3 is more generally useful for per-pixel lighting than either Embossing or EMBM**
- **DOT3 is a texture blending operation that performs a dot product between two vectors**
  - **It yields a value from 0 to 1**

Performing a Per-Pixel Dot Product

- **Directional Diffuse Lighting is computed by LightColor * (LightVector DOT SurfaceNormal)**

- **Directional Specular Lighting is computed via LightColor * (HalfAngle DOT SurfaceNormal)**

- **The DOT3 per-pixel operation allows us to perform L dot N or H dot N on a per-pixel basis**

Per-Pixel Dot Products

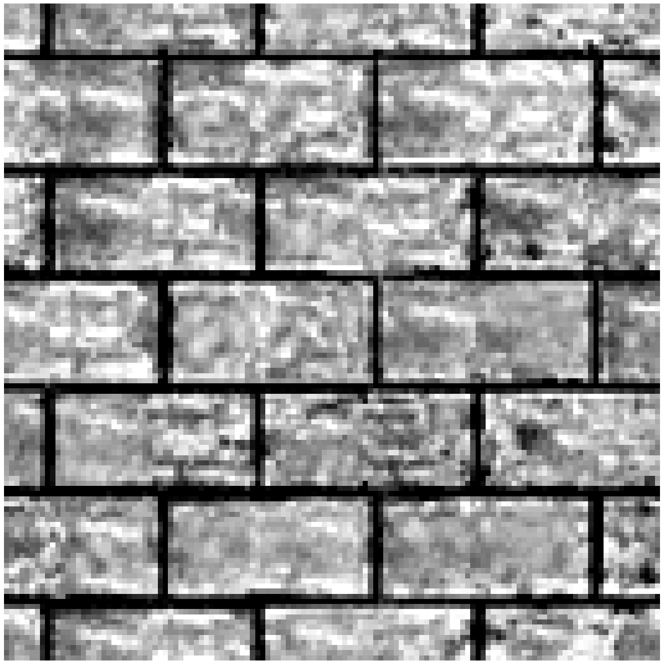
- To perform a per-pixel dot product, we require three things
- A Light Vector L
- A Surface Normal N
- A Common Coordinate System for L and N

The Light Vector L

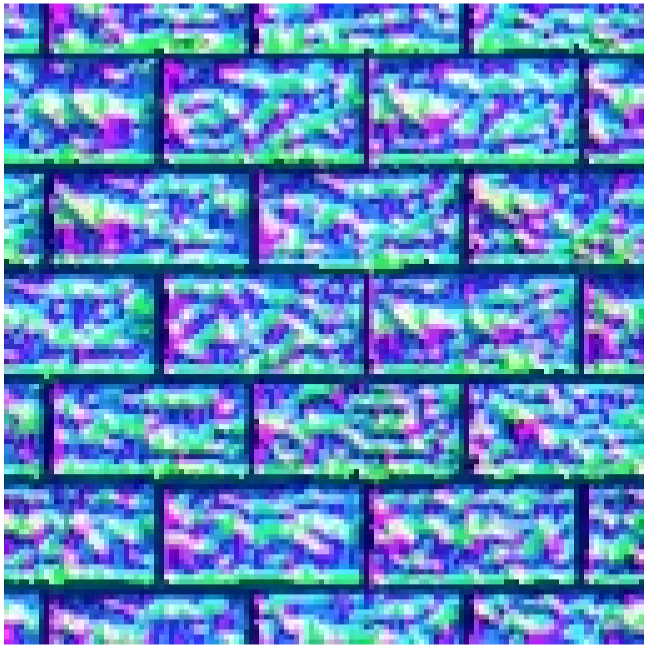
- We can store the Light Vector L on a per-vertex basis in an iterated color
- We can use either the Diffuse or Specular iterated color
- This allows the L vector to be interpolated across a triangle, just like a color
  - perspective correction is important for this

The Surface Normal N

- We also want a per-pixel surface normal N
- This is stored in a "Normal Map" which is typically derived from a Height Map



