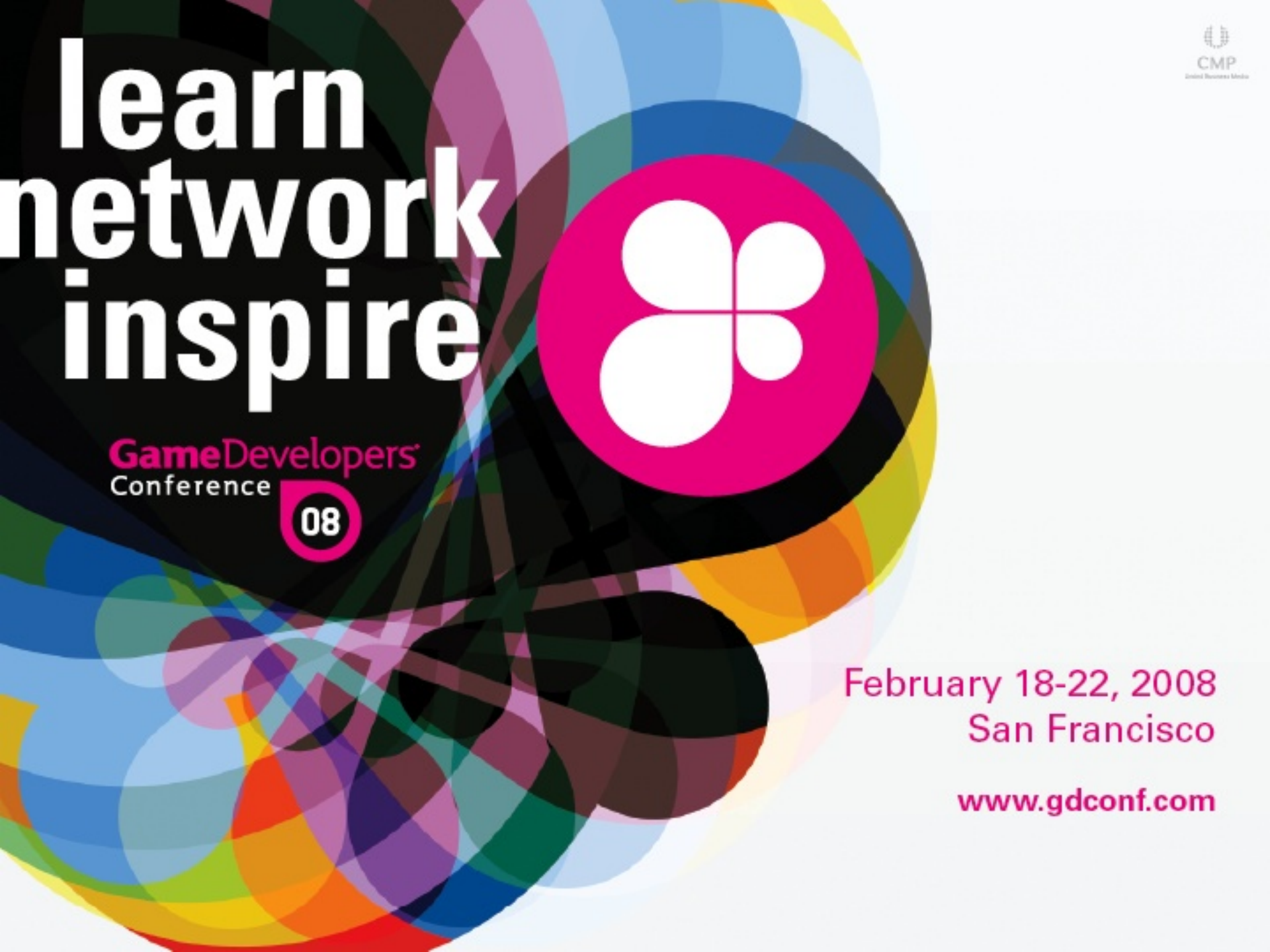
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Practical Spherical Harmonics Based PRT Methods

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Naughty Dog

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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

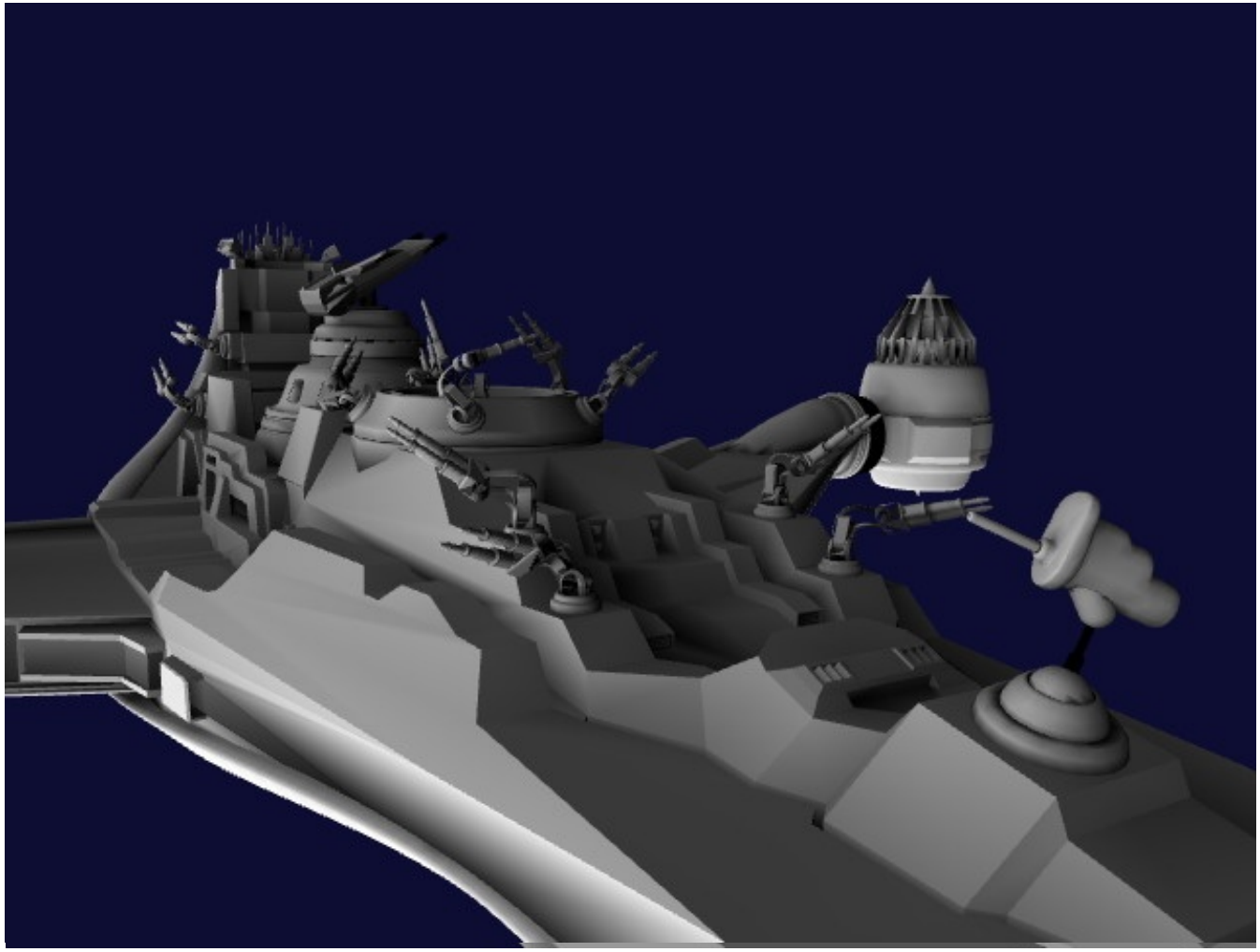
- Diffuse *self-shadowing* for rigid bodies (aka neighborhood transfer)
- Generalizes easily to interreflections
- Decouples *visibility* calculation from lighting
- Pre-integrate *surface variations*

