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CMP

# Practical Spherical Harmonics Based PRT Methods

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# Outline

- Background ambient occlusion, HL2
- Spherical Harmonics theory
- Pre-processing
- PRT compression – 4 to 6 bytes per sample
- Conclusion and game scene demo

# Background

- Many variants of Precomputed Radiance Transfer – self-shadow, interreflections, diffuse vs. glossy
- Power of PRT best understood in the context of ambient occlusion (AO) and HL2 basis

# Goals

- Diffuse *self-shadowing* for rigid bodies (aka neighborhood transfer)
- Generalizes easily to interreflections
- Decouples *visibility* calculation from lighting
- Pre-integrate *surface variations*

# Ambient Occlusion

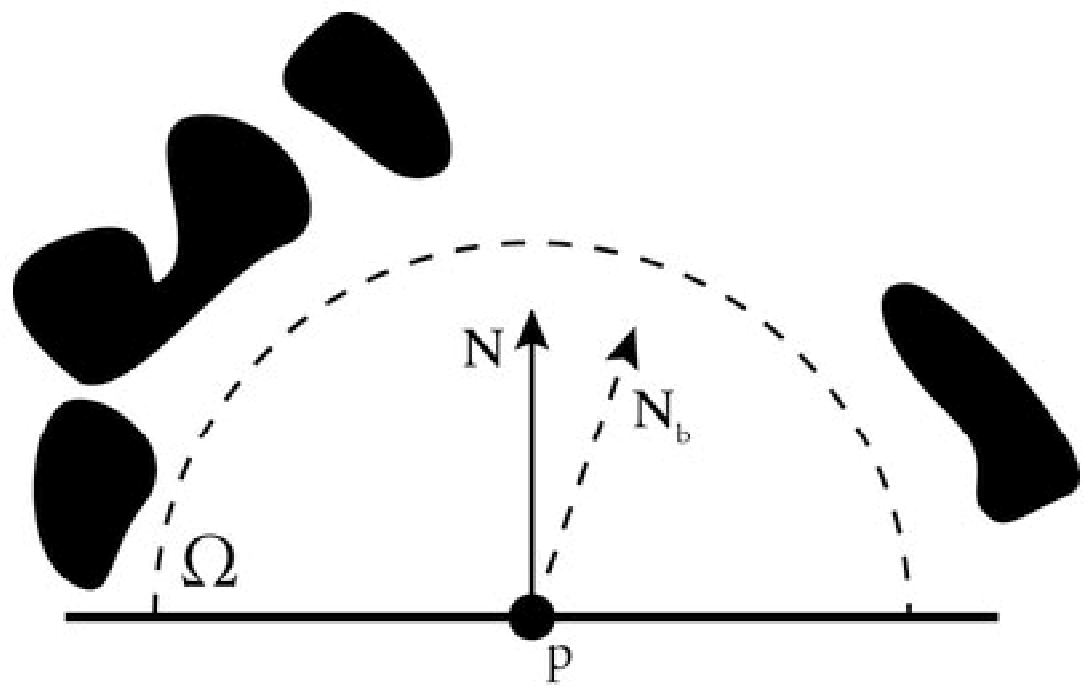
- Pioneered by ILM
- Accessibility shading

# Ambient Occlusion

# Ambient Occlusion Flavors

- Single scalar – cheap but no directional response
- Bent Normal

# Bent Normal: basic idea

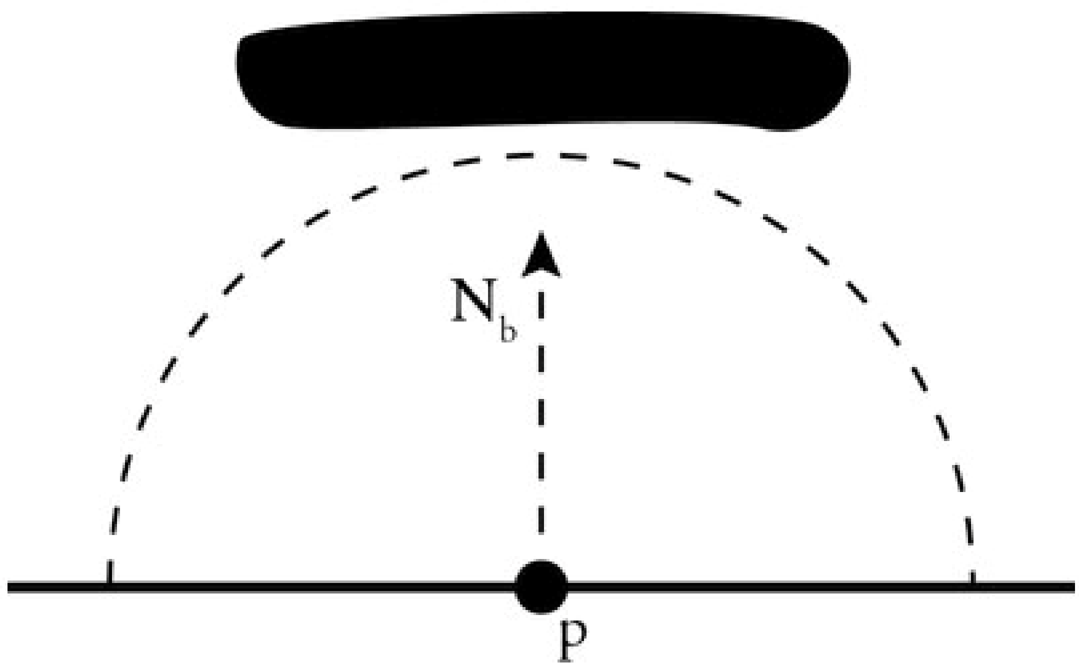



$$A_p = \frac{1}{\pi}\int_\Omega V_{p,\omega}(N\cdot\omega)\,d\omega$$

# Bent Normal

- Half3 + scalar AO = 7 bytes per sample
- Give some directional variations but it does not always work

