Hierarchical Radiosity with Multiresolution Meshes

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Thesis Statement

The Domain

- Radiosity on scenes with detailed models

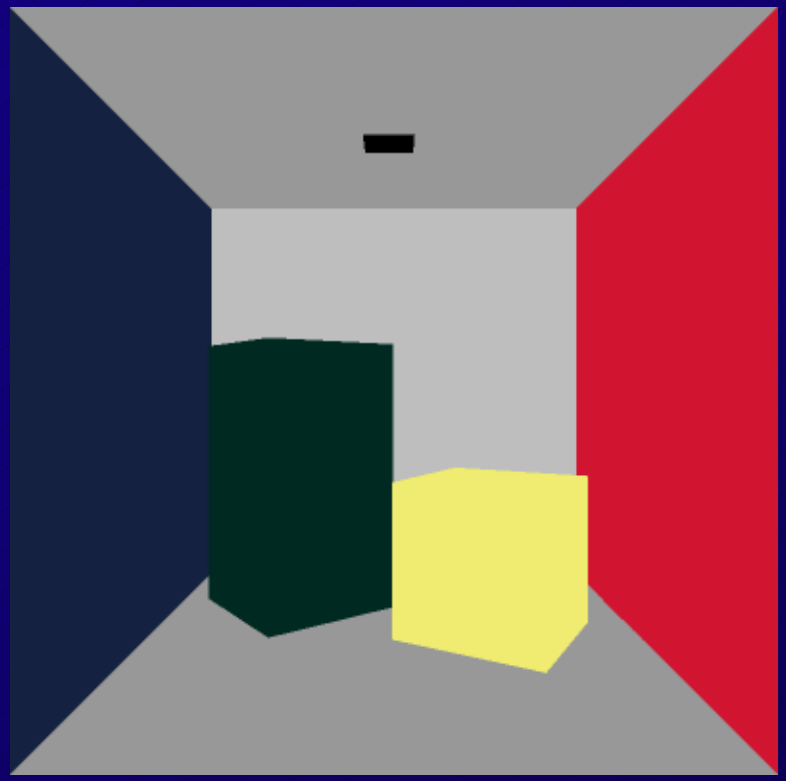
By using face cluster hierarchies we can

- Get sub-linear or constant time complexity
- Better approximate detailed model surfaces

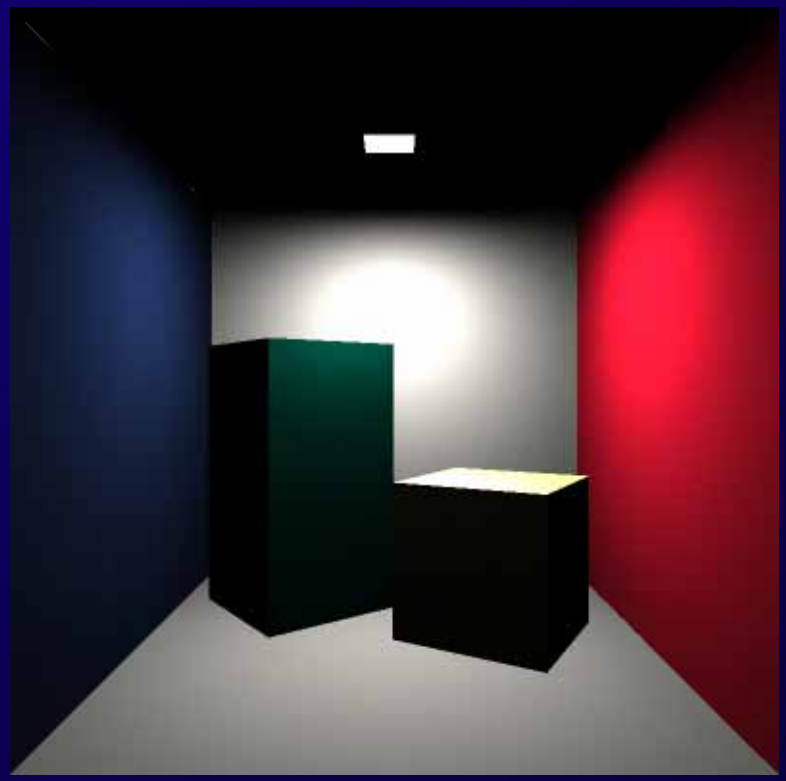
Route

- Global illumination
- Radiosity & Hierarchical Radiosity Methods
- Problems
- Face cluster hierarchies
- Face Cluster Radiosity
- Results