Ambient Occlusion

- Pioneered by ILM

  Accessibility shading

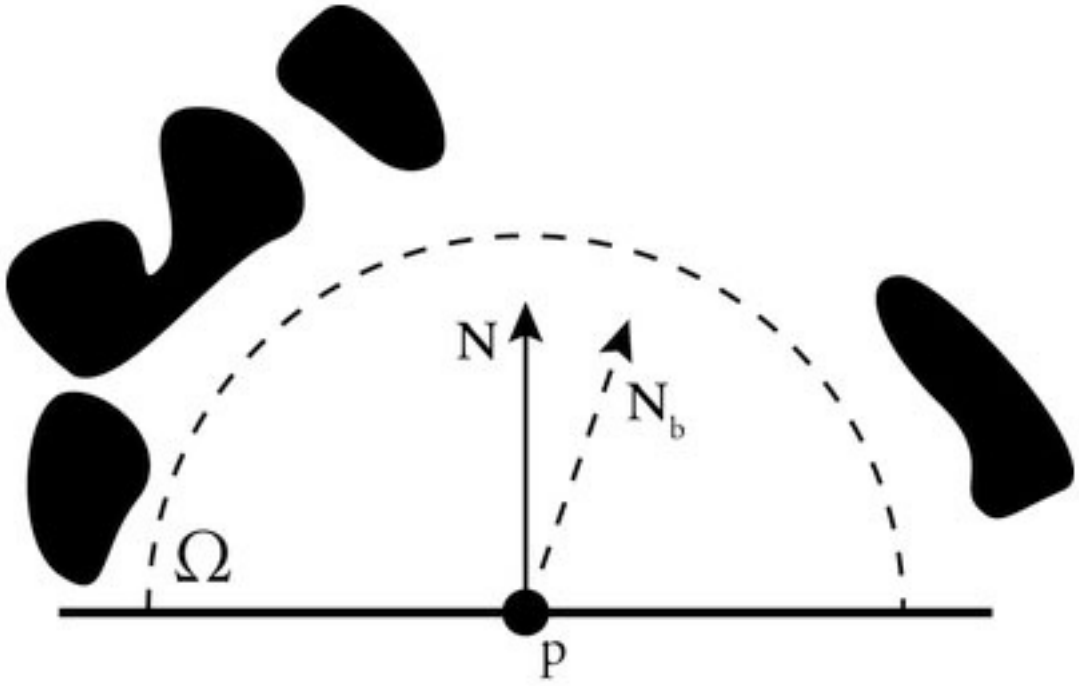
Ambient Occlusion



Ambient Occlusion Flavors

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

Bent Normal: basic idea

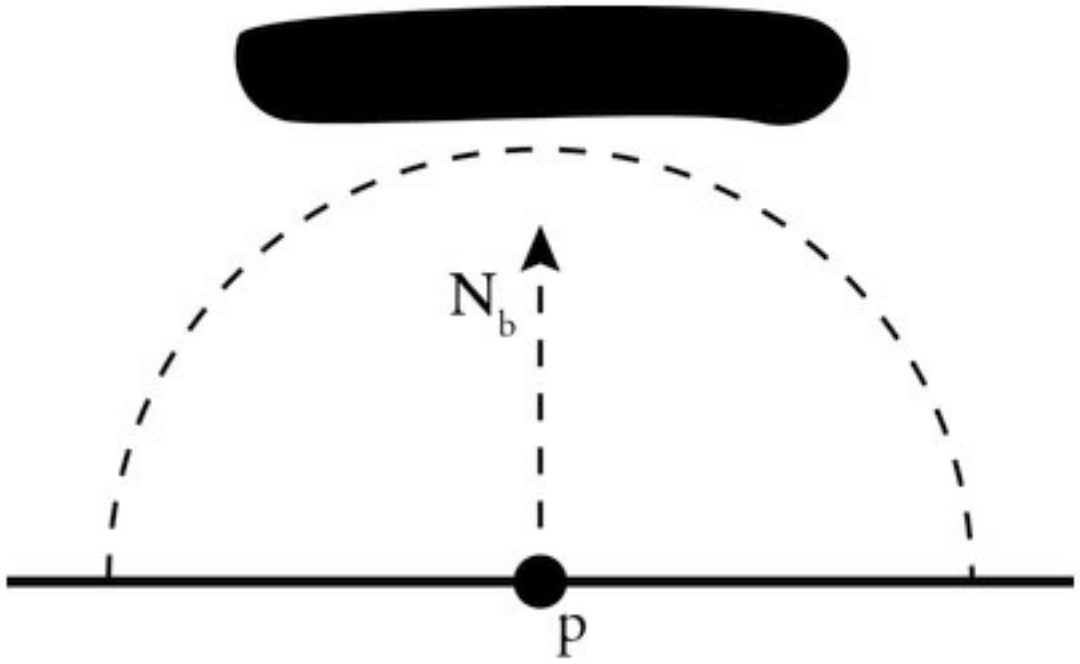


$$A_p = \frac{1}{\pi} \int_{\Omega} V_{p,\omega} (N \cdot \omega) \, d\omega$$

Bent Normal

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

Bent Normal: fail case



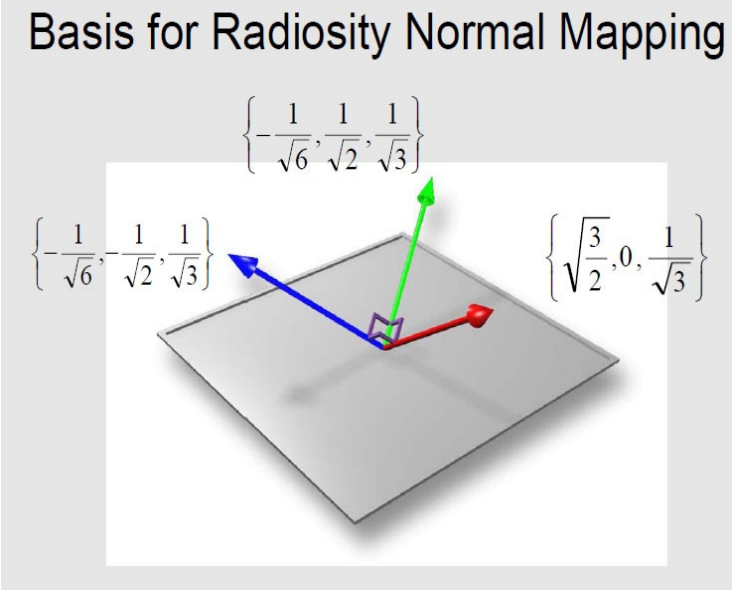
Bent Normal: next step