# Bent Normal: fail case

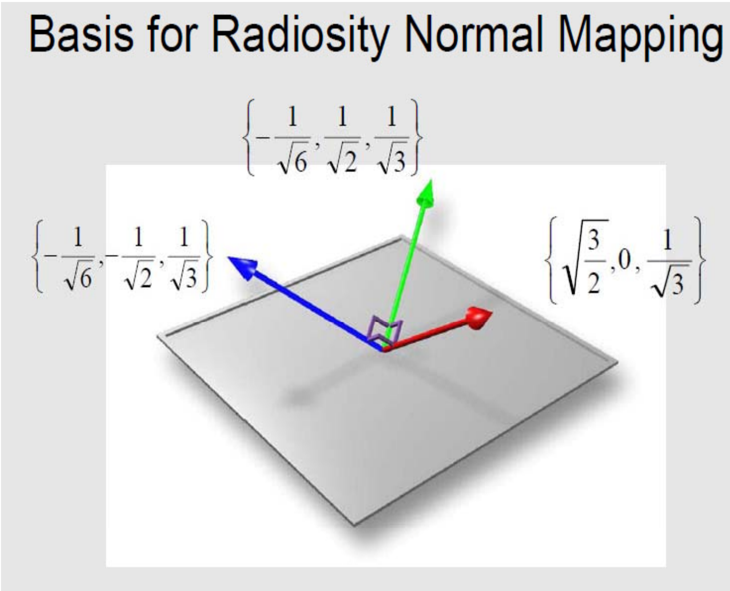


# Bent Normal: next step

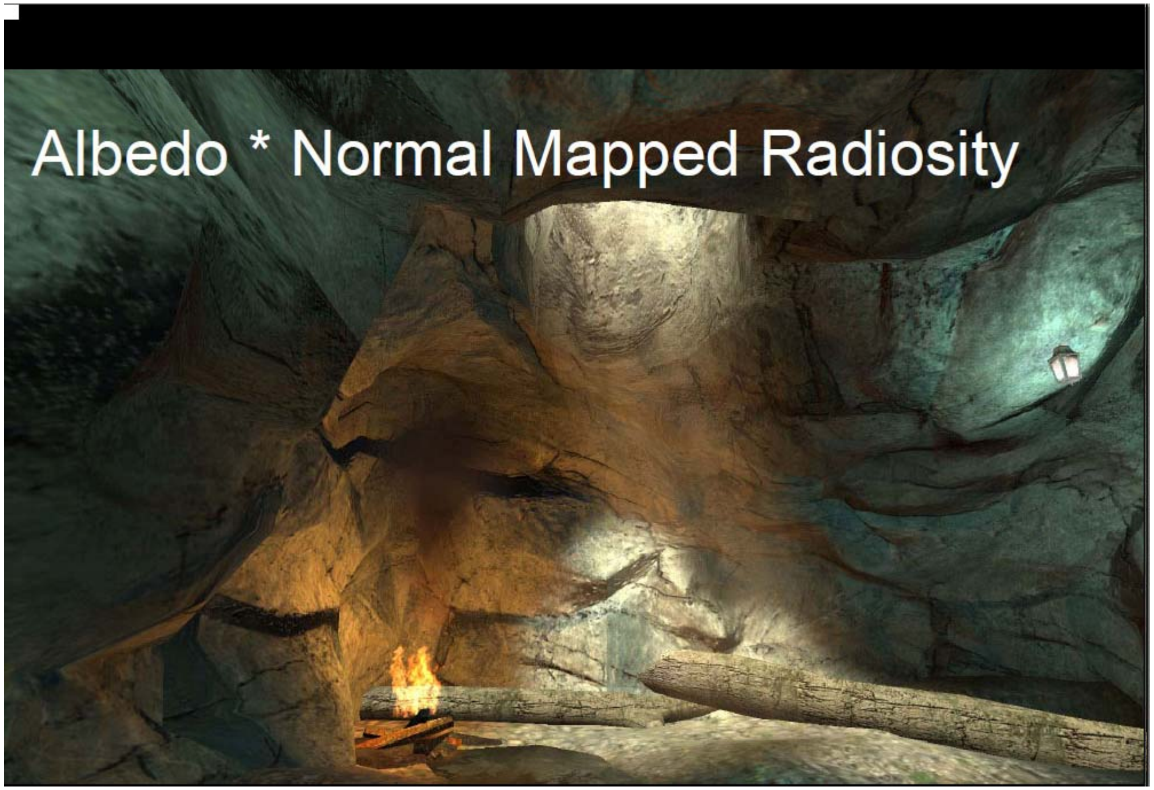
- Overcome the single direction, single weight limitation

# HL2 Basis

- Valve’s “Radiosity Normal Mapping”
- 3 RGB basis vector per sample



# HL2 Samples



# HL2 Strengths

- Successfully integrated GI with surface-details
- Surface details respond to runtime lights
- 1st attempt in games to use a ‘lighting basis’
- Orthonormal basis
- Good for normal-maps

# HL2 Weakness

- Lots of storage – 3 RGB maps per sample plus UVs
- 3 texture lookup + 3 dotp/ pixel after rotating basis into tangent space. Shader cost can be a problem.
- Incomplete coverage of the hemisphere,

  3 directions not enough?