Simple Illumination

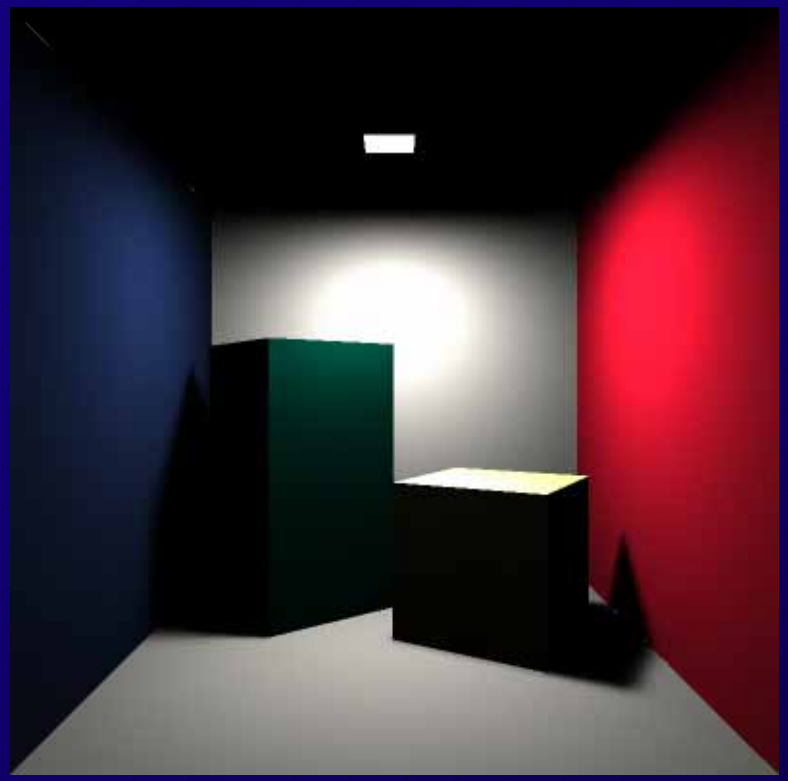


Solid Colours

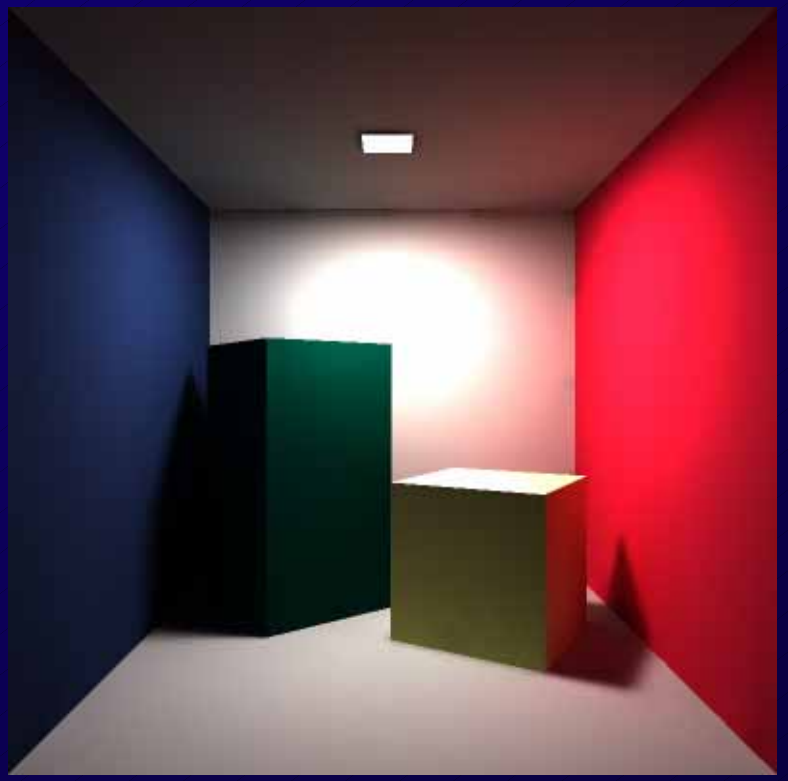


Direct Illumination

Global Illumination



+ Shadows



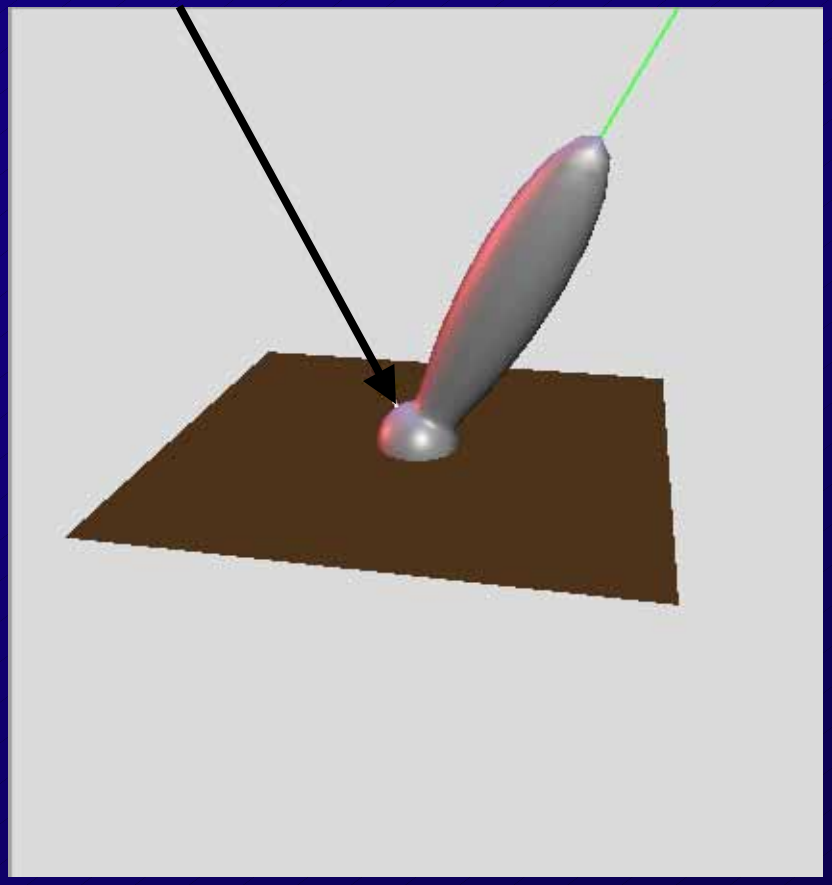