Height Map

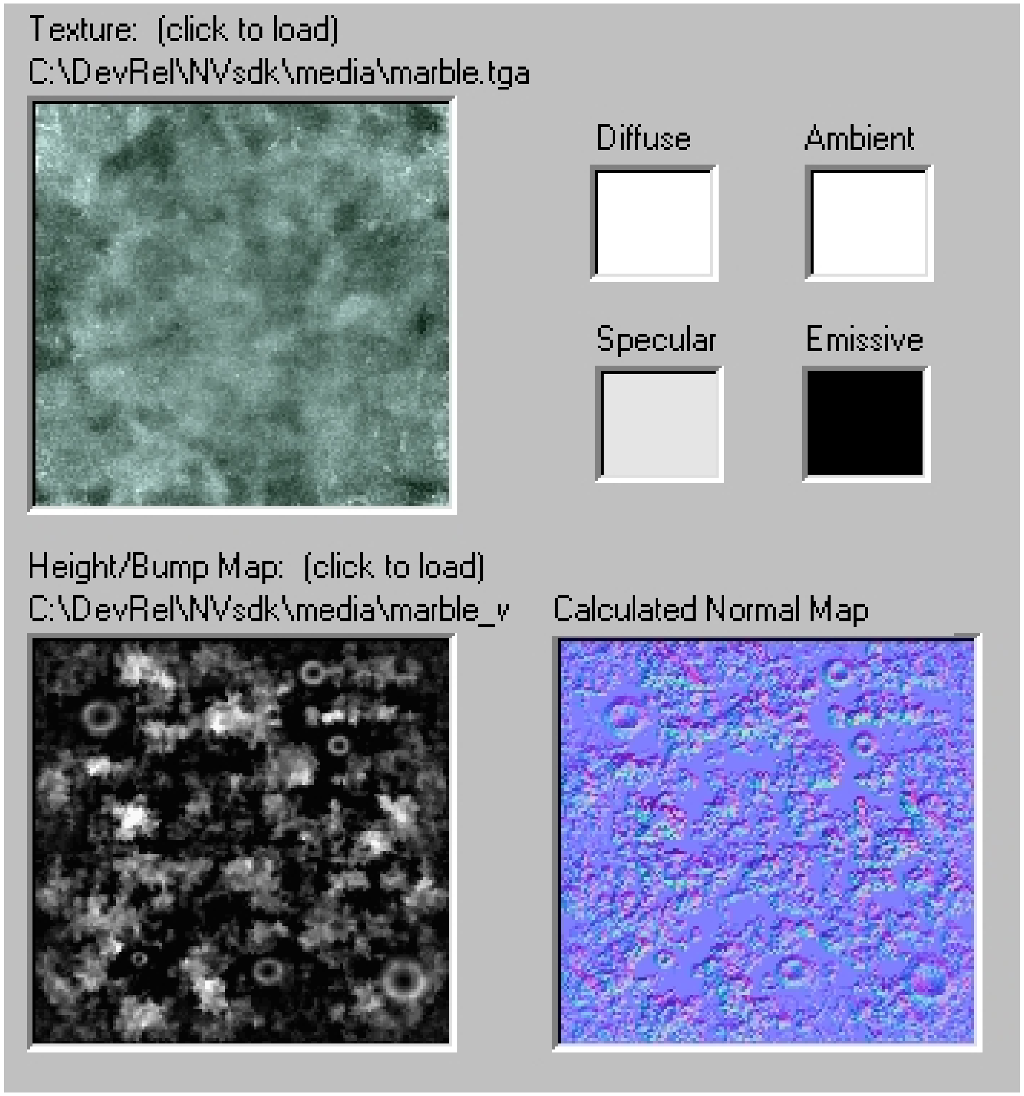


Normal Map

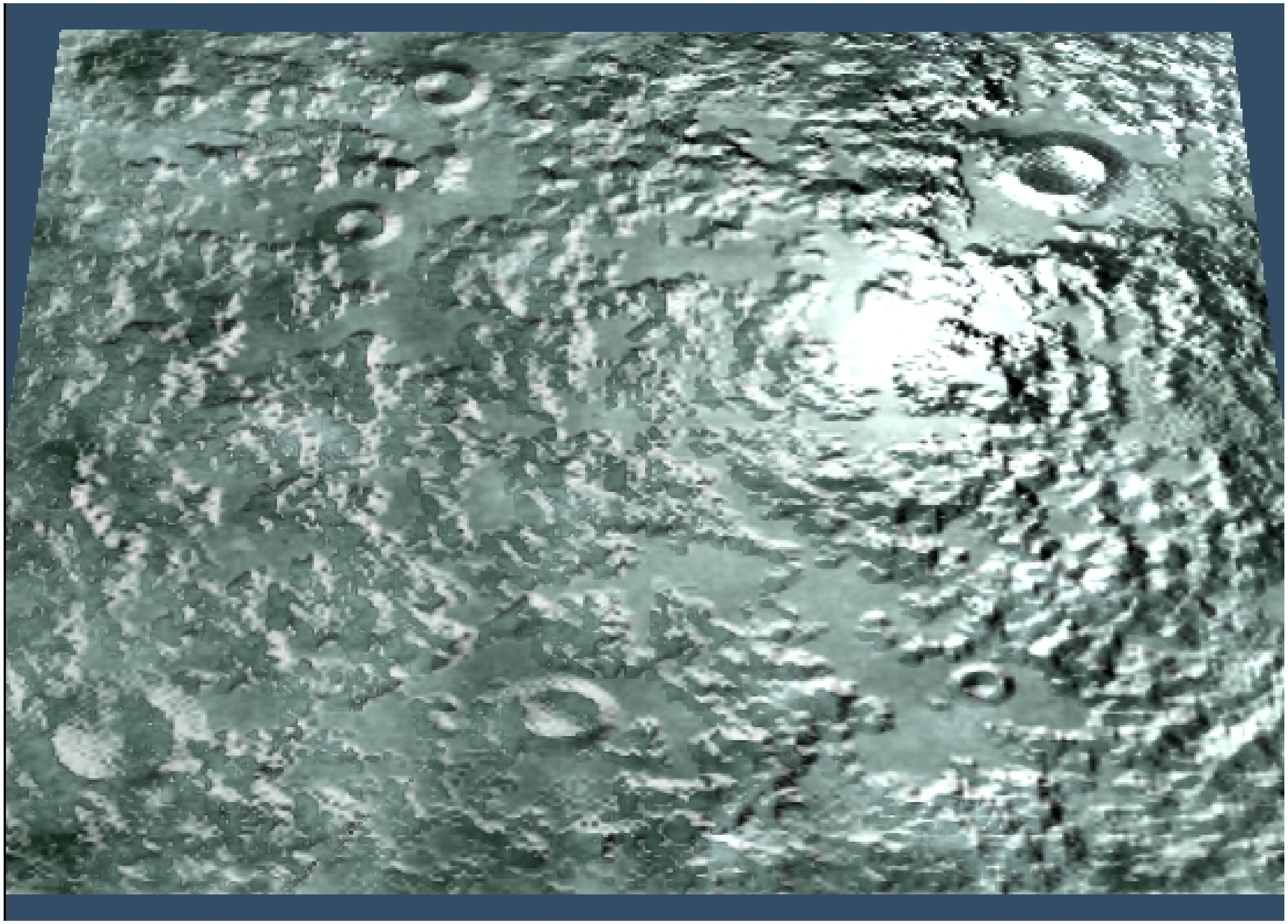
Normal Maps

- Normal Maps are just an array of normalized surface vectors encoded as RGB colors
- They are defined such that :
  - X maps to Red
  - Y maps to Green
  - Z maps to Blue
  - Alpha is available for gloss or other scalar values

Screenshot of BumpMaker Tool



Single Quad Lit With Per-Pixel Directional and Point Lights



What About a Common Coordinate System?