- Overcome the single direction, single weight limitation

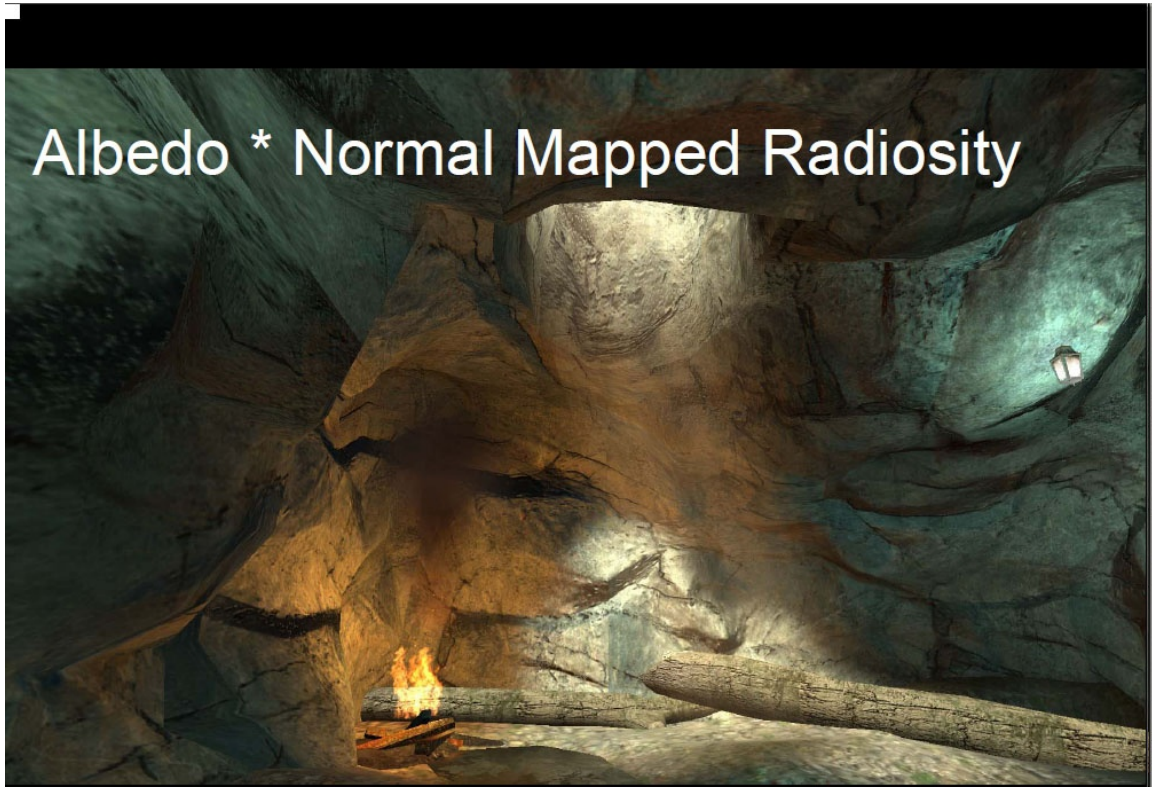
HL2 Basis

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?

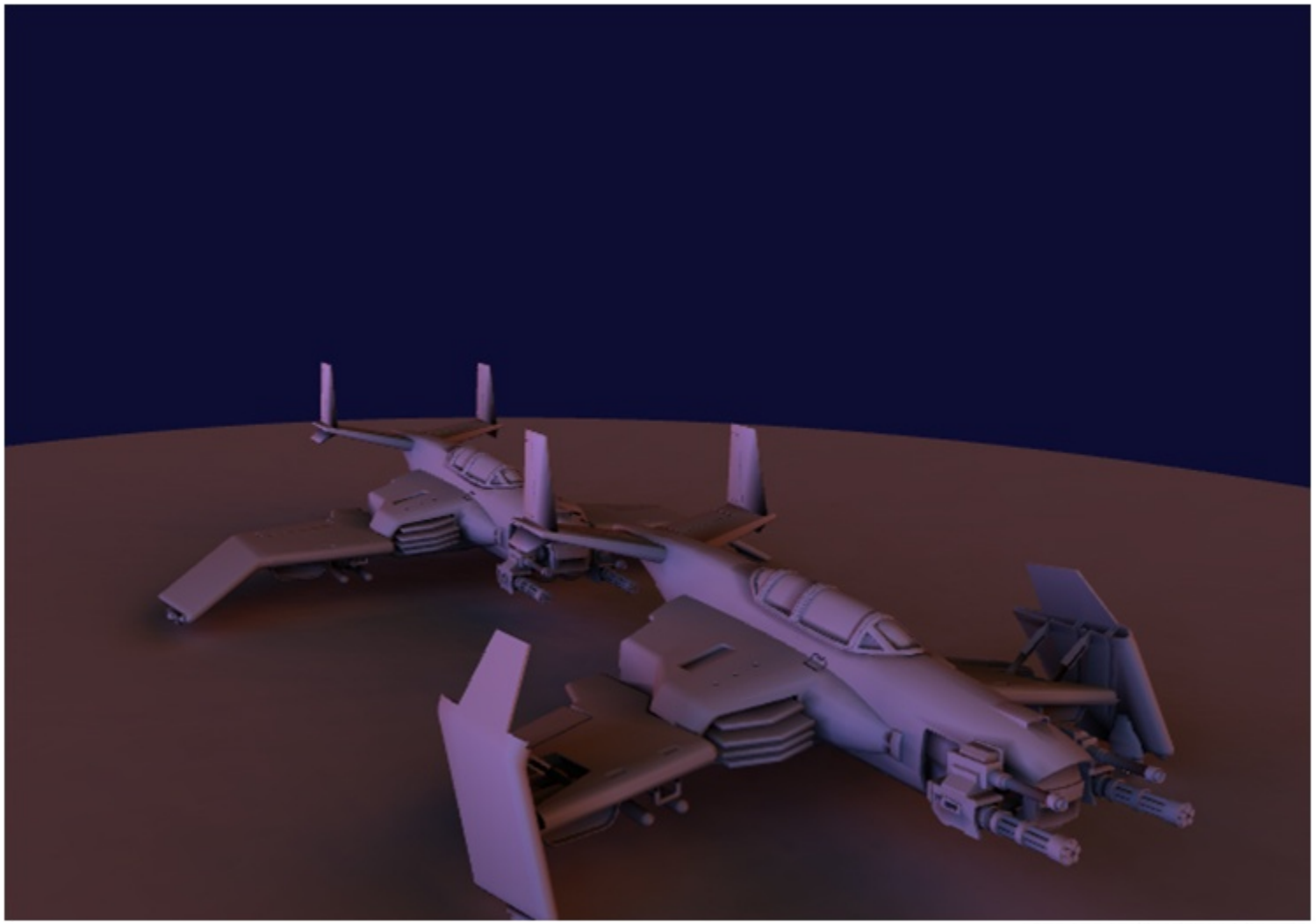
Key Ideas for PRT

- 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 latter
- Works 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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UCSD / Bunkspeed

Outline

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

What are we trying to solve?