+ Indirect Illumination

Reflection Types

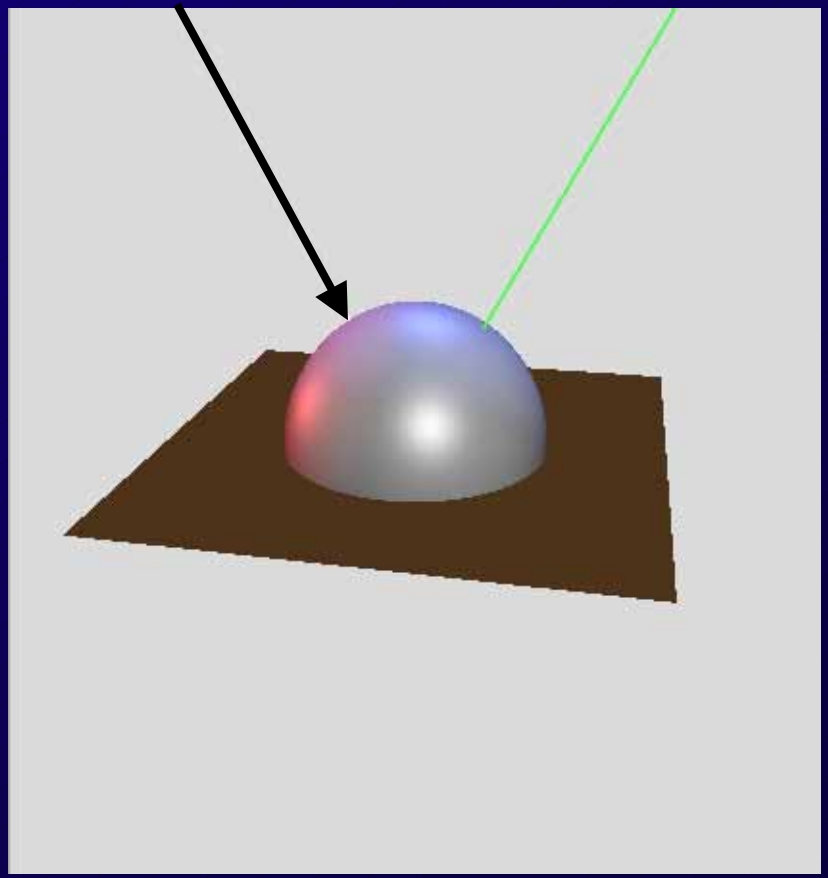
Specular

Diffuse

Reflection Types



Specular



Diffuse

Radiosity

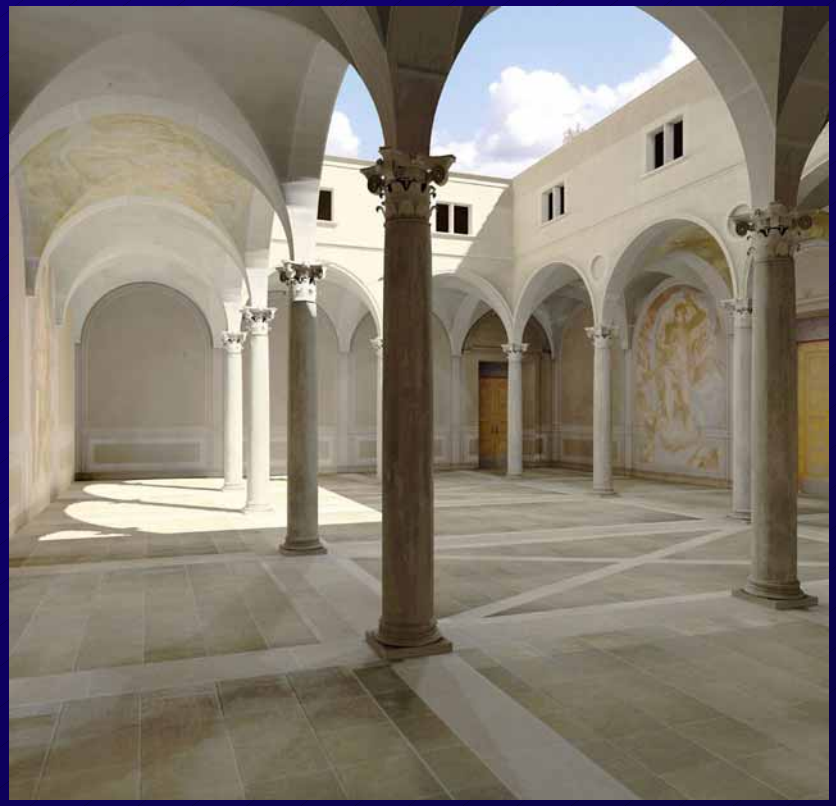
Definition

- The calculation of global illumination for scenes with only *diffuse* surfaces

Consequences

- Easier to solve than the full equation
- Suitable for finite-element methods
- The solution produced is *view-independent*