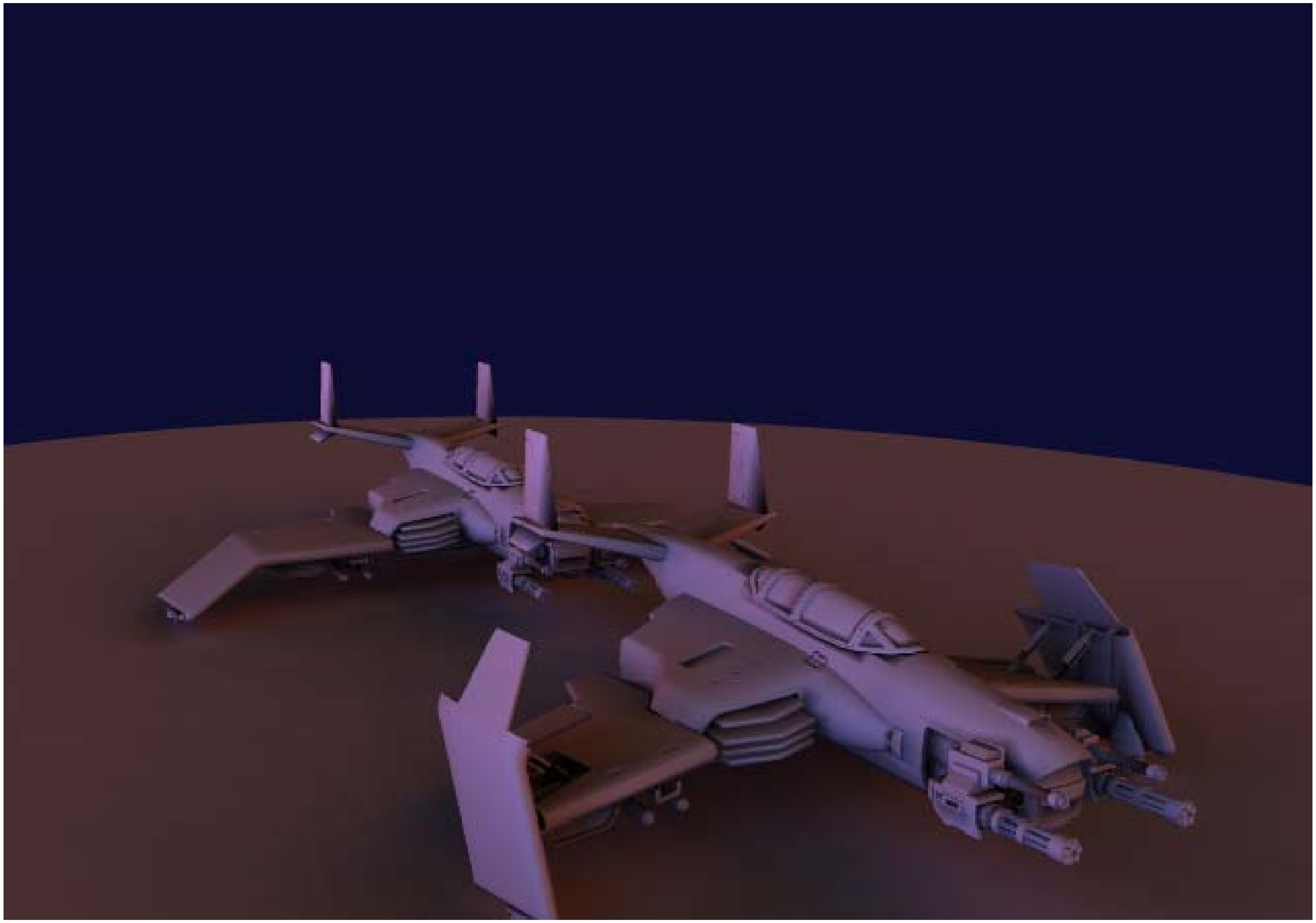
# Key Ideas for PRT

- Visibility is the key bottleneck since it involves sampling the scene
- Take advantage of off-line compute
- Separate pre-integration of visibility from that of incoming light
- Find a basis to store these functions

# Key Ideas for PRT

- SH is a good starting point for a basis
- We do not trace rays using the GPU! Nor do we take tons of samples inside the pixel shader
- Better quality than AO or HL2 but more efficient than later
- Work well for static scene + moving lights

# Hovercraft from Warhawk



# Demo

- Buddha – 1.08 m triangles
  - 33 fps on ATI X700
  - 250 fps on G8800 GTS
  - Vertex shader only method
  - Vertex buffer not optimized, could be faster
- Dragon – 871k triangles
  - 40.7 fps on ATI X700

# Implementation

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# Outline

- Short introduction to SH (very short!)
- Environment map projection
- PRT coefficient generation
- Runtime reconstruction in vertex shader

# Spherical Harmonics

- 2D Fourier series on the sphere
- Represent 2D signals as scaled and shifted Fourier basis.
- Perfect for spherical functions