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

- Use SH to simplify each of these functions

Spherical Harmonics

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

Basis Function Projection

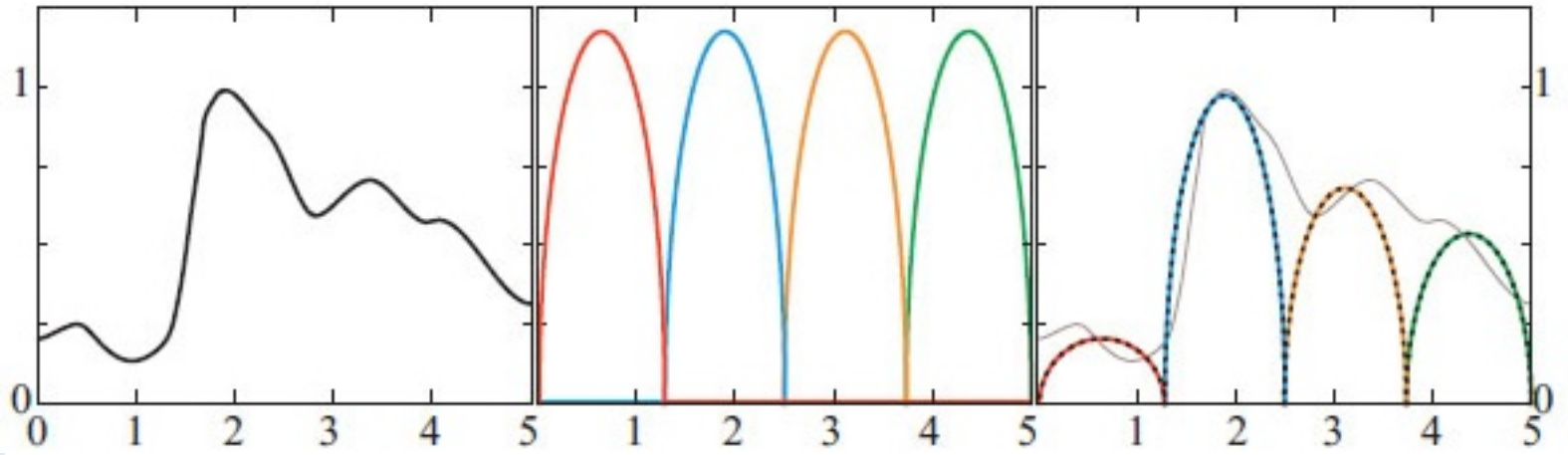


Image courtesy of Real Time Rendering 3rd Edition

Spherical Harmonics Properties

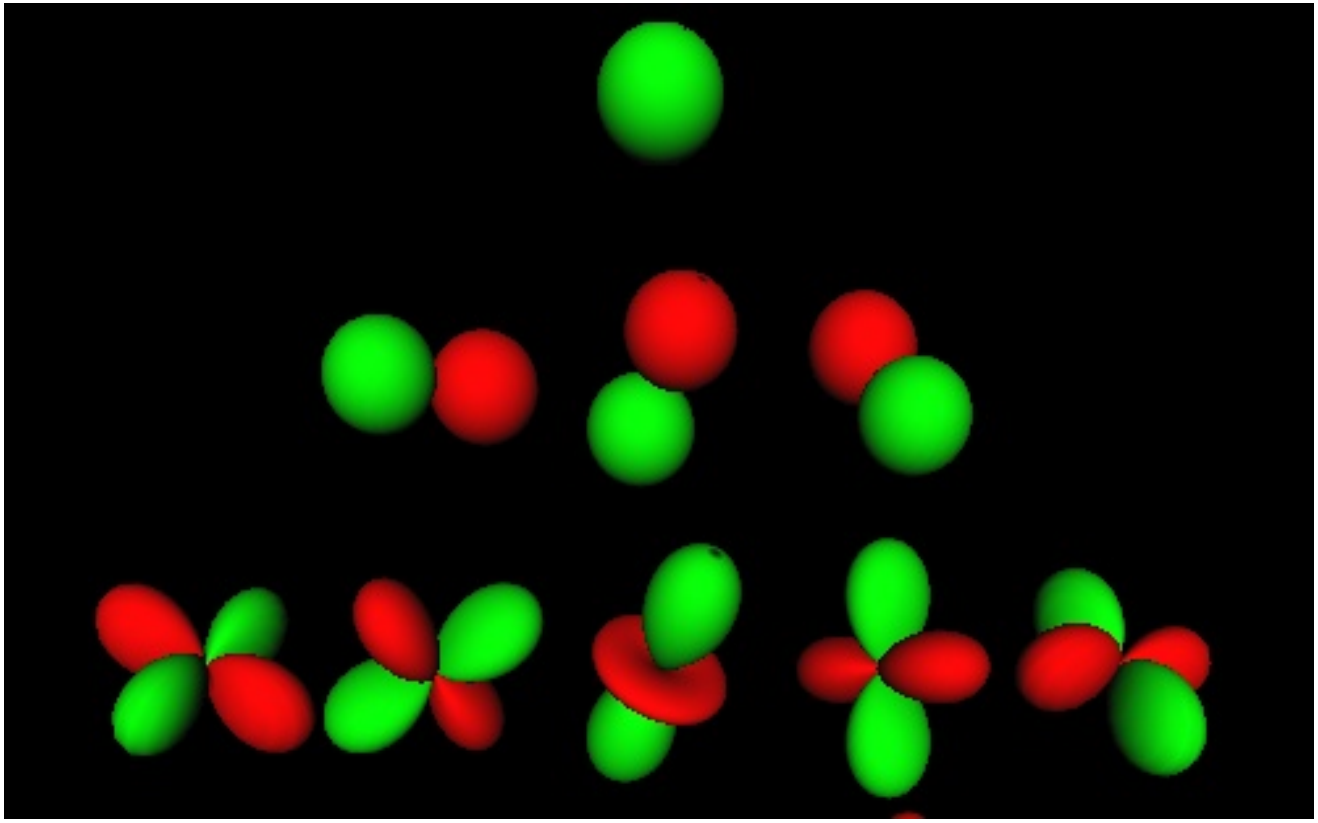
- i Orthonormal basis ->
  - convolution as dot products
  - simple projection
- n Multi-resolution/band-limited, related to Fourier decomposition
- / Solid math foundation
- a Stable rotation, no wobbling lights