- The Surface Normals are expressed in their own coordinate system, such that
  - +X points to the Right
  - +Y points Up
  - +Z points Out of the screen
- The Light Vector is expressed in World Space
- Either N must be transformed into World Space with L, or we must transform L into this Normal Map coordinate system

Normals In World Space?

- We can generate Normal Maps in World Space, but then our world needs to be more or less uniquely textured, wasting texture memory
- This also only works for static geometry – what would happen if the geometry rotated?
- Here is the underlying problem : Texels Don’t Rotate

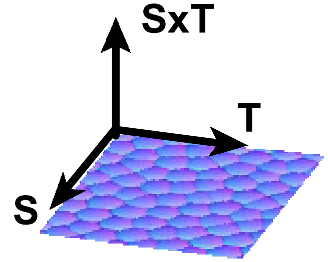
Help, My Texel Won’t Rotate!

- When we rotate Bump-Mapped geometry, the texels within the Normal Map don’t rotate along with the geometry
- Even if we could rotate each texel, it would be an expensive proposition to perform a per-texel rotation matrix
- This implies we need a way to move a light vector L from World Space into the Normal Map’s coordinate Space

Enter Texture Space

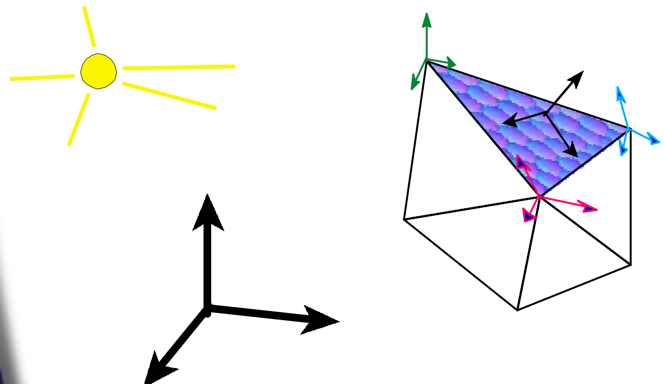
- Texture Space is a per-vertex coordinate system that expresses how to go from Model Space into the Normal Map Coordinate System, where :
  - +X Axis points to the Right
  - +Y Axis points Up
  - +Z Axis points Out of the screen

Texture Space Diagram



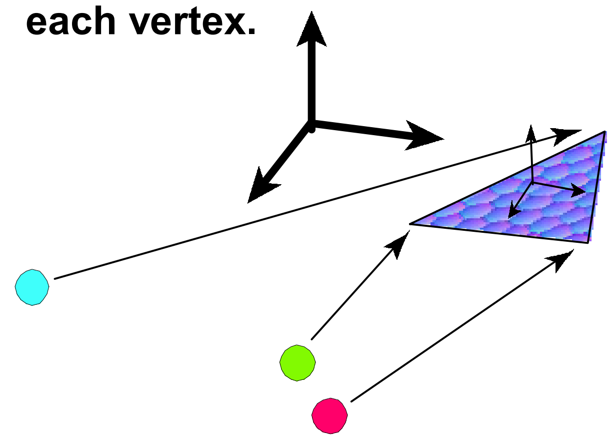
Normal Map – A flat plane in S,T direction

L and N are expressed in different coordinate systems



Solution = Rotate Light position into S,T,SxT space.

Result: New light position for each vertex.



How to Author for Texture Space

- The best method for generating Texture Space for your geometry is as follows :
  - Have the artist apply bump maps in their authoring tool – or just use the same mapping as the decal
    - Don't let them use texture mirroring
    - Don't use degenerate projections (ie stretched textures)
  - When loading in a model, create an extra set of 3 3D vectors per vertex
    - These will store the axes of the Texture Space basis
    - Generate the Texture Space vectors from the vertex positions and bump map texture coordinates

How to Generate Texture Space?

- For each triangle in the model :
  - Use the x,y,z position and the s,t bump map texture coordinates
  - Create plane equations of the form :

  - $Ax + Bs + Ct + D = 0$
  - $Ay + Bs + Ct + D = 0$
  - $Az + Bs + Ct + D = 0$

- Solve for the texture gradients dsdx, dsdy, dsdz, etc.