# Basis function Projection

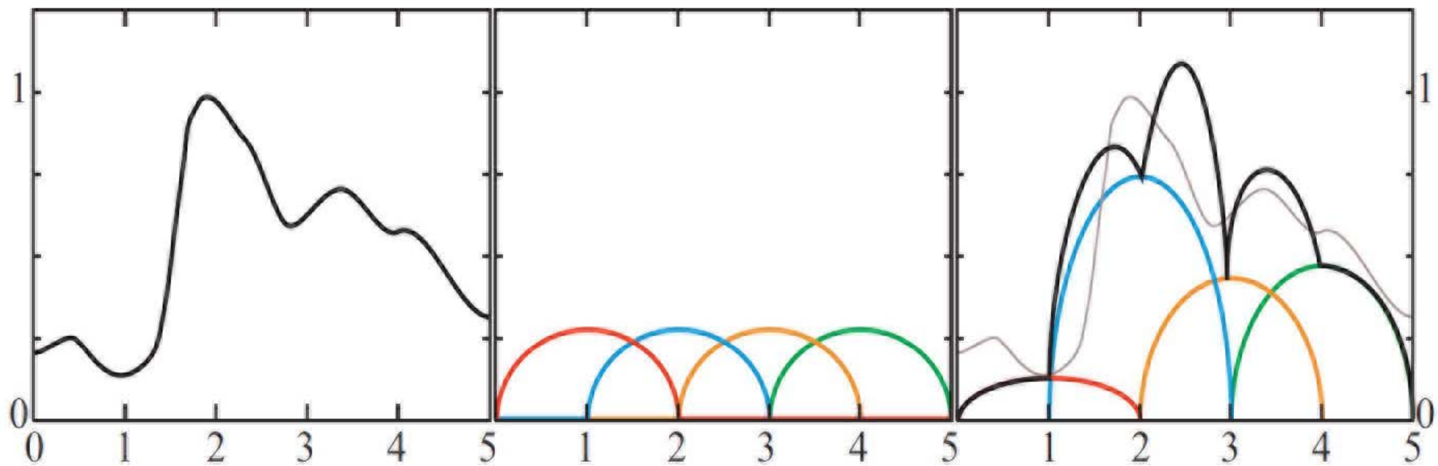



Image courtesy of Real Time Rendering 3rd Edition

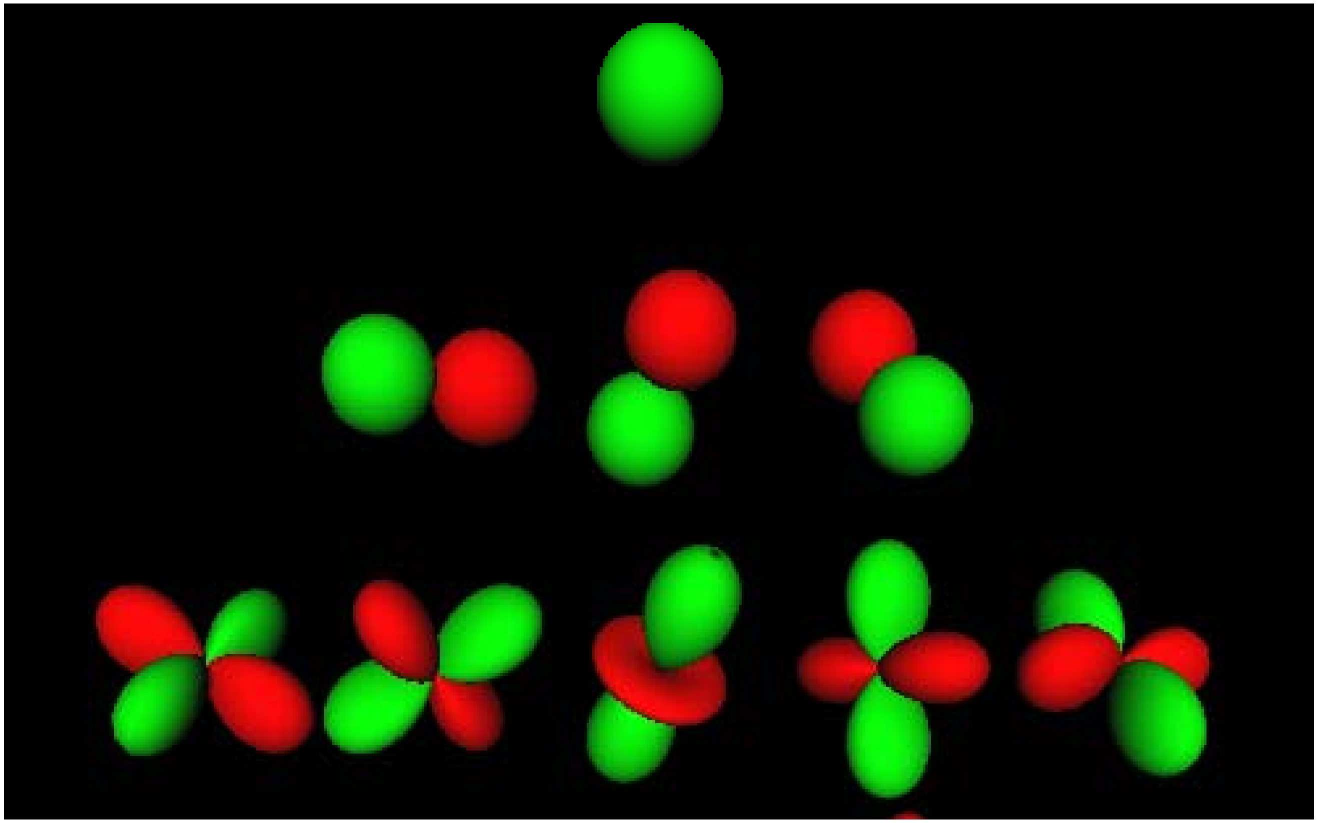
## Spherical Harmonics Characteristics

- Orthonormal basis ->
  - convolution as dot products
  - simple projection
- Multi-resolution/band-limited, related to Fourier decomposition
- Solid math foundation
- Stable rotation no wobbling lights
- Can add/subtract, *lerp.*

# SH: bands *(l,m)*

- SH-order: order is the number of bands. '*l*' is the order
- $0^{th}$ order: just a constant (DC) which is your AO term
- $1^{st}$ order: 3 linear terms which is your 'bent normal' term
- $2^{nd}$ order: 5 terms – these give the extra directional response we want
- In general $(2l+1)$ terms

# Spherical Harmonic Functions



# Spherical Harmonics - Issues

- Scary math!
- Looks difficult to implement
- Lots of coefficients, too much storage?
- Difficult or time consuming to generate?

# Environment Map Projection

- First we need a light source
- Ravi R. introduced a technique to light diffuse surfaces with distant environment map illumination
- Code available on Ravi's site, we integrated it into our demo app

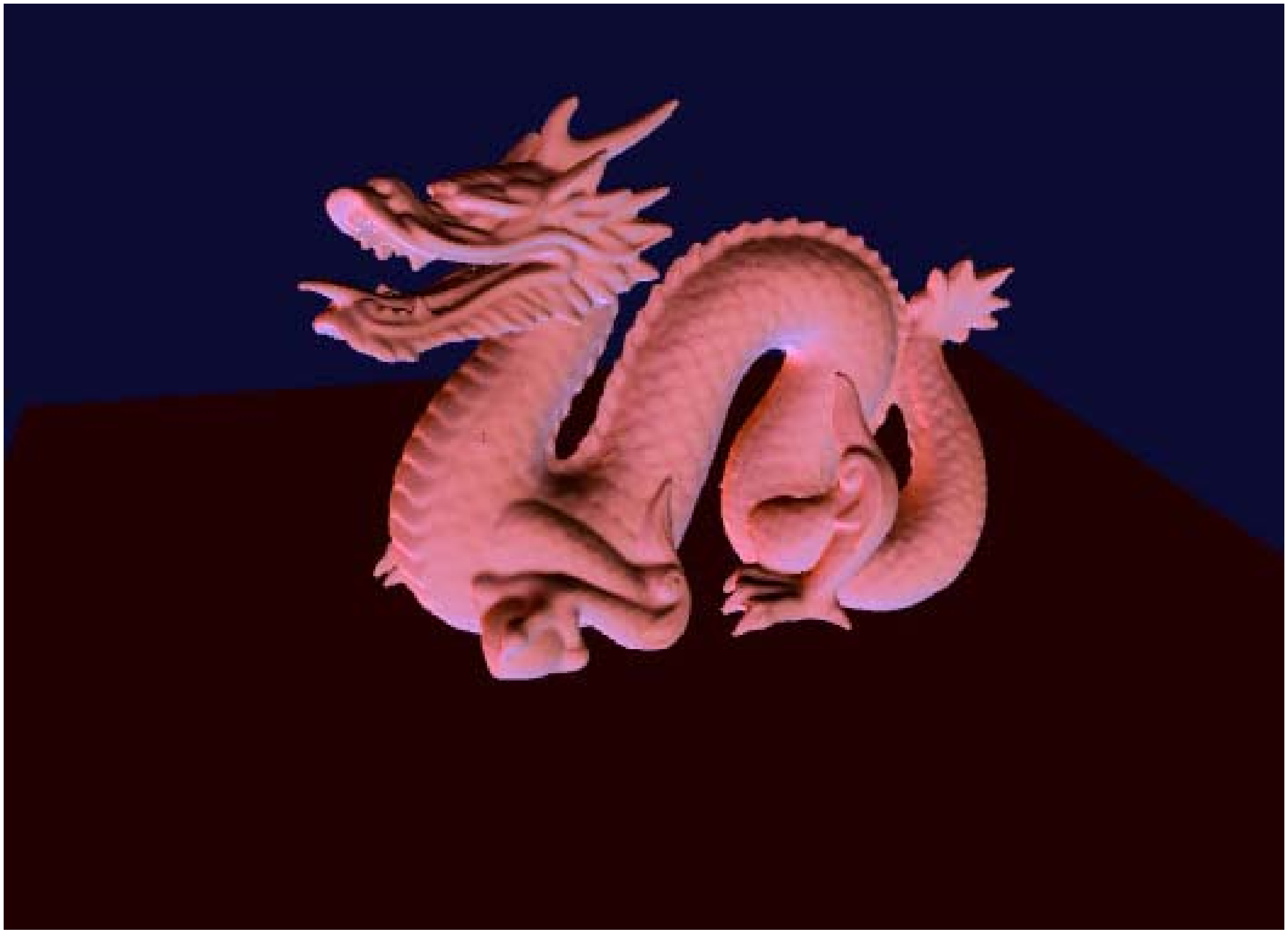
# Environment Map Projection

- 9 SH-compressed coefficients
- Instead of a large cubemap you only need 27 numbers!
- Secret lies in the solid angle formula
- For each pixel evaluate the SH basis then weighted it by the solid angle