  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



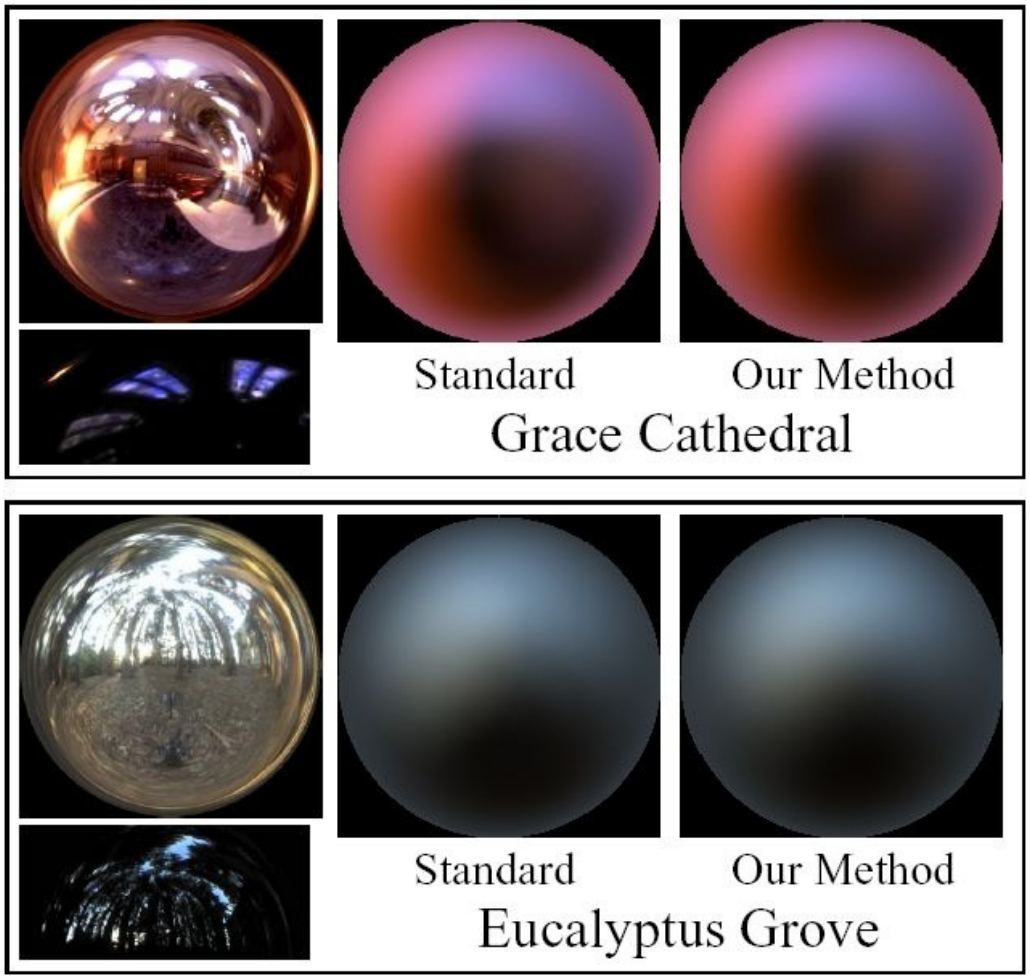
Spherical Harmonics - Issues

- 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



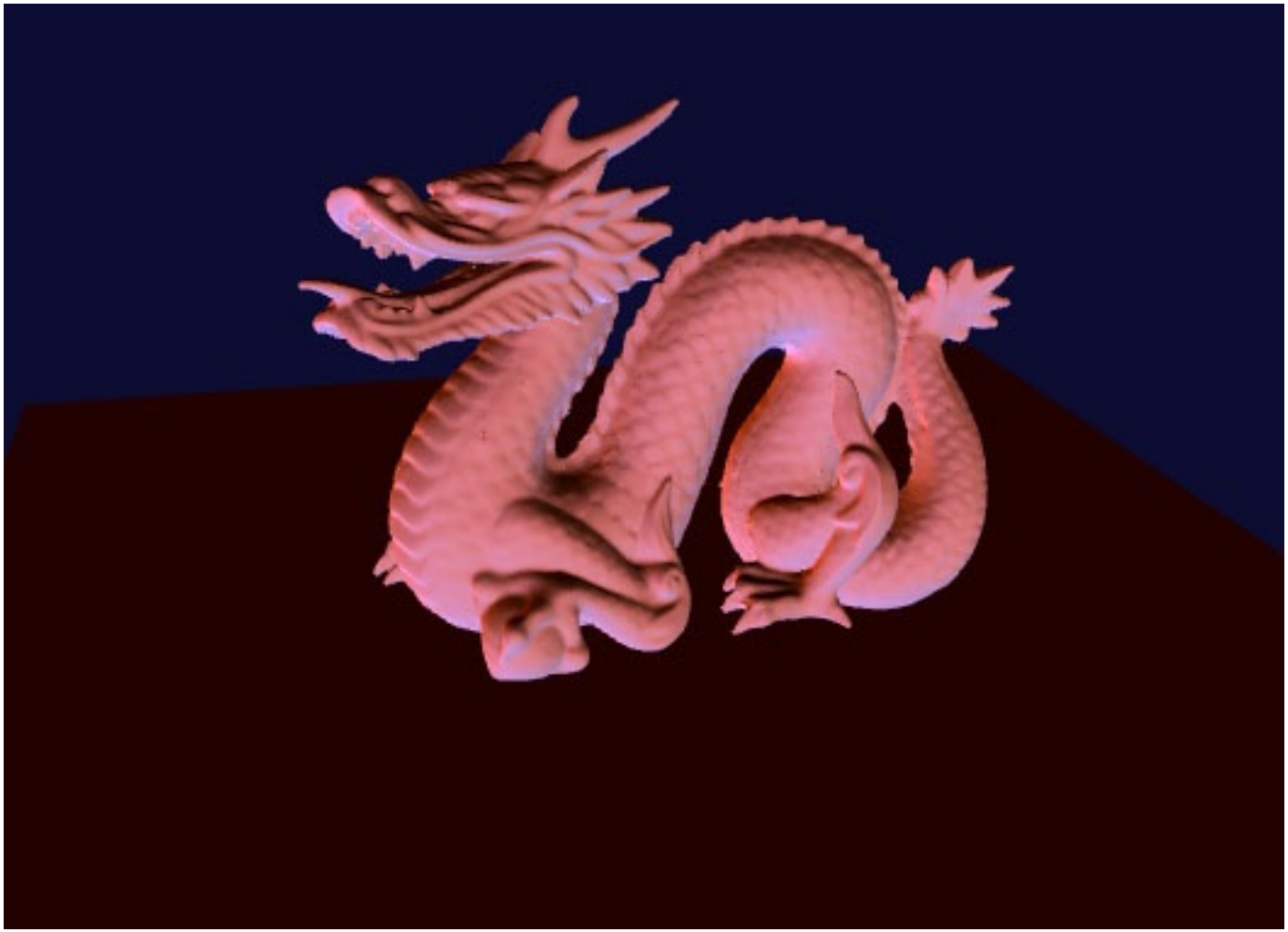
Environment Map Projection

- 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 weight it by the solid angle

Solid Angle

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

Envmap Demo



PRT Coefficient Generation

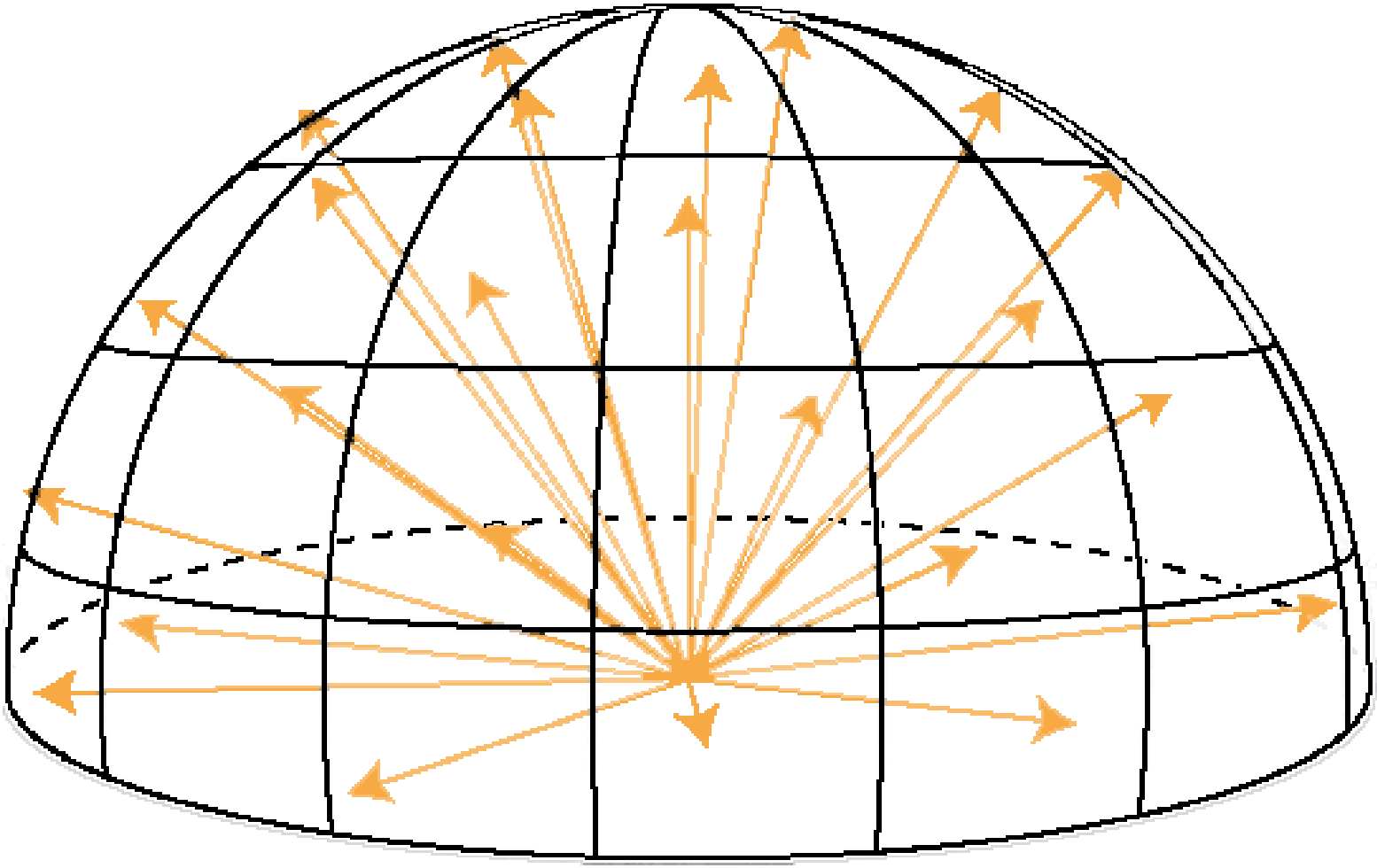
- We have simplified the light source, now we must also project the visibility function using SH