Generating Texture Space

- Now treat the dsdx, dsdy, and dsdz as a 3D vector representing the S axis < dsdx, dsdy, dsdz >
- Do the same to generate the T axis
- Now cross the two to generate the SxT axis – this is the ‘Z’ or up axis of Texture Space, and is typically close to parallel with the triangle’s normal
- If your SxT and the triangle normal point in opposite directions, the artist applied the texture backwards – have the artist fix this, or negate the SxT axis

Generating Texture Space

- These 3 Axes together make up a 3x3 rotation/scale matrix

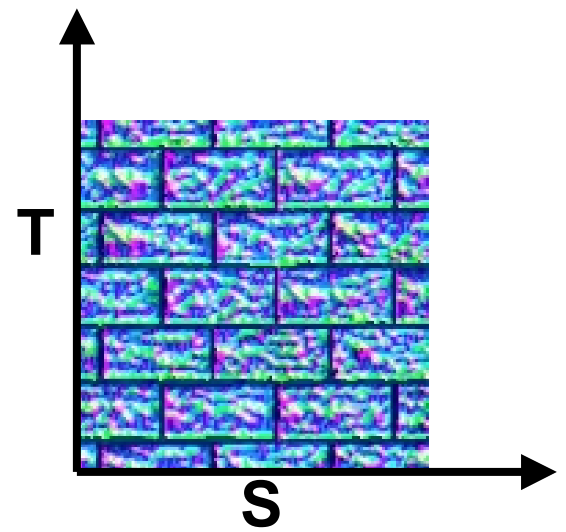
dsdx dtdx SxTx

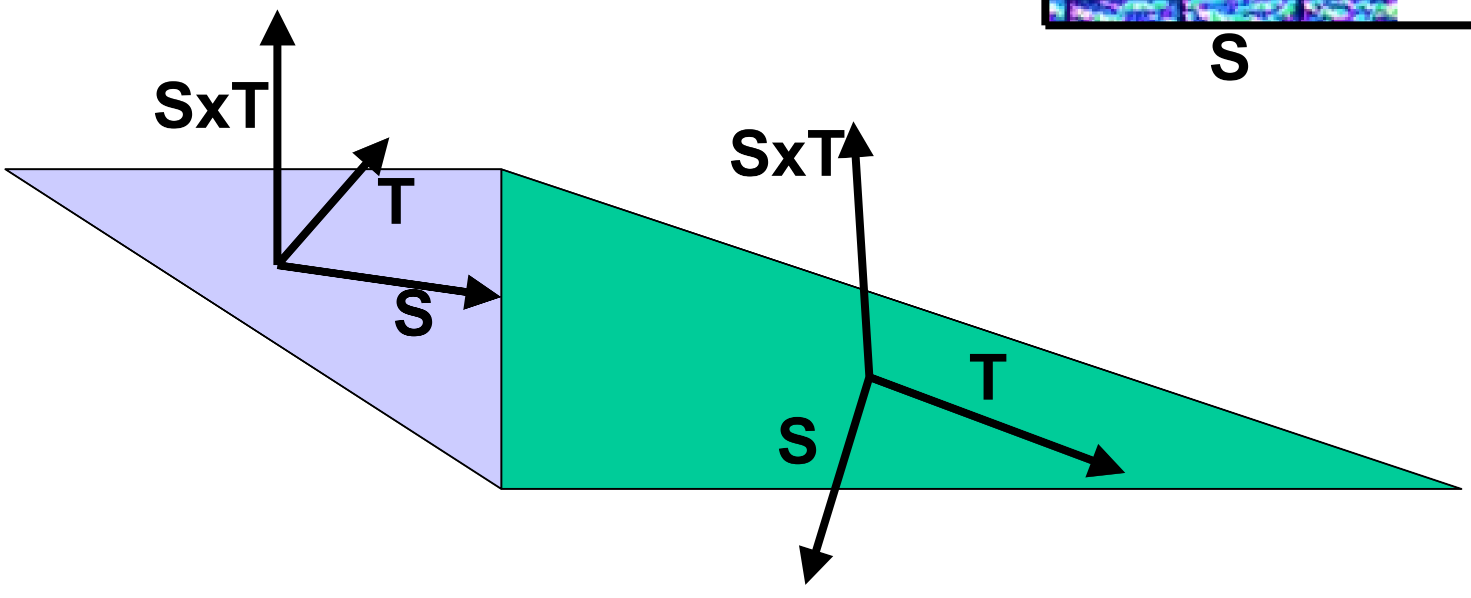
dsdy dtdy SxTy

dsdz dtdz SxTz

Putting an XYZ model-space vector through this 3x3 matrix produces a vector expressed in local Texture Space

Per-Triangle Bases





Per-Triangle Bases

- We now have a coordinate basis for each triangle
- We need them on a per-vertex basis so they can vary smoothly across our geometry
- The solution :
  - For each vertex, sum up the S vectors from each face that shares this vertex
  - Do the same for all T and SxT vectors
  - Normalize each sum vector
  - Optionally scale by the average original magnitude of S,T or SxT if your texture map is applied anisotropically
  - The result is per-vertex Texture Space
  - This is analogous to calculating vertex normals for lighting

Per-Vertex Texture Space

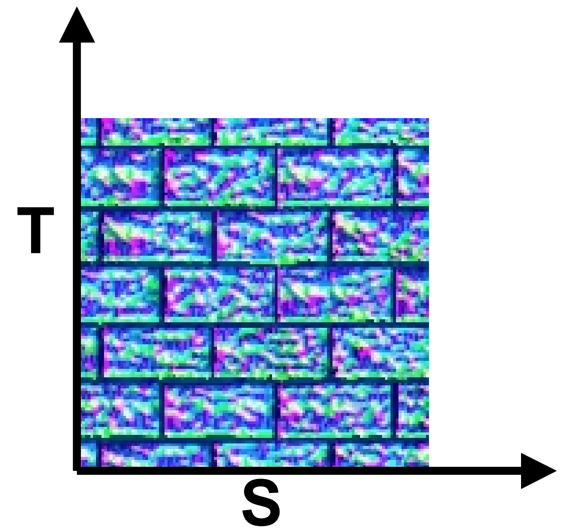
- Now we have what we need to move a light into a local space defined at each vertex via the Texture Space Basis Matrix