# Solid Angle

```
domega = 2*PI/width *
         2*PI/height *
         sinc(theta);
```

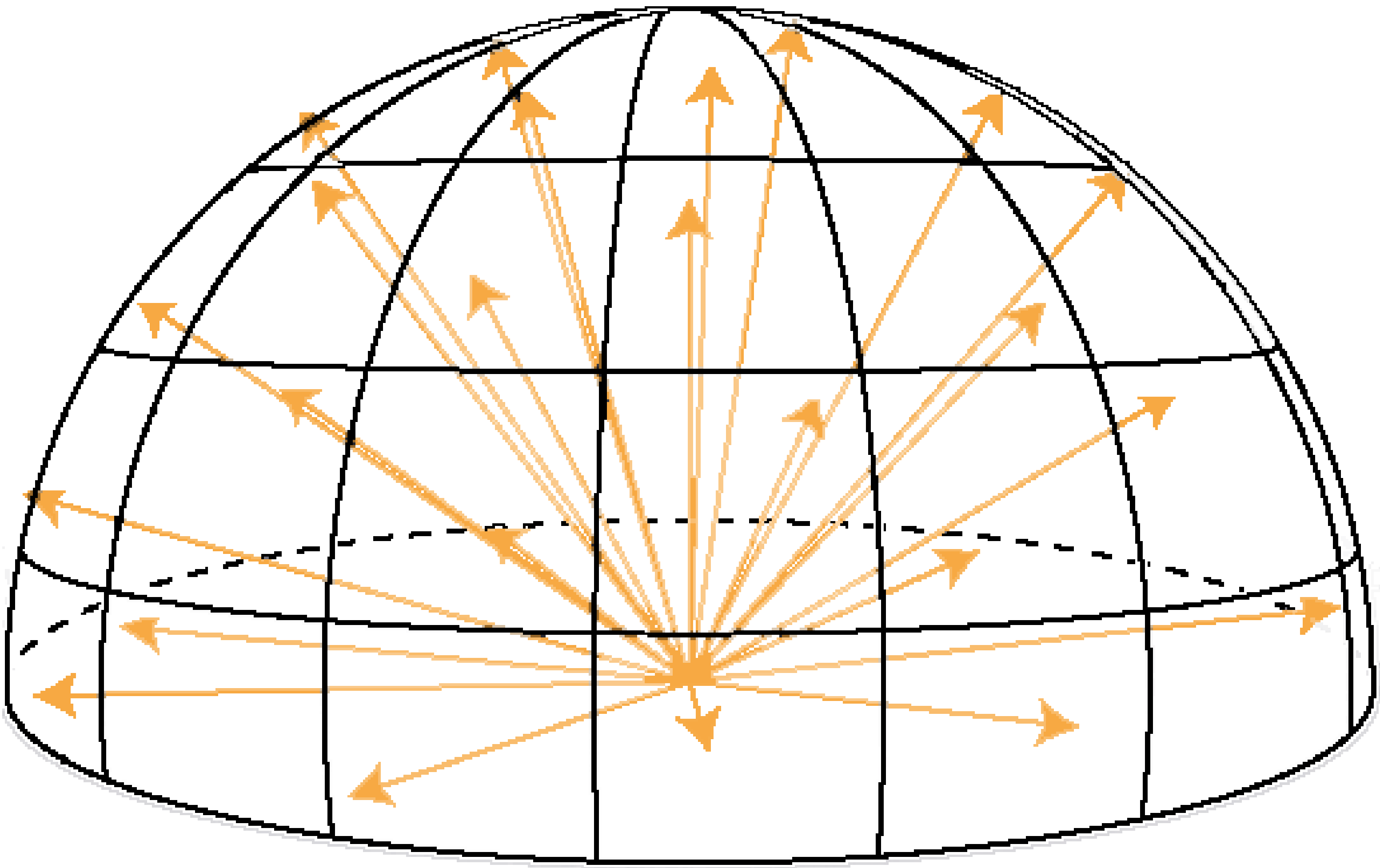
# Envmap Demo



# PRT Coefficient Generation

- We have simplified the light source, now we must also project the visibility function using SH
- This gives us compact storage of self-shadowing information
- Encodes the directional variations more accurately than AO or HL2

# Projecting Visibility Function



# Projecting Visibility Function

```
for all samples {
    stratified2D( u1, u2 ); //stratified random numbers
    sampleHemisphere( shadowray, u1, u2, pdf[j] );
    H = dot(shadowray.direction, vertexnormal);

    if (H > 0) { //only use samples in upper hemisphere
        if (!occludedByGeometry(shadowray)) {
            for (int k = 0; k < bands; ++k) {
                RGBCoeff& coeff = coeffentry[k];
                //project onto SH basis
                grayness = H * shcoeffs[j*bands + k];
                grayness /= pdfs[j];
                coeff += grayness; //sum up contribution
            }
        }
    }
}
```

# Projecting Visibility Function

- 100-400 shadow rays per vertex are sufficient
- Use your best acceleration structures
- Vertex normal is accounted for in computation of H, thus no need for normal in shader
- Full visibility function is preserved
- Group objects together in acceleration structure to get inter-object shadowing

# Runtime Reconstruction in Vertex Shader

- The hard work has been done!
- Thanks to the orthogonality of SH functions, reconstruction is reduced to a simple dot product of 9 float3's

$$E = \int_S L_i(\mathbf{x}) \cdot BRDF(\mathbf{x}, N) \cdot V(p, \mathbf{x}) dx$$

$$E \cong \sum L_{lm} \cdot P_{lm}$$

# Runtime Reconstruction in Vertex Shader

```
uniform vec3 Li[9];
attribute vec3 prt0;
attribute vec3 prt1;
attribute vec3 prt2;

color  = Li[0]*(prt0.xxx) +
  Li[1]*(prt0.yyy) + Li[2]*(prt0.zzz);
color += Li[3]*(prt1.xxx) +
  Li[4]*(prt1.yyy) + Li[5]*(prt1.zzz);
color += Li[6]*(prt2.xxx) +
  Li[7]*(prt2.yyy) + Li[8]*(prt2.zzz);
```

# Comparison: With and Without Self-Shadows

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# PRT in HyperDrive™

# PRT Compression


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# PRT Compression

- 3rd order SH occupies 36 bytes per sample
- Normals encoded as Lambertian response during pre-processing
- World-space => no tangent space needed.
- Bandwidth is key to GPU performance.
- PRT data size is key to pervasive usage in game scenes.