  This gives us compact storage of self-shadowing information
- Encodes the directional variations more accurately than AO or HL2

PRT Coefficient Generation

- Monte Carlo raytracing method
- Project, weight, accumulate

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
project             grayness = H * shcoeffs[j*bands +
 k];
weight          grayness /= pdf[j];
accumulate      coeff += grayness; //sum up
 contribution
            }
        }
    }
```

Projecting Visibility Function

- i 100-400 shadow rays per vertex are sufficient
- a Use your best acceleration structures
- c Vertex normal is accounted for in computation of H, thus no need for normal in shader
- a Full visibility function is preserved
- f 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

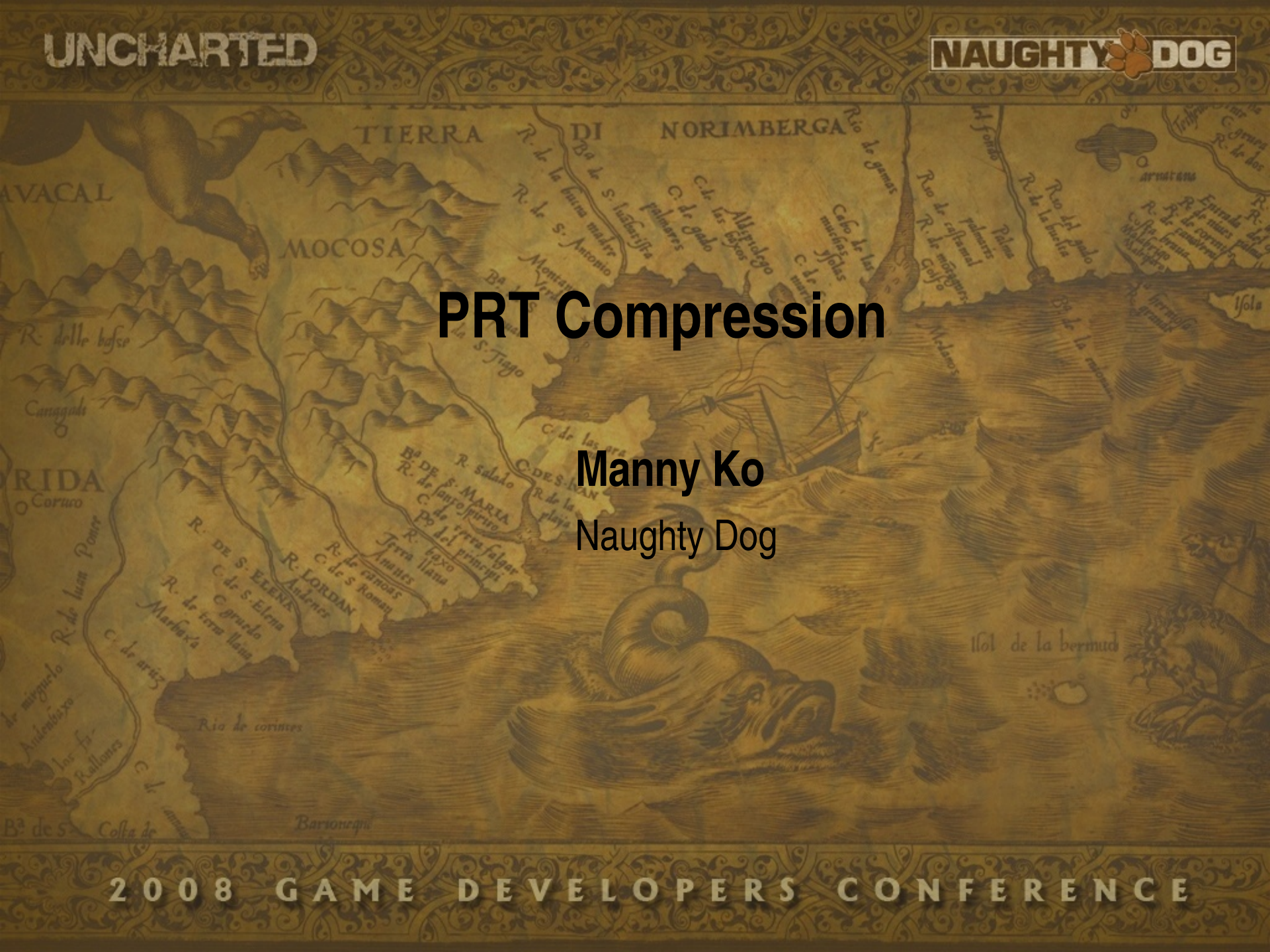
```
uniform vec3 Li[9];
attribute vec3 prt0;
attribute vec3 prt1;
attribute vec3 prt2;

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

Comparison: With and Without Self-Shadows

PRT in hyperDrive™


UNCHARTED
NAUGHTY DOG
TIERRA DI NORIMBERGA
MOCOSA
PRT Compression
Manny Ko
Naughty Dog
2008 GAME DEVELOPERS CONFERENCE

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 bases
- 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)