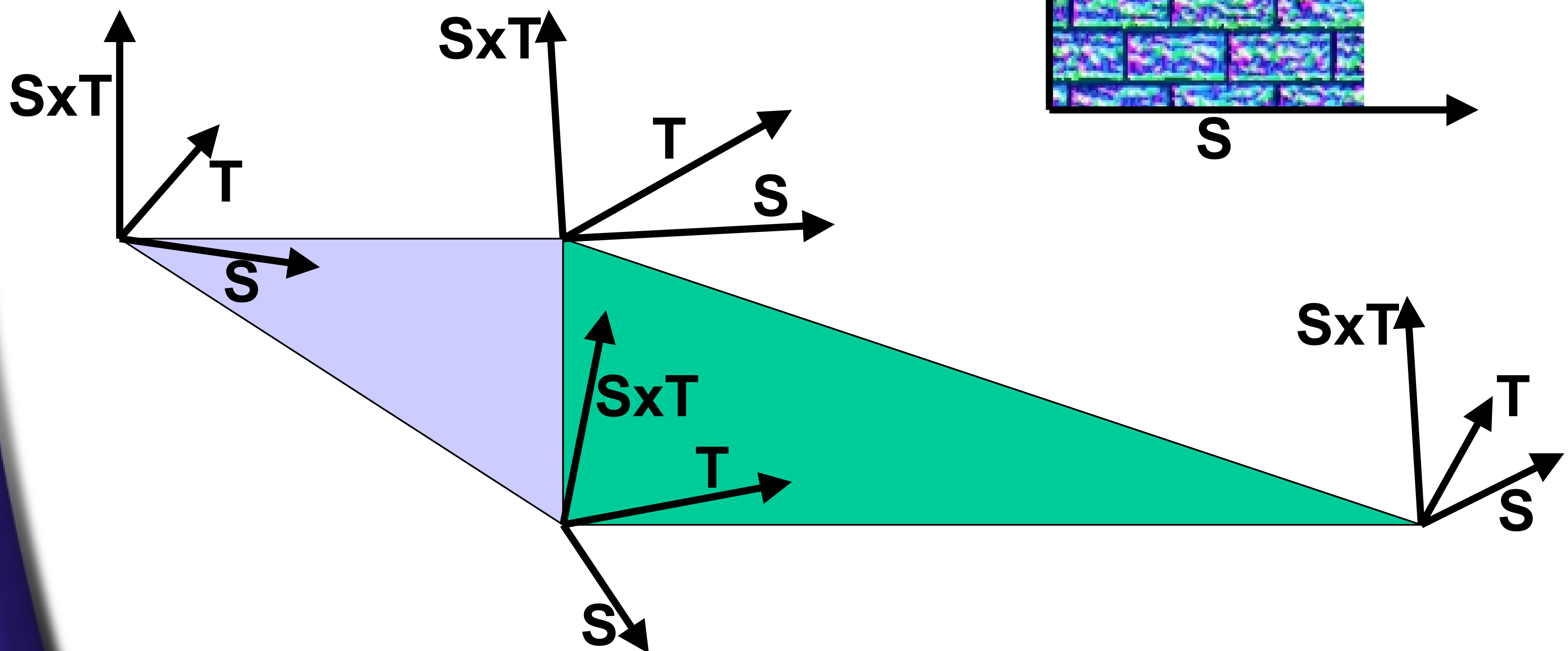
- For each per-pixel light, we move it's L or H vector into local Texture Space

  - On the CPU with C code
  - Or on the GPU with a vertex program

The Resulting Per-Vertex Texture Space

Per Vertex Texture Space is derived From Shared Faces





Texture Space In Practice

- **The L or H vector is linearly interpolated across the polygon in Texture Space :**
- ***In the diffuse or specular color***
  - **It must be normalized before storing in the iterated color**
  - **It will get de-normalized across large polygons**
  - **Doesn't handle anisotropy well**
- ***Or in a set of 3D texture coordinates***
  - **Use a Cube Map to renormalize the vector**
    - **Able to support scaling on textures**
    - **Can avoid CPU or GPU work**
  - **The L or H vector can be renormalized per-pixel via a texture, such as a Cube Map, Volume Map or Projected Texture**

What about Animation?

- When triangles distort, so do their texture gradients, invalidating the Model Space->Texture Space matrix
- When triangles rotate relative to Model Space, the Model Space->Texture Space matrix is invalid
- Therefore, the Texture Space will need to be updated or recomputed during animation
- The obvious approach, and one practical for simple models, is to simply go through the previous steps for each animation frame
  - Regenerate Texture Space for each triangle, then each vertex

A Better Way – Update the Bases

- The two most popular animation techniques both work with Texture Space bump mapping WITHOUT requiring recalculating the entire basis

- Bone-Based Skinning (Indexed or Not)

- Keyframe Interpolation

Bone-Based Skinning

- **For each axis of the Texture Space – S, T and SxT, "skin" the axis by putting it through the same matrix as the vertex normals**

- **Alternatively, skip the SxT axis and perform S cross T instead – can be cheaper if you have many bones**

Keyframe Interpolation

- Create keyframes for the S, T and SxT axes as well
- Linearly interpolate between the S(0) and S(1) using the keyframe weight from 0 to 1

  (1 – Weight) S0 + (Weight) * S1

- Now Normalize the result
- To handle scaled or stretched textures
  - Rescale by the linearly interpolated length of the two keyframe vectors
  - NormalizedVector *=

    (1 – Weight) LengthOf(S0) + (Weight) * LengthOf(S1)

Keyframe Interpolation

- **The normalizing of the vector approximates a spherical interpolation, or SLERP**
- **The rescaling ensures that any stretching or scaling in the textures is preserved**
  - **especially important if morphing**