# Previous Work in PRT Compression

- Sloan introduced CPCA
    - Break mesh into small clusters
    - PCA applied to each cluster to obtain a reduced set of basis
- Fairly effective if the clusters are small but that will add draw call overhead
- Hard to apply your vertex cache optimizer

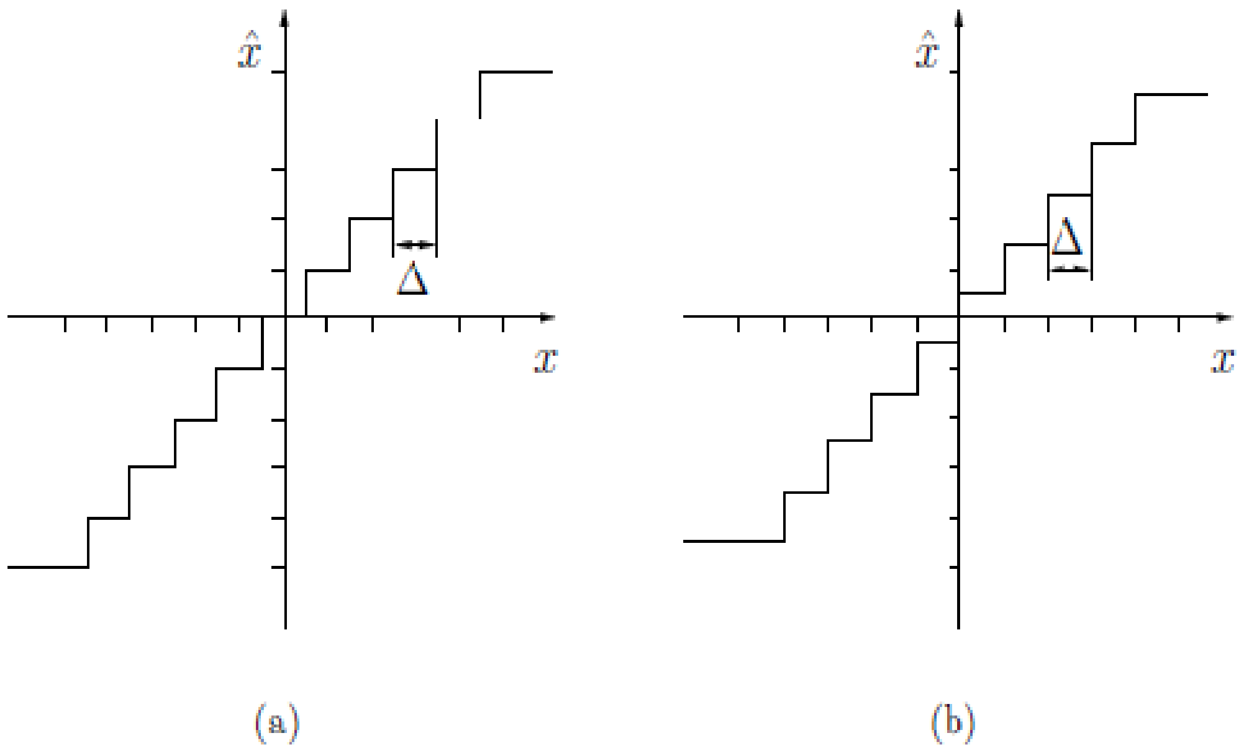
# Our PRT Compression

- M 1: 9 bytes using scale-bias
- M 2: 6 bytes (8; 6,6,6; 6,4,4,4,4)
- M 3: 6 bytes using Lloyd-Max relaxation
- M 4: 4 bytes (5; 4,4,4 ;3,3,3,3,3)
- All very simple to implement

# Scalar Quantizer and Scale-Bias

- How to convert floats to bytes?
- Scan each sets of coefficients to get range
- $C_i = (P_i - Bias_i) * Scale_i$ ?
- We are dealing with a scalar quantizer

# Mid-rise vs. Mid-thread Quantizer



# Mid-rise Quantizer

- A 2 bit mid-rise quantizer has only 3 decision levels
- Advantage: can construct the DC-level exactly. This can be critical in some cases

# Mid-thread Quantizer

- Even number of levels – e.g. 4 levels for a 2 bit code
- More accurate overall but cannot reconstruct the DC-level
- For 4 bit codes we improved the PSNR by ≈1db

# ScalarQuantizer

```
float half = (qkind == PRT::kMidRise) ?
  0.5f : 0.f;

  for (int i=0; i < nc; i++) {
    float delta = scalars[i] – bias[i];
    p[i] = delta * scales[i];
    output[i] = floor(p[i] + half);
  }
```

# Method 1: 9 Bytes

- Use Mid-rise quantizer
- Remove 4PI factor from coefficients
- ¼ the memory and 2X improvement in speed
- No visible quality lost, PSNR > 78db

# Method 2: 48 Bits

- Method 1 takes us down to 9 bytes. Can we do better?
- (8,6,6,6,6) (4,4,4,4) – bit fields
- Choice of bit allocation motivated by
  - Fourier theory => energy compaction
  - shader efficiency
- Cannot be optimal but try to be close

# Square Norms by Band

- Energies by band
  - [0]: 34.8%
  - [1]: 17.1%
  - [2]: 15.3%
  - [3]: 17.1%
- 85% of energies in 1st 4 bands

# 1st word: 8,6,6,6,6


P0(b31..24),p1(23..18)..