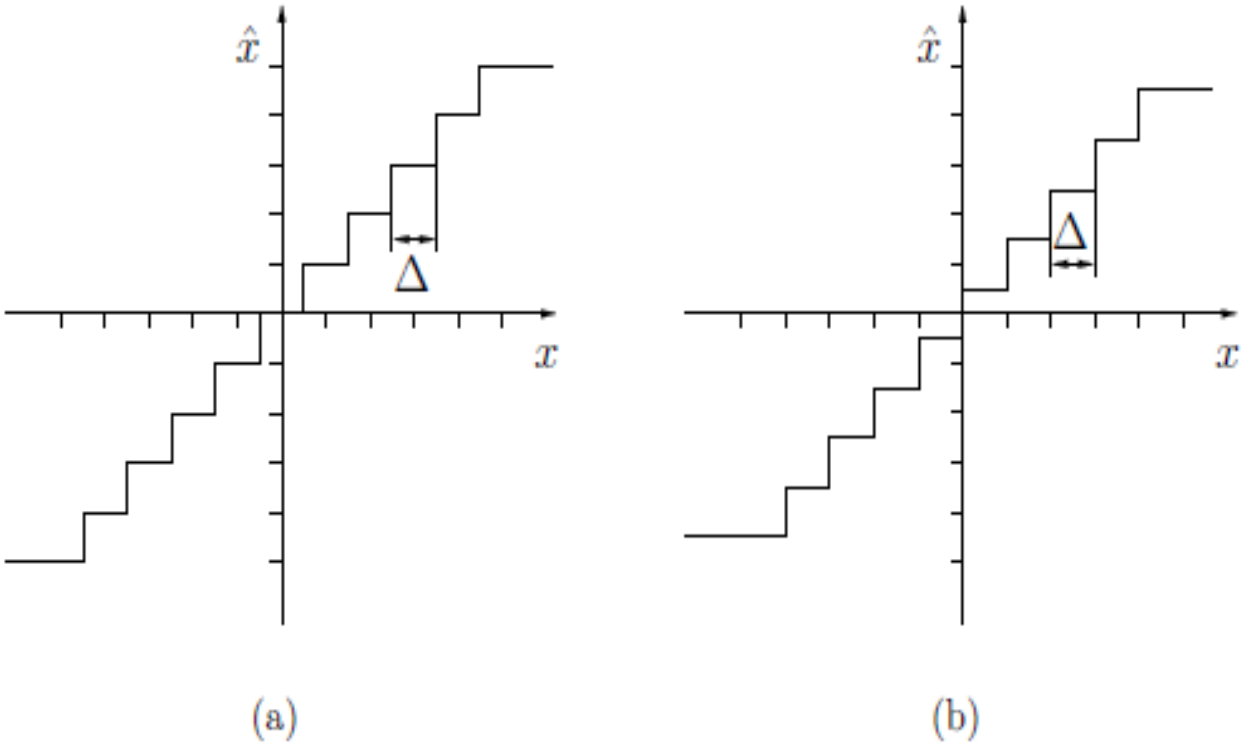
  M 3: 6 bytes using Lloyd-Max relaxation
- M 4: 4 bytes (5; 4,4,4 ;3,3,3,3,3)

  All very simple to implement

Scalar Quantizer and Scale-Bias

- How to convert floats to bytes?
- Scan each set 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

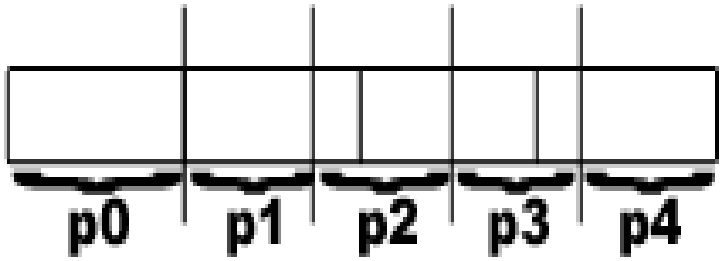
- Method 1 takes us down to 9 bytes. Can we do better?
- (8,6,6,6,6) (4,4,4,4) – bit fields
- Choice of bit allocation motivated by
  - Fourier theory => energy compaction
  - shader efficiency
- Cannot be optimal but try to be close

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

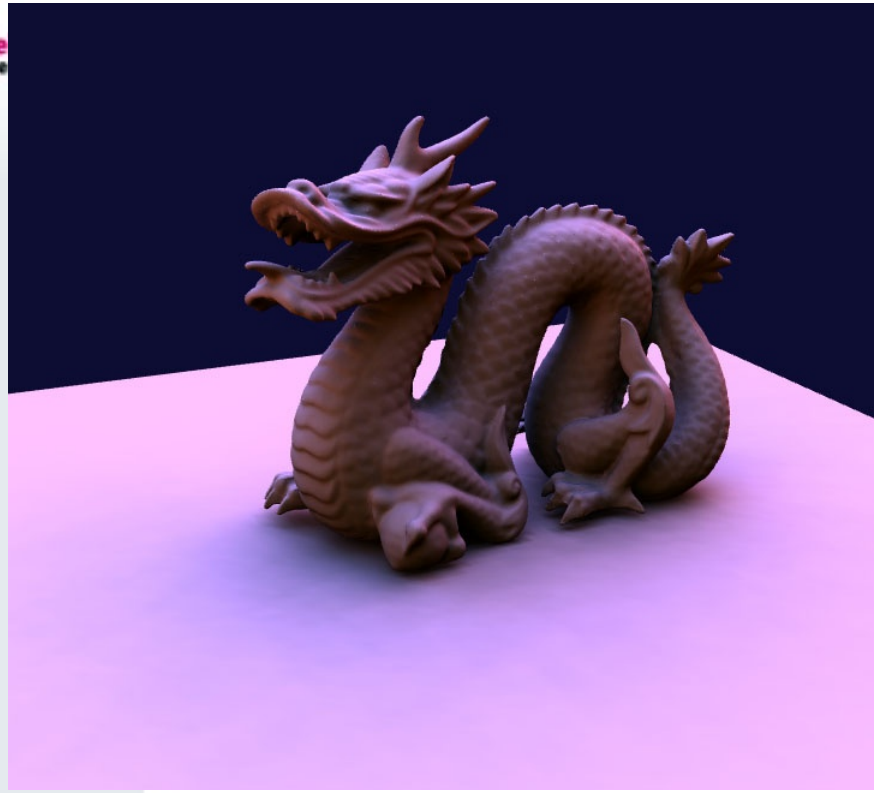
  Mul/div by power-of-2 for L/R shifts
- Fract and trunc() to isolate the 2 pieces. Add for ‘or’
- Tries to take advantage of SIMD

Vertex Shader

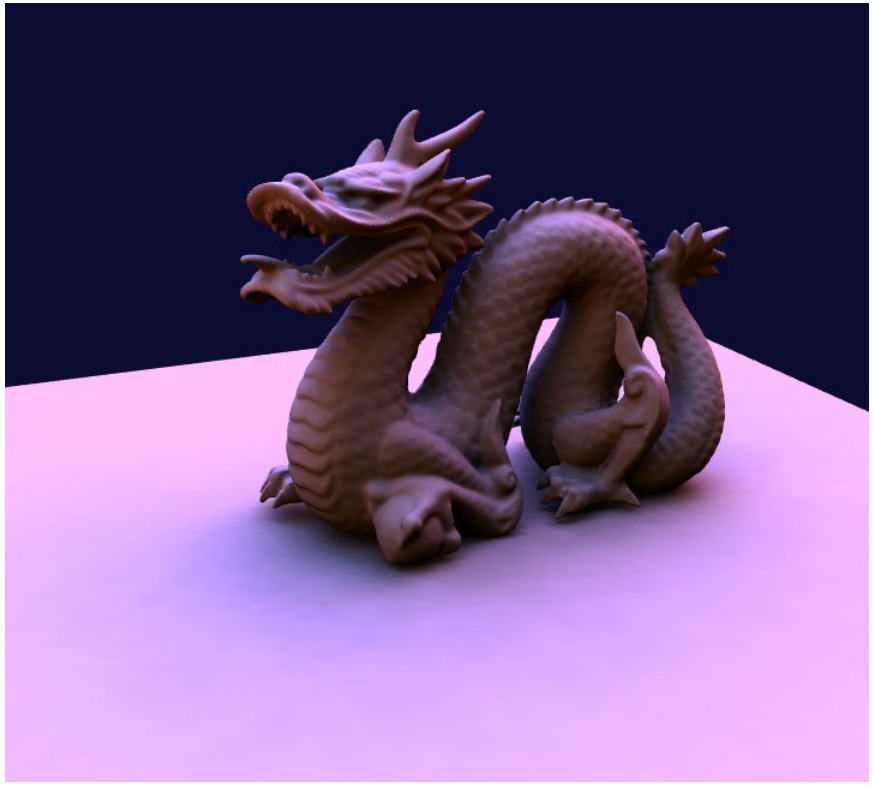
```
0   // rshft(s[0], 1/4, 1/16, 1/64)
/   p14 = prt0 * rshft;
f   lhs3.yzw = fract(p14.yzw);
    // lshft(0, 16.*4., 4.*16., 64.);
4   lhs3 *= lshft;
4
4   //p[0]:
    pp0 = p14.x + bias0;
a   //p[1..4]:
a   p14.xyz = (lhs3.xyz + floor(p14.yzw)) *        scales.xyz + bias.xyz;

    p14.w = lhs3.w * scales.w + bias.w;
```