Texture Space Calculations

- These calculations are a prerequisite for practical Per-Pixel Lighting
- The cost of computing and updating Texture Space for moving models can seem large
- Keep it in perspective :
  - For a certain amount of per-vertex work, you are getting tremendous per-pixel detail
- All of the previous techniques for moving lights into Texture Space and updating the Texture Space vectors for moving objects can be handled with Dx8 Vertex Shaders

Texture Space Overview

- Texture Space is necessary to handle arbitrary, animating bump mapped geometry correctly
- It allows us to setup the per-pixel dot product
- For each vertex, we rotate the L or H vector into local Texture Space, where it is interpolated across the polygon as a color
- Now, we can perform L dot N or H dot N per pixel and achieve per-pixel lighting

Implementing Per-Pixel Light Types

- **Directional Lights**
- **Spot Lights**
  - **Attenuation**
- **Point Lights**
  - **Attenuation**

Directional Lights

- **Directional Lights are the simplest – just perform L dot N or H dot N, then multiply by the light color**

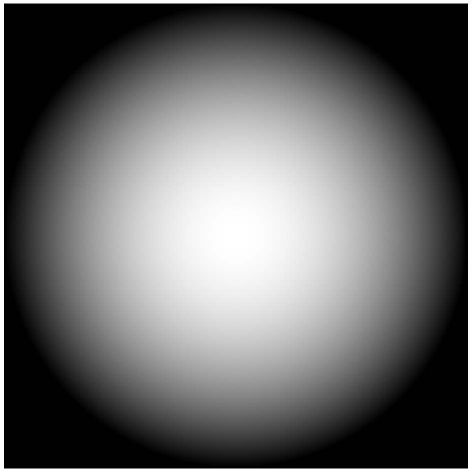
- **LightColor * (L dot N)**

  or

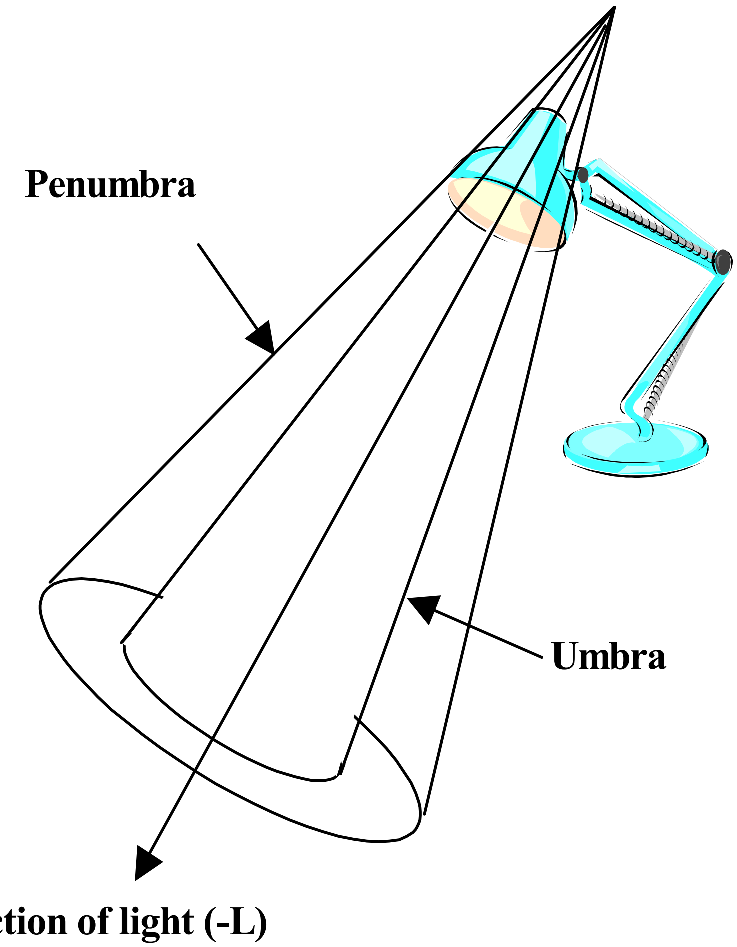
- **LightColor * (H dot N)**

Spot Lights

- Spot lights are a little harder
- We need to use a projective texture to represent the spotlight’s cosine attenuation from the umbra and penumbra
- This is pre-generated as a circular texture map, like so :



Spot Light Directional Falloff



Spot Light Texture

- The interior should hold the cosine falloff term from 1 (everywhere in the umbra) ramping down to 0 (at the edge of the penumbra)
- Ensure that the edges of the texture are black
- Set up a ‘Light Plane’ at the spotlight, pointing in the same direction as the light
- Set up texture coordinate generation and the texture matrix to so that the vertex positions are projected onto the Light Plane

Getting Clever

- Since it is a scalar value, one can place the cosine falloff term in the texture alpha only
- That frees up the RGB values to hold the L vector
- This has two benefits :
- Per Pixel Spotlights with a single 2D texture
  - Handles self-shadowing automatically
- Put the distance attenuation in the diffuse color or alpha
- (SpotLight.RGB DOT3 Normal.RGB) *

  (SpotLight.Alpha * Diffuse.RGB)

Point Lights

- Point Lights are similar to SpotLights in complexity
- They require a per-pixel distance attenuation value
- There are four basic ways to achieve this…

Four Attenuation Techniques

- 3D Texture holds Attenuation function
  - + Can be an arbitrary function
  - - Not all cards have 3D Textures
  - - Lots of Texture Memory

Use 2 2D Textures to compute 1 – d*d

- [1 – x * x – y * y] – [z * z]