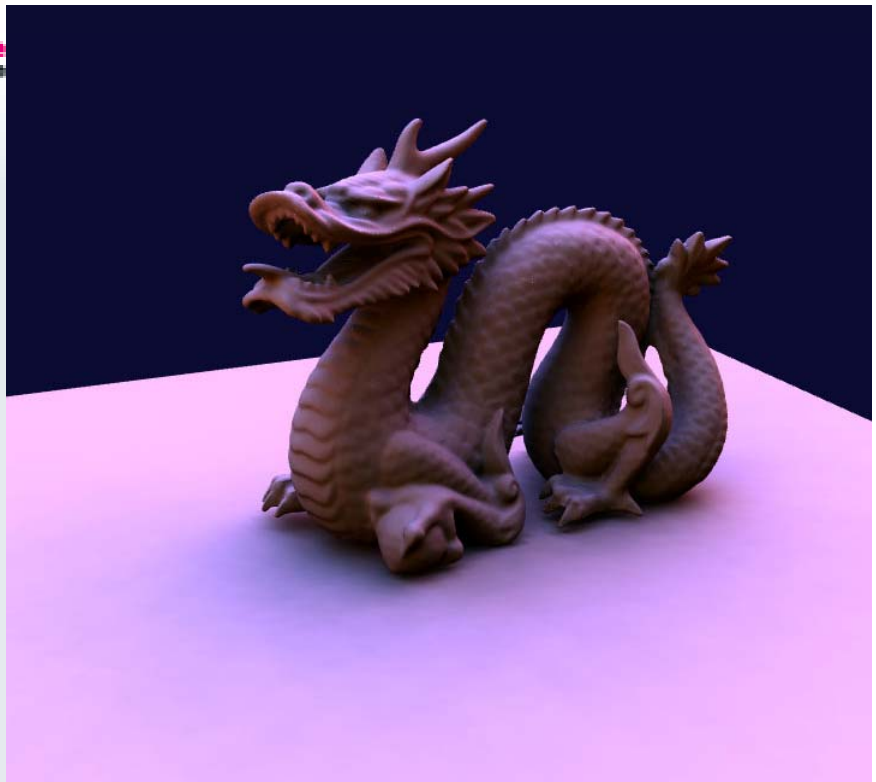
# Vertex Shader: Method 2

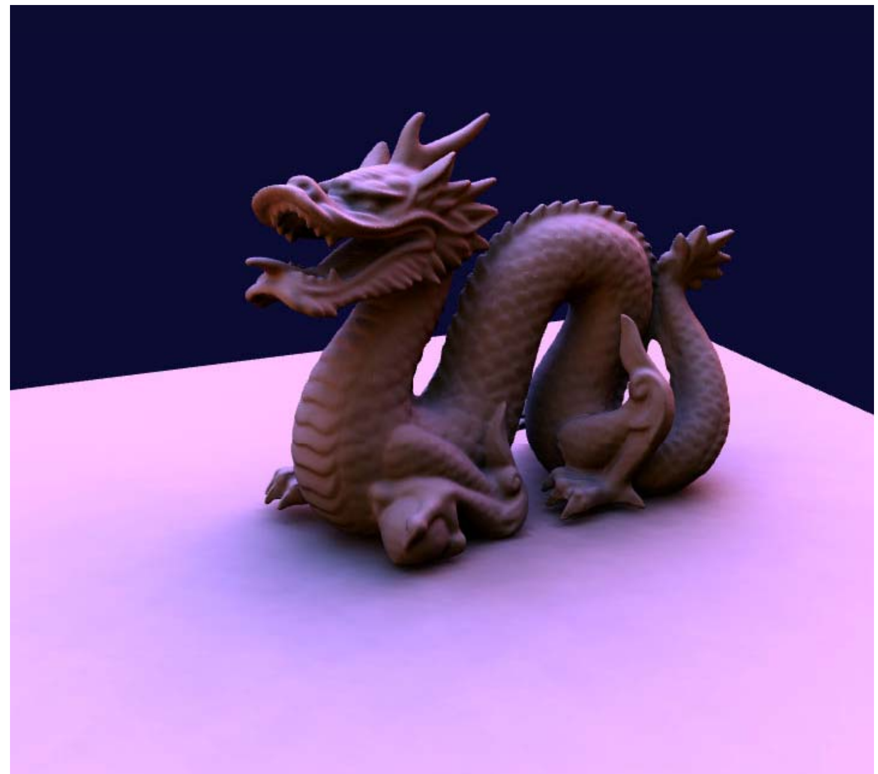
- Coefficients will straddle input registers
- No bit operation in shaders – use floating point ops to simulate
- Mul/div by power-of-2 for L/R shifts
- Fract and trunc() to isolate the 2 pieces. Add for ‘or’
- Tries to take advantage of SIMD

# vertex shader

- // rshft(s[0], 1/4, 1/16, 1/64)
- p14 = prt0 * rshft;
- lhs3.yzw = fract(p14.yzw);
  // lshft(0, 16.*4., 4.*16., 64.);
- lhs3 *= lshft;
-
- //p[0]:
- pp0 = p14.x + bias0;
- //p[1..4]:
- p14.xyz = (lhs3.xyz + floor(p14.yzw)) * scales.xyz + bias.xyz;
- p14.w = lhs3.w * scales.w + bias.w;

# Comparison:M1 vs M2





184 fps

243 fps

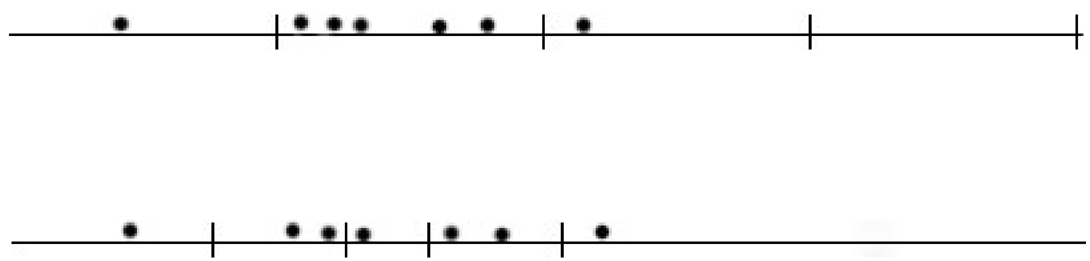
# Method 2: Demo and Discussion

- Improved fps by ~17% compared with M1
- Reduced memory usage by 33%. More with alignment restrictions
- Reduced the number of streams by 1 with room to spare
- GFLOPS for modern GPU going up much faster than bandwidth
- Looking for more mathops per byte?

# Uniform vs. Non-Uniform Quantizer

- A uniform quantizer divides the range evenly
- Optimal only if all the inputs are equally probable
- Intuitively in regions of low probability the bin should be wider

# Non-uniform quantizer



How can we design such a set of bins?