Comparison:M1 vs M2



184 fps



243 fps

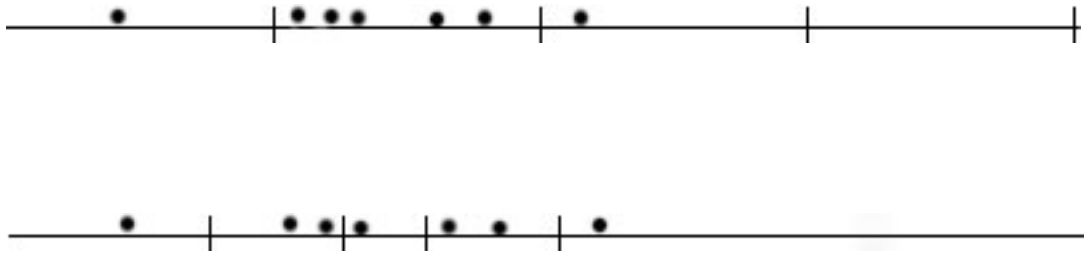
Method 2: Demo and Discussion

- 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?

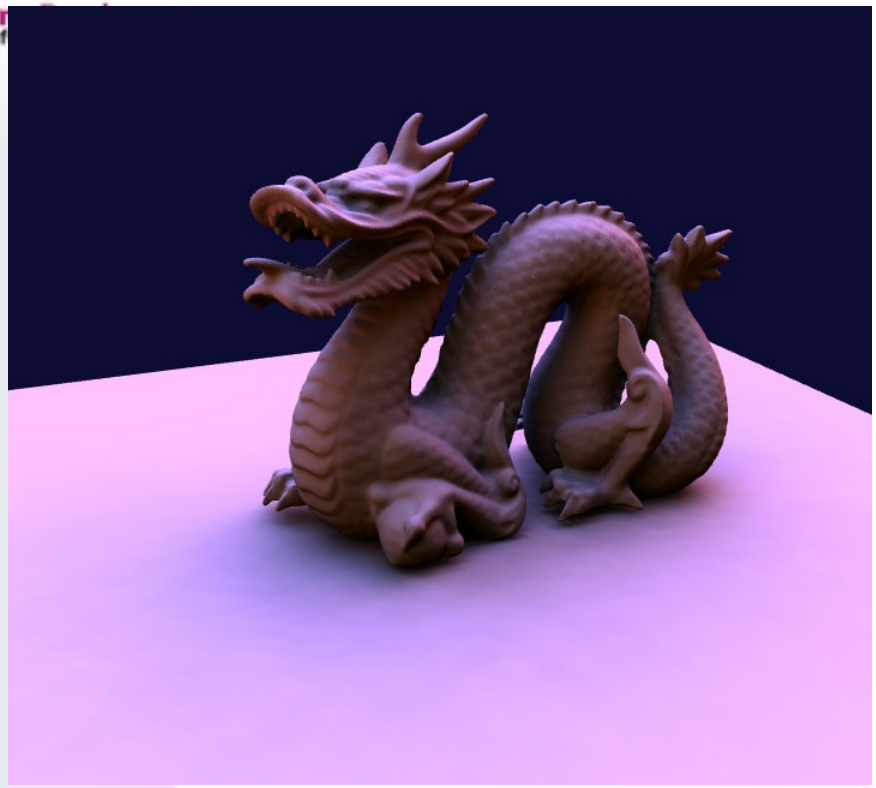
Lloyd-Max Algorithm

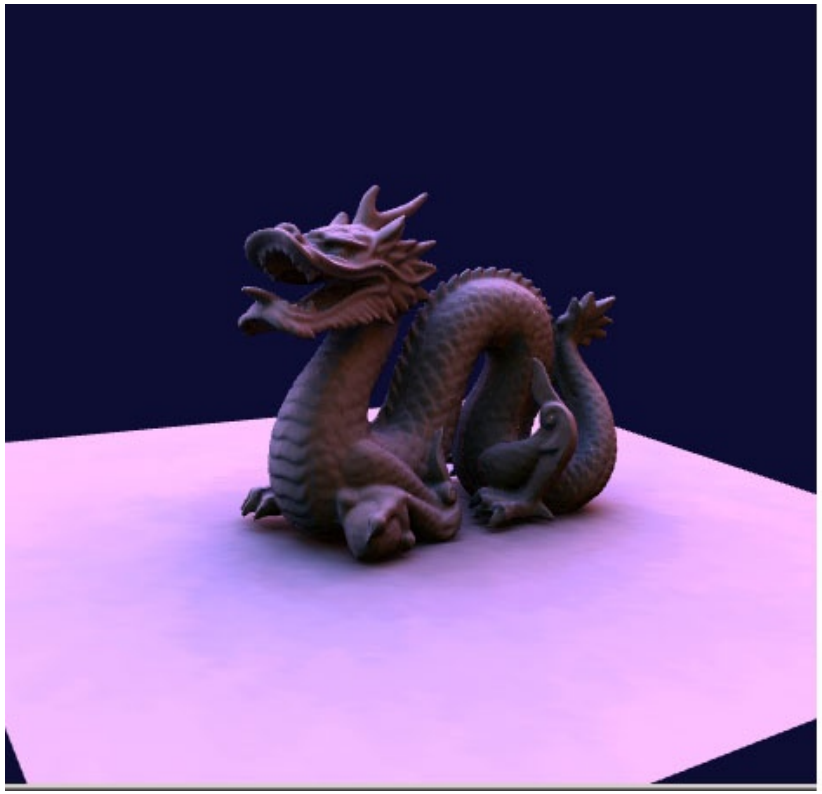
- A version of k-means clustering algorithm
- Given a fixed number of bins iteratively solves for an optimal set of bins
- Converges quickly
- Key is a probability distribution table (*pdf)*
- Applied to all 9 bands separately
- Details in ShaderX6

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 Summary

- 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 source – preferably area lights or a large collection of lights, or use probes

  Runtime methods to generate *Lis*
- Add or subtract lights easily – just add/sub the *Lis*
- 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

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

Contact Info

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- Jerome Ko – submatrix@gmail.com

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