- Or Use 1 texture, and compute z*z in texture blender via Diffuse or Specular
- + Works on all cards
- - Not very flexible for attenuation

Alternate 2 Texture Attenuation

- Use 2 2D Textures to compute e ^ - d*d
  - [e ^ (- x*x – y*y)] * [e ^ (- z * z)]
  - + Works on All Cards
  - + Smoother Attenuation Function
  - + Can use other factors other than e
  - - Must use 2 Textures

Last Attenuation Technique

- 3D Texture - Store 3D L vector in RGB of texture, put Attenuation Function in Alpha only
  - + Less Textures used, easier to reduce passes
  - - Not all cards have 3D Textures
  - - Lots of Texture Memory
  - - May have to Point Sample if close to the Light

Attenuation Tips

- Always keep the edge of the Attenuation textures black if using scalars, or use the zero vector if encoding vectors, and use CLAMP mode
- Use Alpha Test to eliminate pixels that map to the border of the Attenuation Map
- Set up the texture coordinate generation / texture matrix to offset to the light's position and scale by 1 / LightRange
- You can use Destination Alpha to hold Attenuation for multi-pass effects

$1-d*d$ | $e^{(-d*d)}$

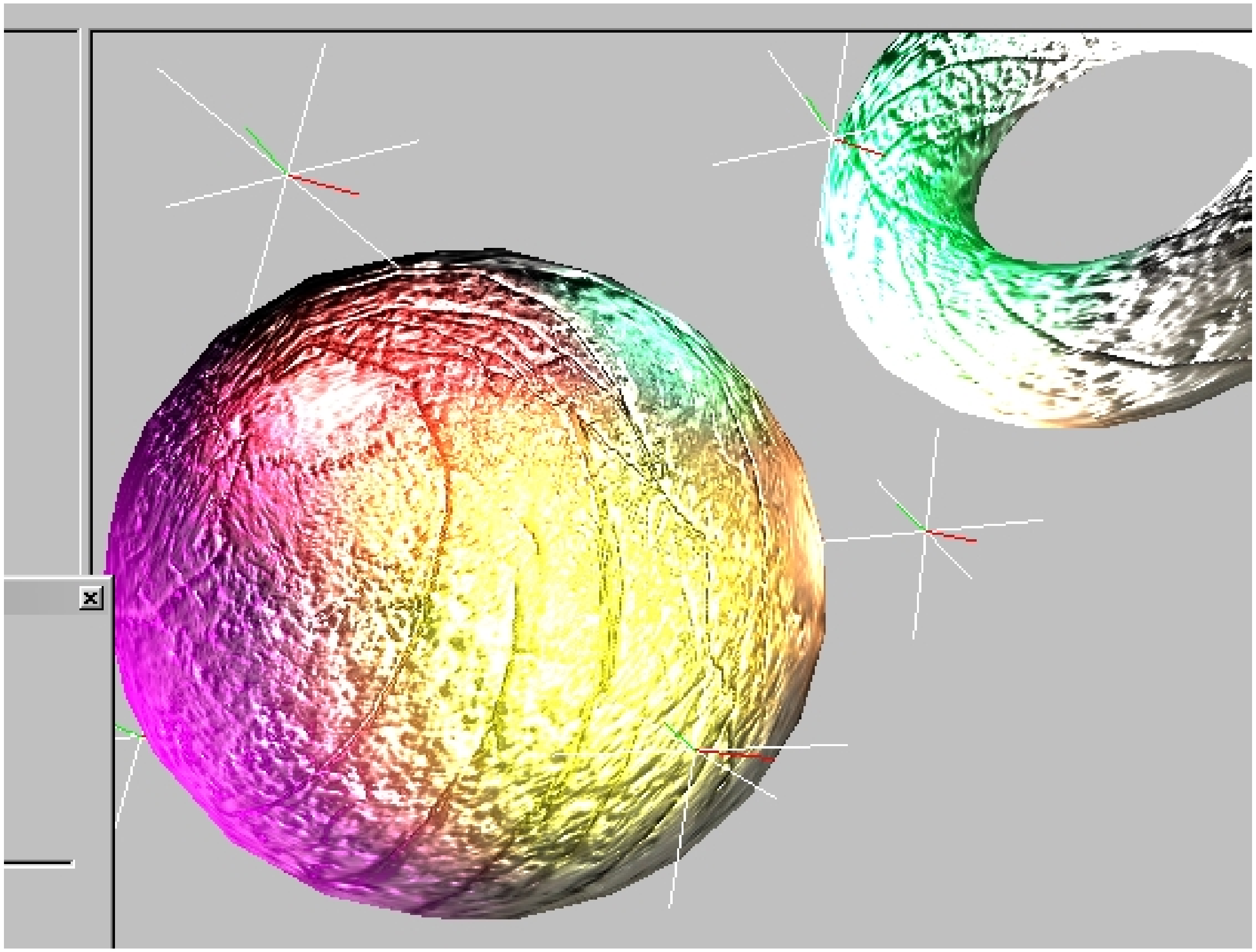
Bringing It All Together

- At Author Time
  - Apply Bump Maps (Actually Normal Maps) to your models
  - NEVER Pre-Light Textures
    - You can’t combine pre-lit and real-time lights
  - Storing global ambient light / shadows in a *separate* light map is OK
- At Load Time
  - Per Triangle
    - Generate Per-Triangle Texture Space
  - Per Vertex
    - Generate Texture Space Matrices from Per Triangle Bases

Bringing It All Together - Runtime

- Per Vertex
  - Move L or H into Local Texture Space
- Per Pixel
  - Perform Dot Product
  - Apply Attenuation
  - Apply Light Color