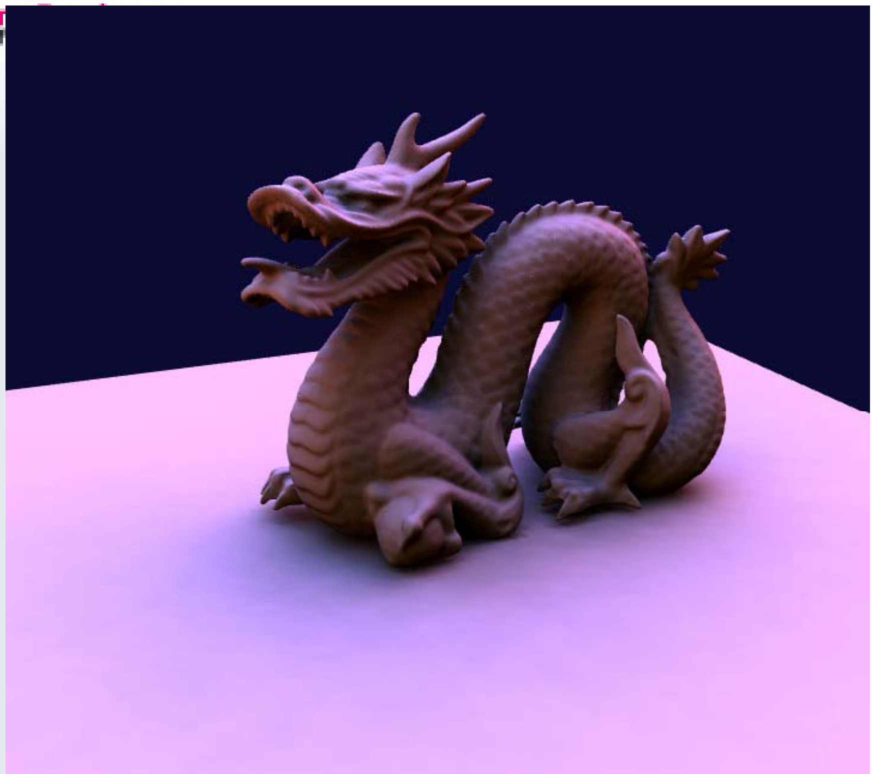
# Lloyd-Max Algorithm

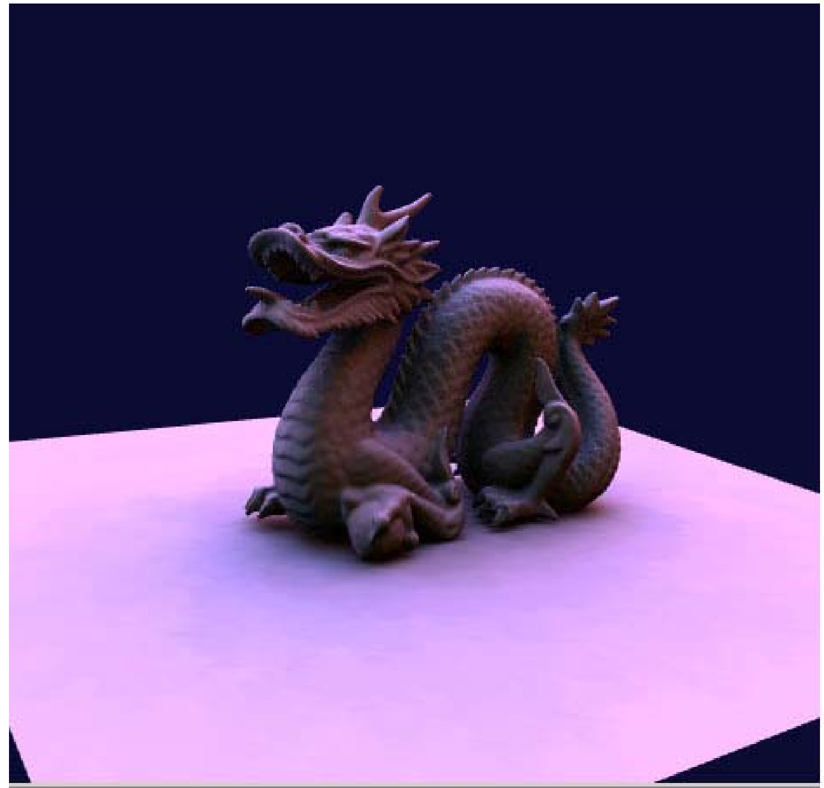
- A version of k-means clustering algorithm
- Given a fixed number of bins iteratively solves for an optimal set of bins
- Converges quickly
- Key is a probability distribution table (*pdf*)
- Applied to all 9 bands separately
- Details in ShaderX6

# Lloyd-Max Iteration

- Given an initial set of bins $t_{k}..t_{k+1}$
- Find $q_k$ such that it is the centroid of $t_k..t_{k+1}$
- Find $t_k$ so that it is the mid-point of $q_k..q_{k+1}$
- Repeat for all the bins
- Check for convergence
- $q_k s$ become the reconstruction levels.

# Comparison:M2 vs M3





# Quality increase for LM

- Improved the PSNR by 1.3 - 1.5db

# Shader for Lloyd-Max

- Almost the same as M2 since we are using the same bit-allocation scheme
- Decoded bit-fields used to index a table of reconstruction levels `recon[]` - the centroids of the bins used in the quantizer
- can be constants or a small vertex texture
- Only used for 4 of the 2nd order terms

# Lloyd-Max demo

- Fps is about the same or a little slower on older GPUs. Same speed on new GPUs
- Better quality
- Sensitive to initial condition see paper for literature references.

# Game Scene Demo

# Limitations

- Methods equally good for a map based approach
- Distant Illumination
  - Good for smaller objects
  - For large objects either split them or blend multiple *Lis* within shader to avoid seams

# Generalize to Interreflections

- Instead of sampling visibility gather indirect illumination
- Use a photonmap or irradiance cache or iteratively gather using visibility PRTs
- Use 3x48 or 3x32 bits per sample
- Or pack a 5,6,5 color with one of the 48 bit PRT methods.

# Light Sources

- Not limited to environment maps
- Pre-integrate any kind of light sources – preferable area lights or a large collection of lights or use probes
- Runtime methods to generate *L*is
- Add or subtract lights easily – just add/sub the *L*is.
- Rotating lights is cheap

# Normal maps

- Bake the normal variations and fine surface details into the PRT
- Or use Peter-Pike's [06] method

# Good tool

- DirectX SDK comes with an offline PRT tool

# Conclusions

- Demonstrate how to implement all key elements of a SH-based PRT shader system
- Compact and efficient even for older GPUs and no tangent space required
- Better than simple AO and bent-normal
- Smaller than bent-normal
- Groundwork for more GI effects

# More on SH and PRT

- Peter-Pike's talk Wed. 2:30pm
- Hao's talk Thu. 4pm
- Yaohua's talk Fri. 2:30pm

# Contact Info

- Manny Ko – man961.great@gmail.com
- Jerome Ko – submatrix@gmail.com

# Credits

- Matthias Zwicker for his guidance and advising on the PRT research
- Ravi for all his help and generosity
- Peter-Pike S. for sharing his insights
- Incognito Studio for game assets
- Eric H. and Naty H. for figures
- Bunkspeed for screenshots
- All our friends

# References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- [Ko,Ko 08] "Practical Spherical Harmonics based PRT Methods", ShaderX6 2008.
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