Multiple Per-Pixel Point Lights



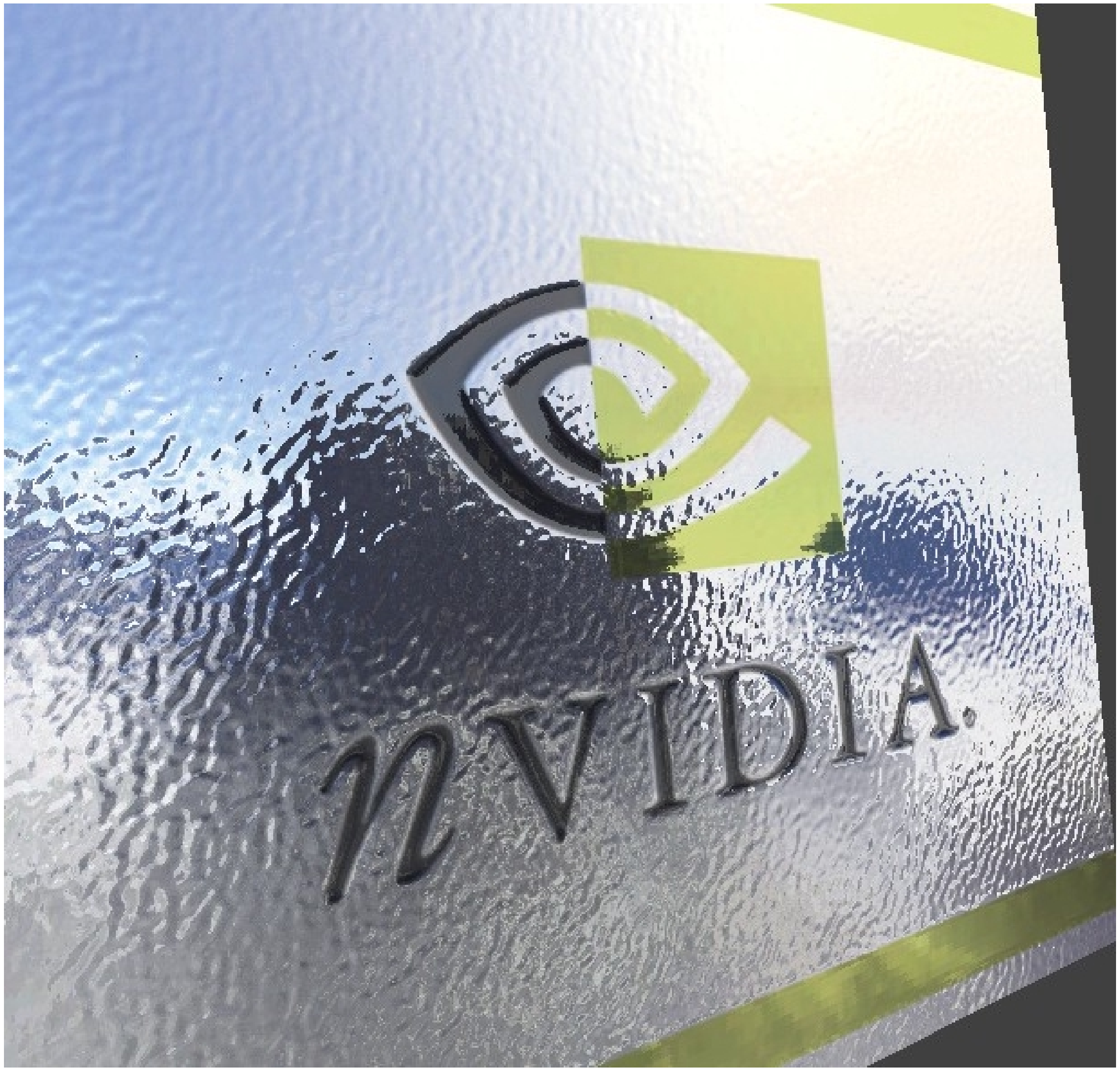
What About Dx8 / Pixel Shaders?

- **All of the preceding material applies directly to Dx8 and more advanced Pixel Shading**
- **Understanding the preceding sections is extremely helpful when investigating Dx8-Level Pixel Shading**
- **Dx8 Pixel Shaders are mostly extensions of the same ideas behind DOT3**

What's New With Dx8 Pixel Shaders?

- Math is performed in floating point instead of fixed point
- Can perform dependent textures
  - Texture1.S = (Texture0.AR)
  - Texture1.T = (Texture1.GB)
- Can perform a per-pixel reflection vector lookup into a CubeMap
  - True per-pixel bumpy reflections

Pixel Shaders Allow Per-Pixel Bumpy Reflections



Further Topics

- Using Cube Maps To Normalize Light Vectors
  - + Keeps Vectors Normalized
  - - Takes up a Texture
  - See my GDC 2000 presentation on Cube Maps
- Creating Normal Maps from Height Values or Other Textures
  - See my GDC 2000 presentation on Per-Pixel Lighting
- Both of these are employed in the Bump Maker tool on NVIDIA’s public developer website

Credits :
Where I First Learned of These Techniques

- Texture Space Generation Idea
  - Sim Dietrich
- Texture Space Generation Details
  - Sim Dietrich and Doug Rogers
- 3D Texture Attenuation
  - John Carmack
- SpotLight Attenuation w/ Normals
  - Sim Dietrich
- 1 – d*d Attenuation w/ 1 or 2 Textures
  - Sim Dietrich
- e ^ (-d*d) Attenuation w/ 2 Textures
  - Cass Everitt
- 3D Texture w/ Normals & Attenuation
  - Sim Dietrich