Indirect Illumination

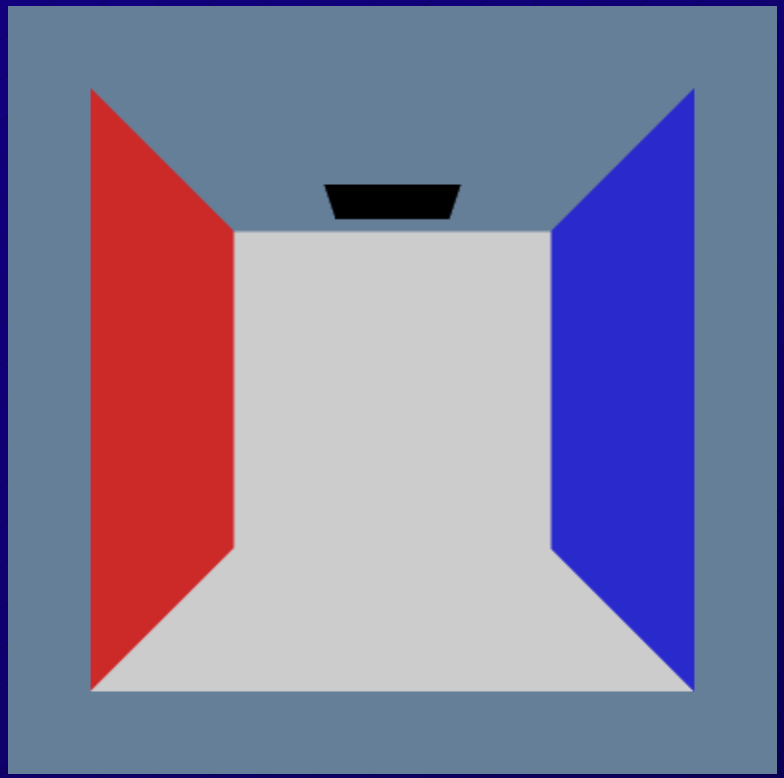


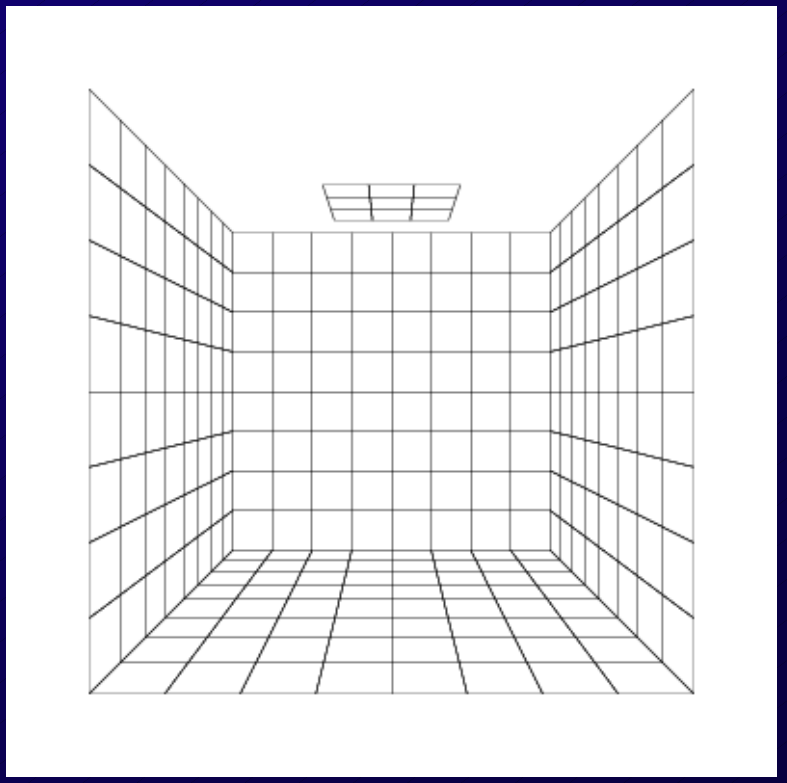
Lightscape Technologies

View-Independence

Quake: ID

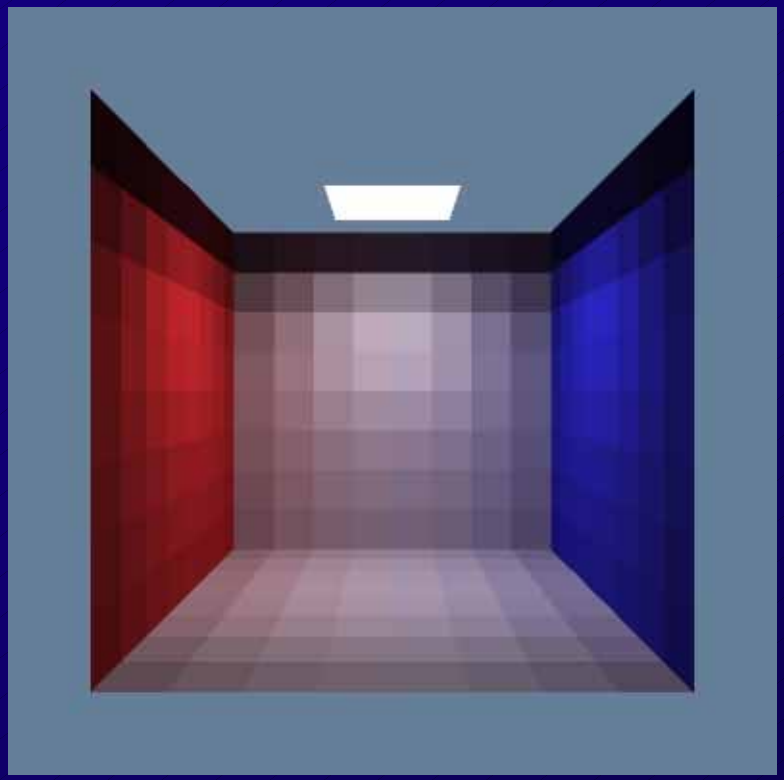
Finite Elements





Discretize scene into *n* elements, solve for each element

Solving for Radiosity



- Each element emits **radiosity** [Watts/sr/m^2]
- Can write in terms of all other elements:

$$b_i = \rho_i \sum_j F_{ij} b_j + e_i$$

- Gives system of linear equations

Early Radiosity Methods

Matrix Radiosity [Cohen '85]

- Initially used standard matrix techniques (Jacobi, Gauss-Seidel)
- **But** this is $O(n^2)$ in time and space

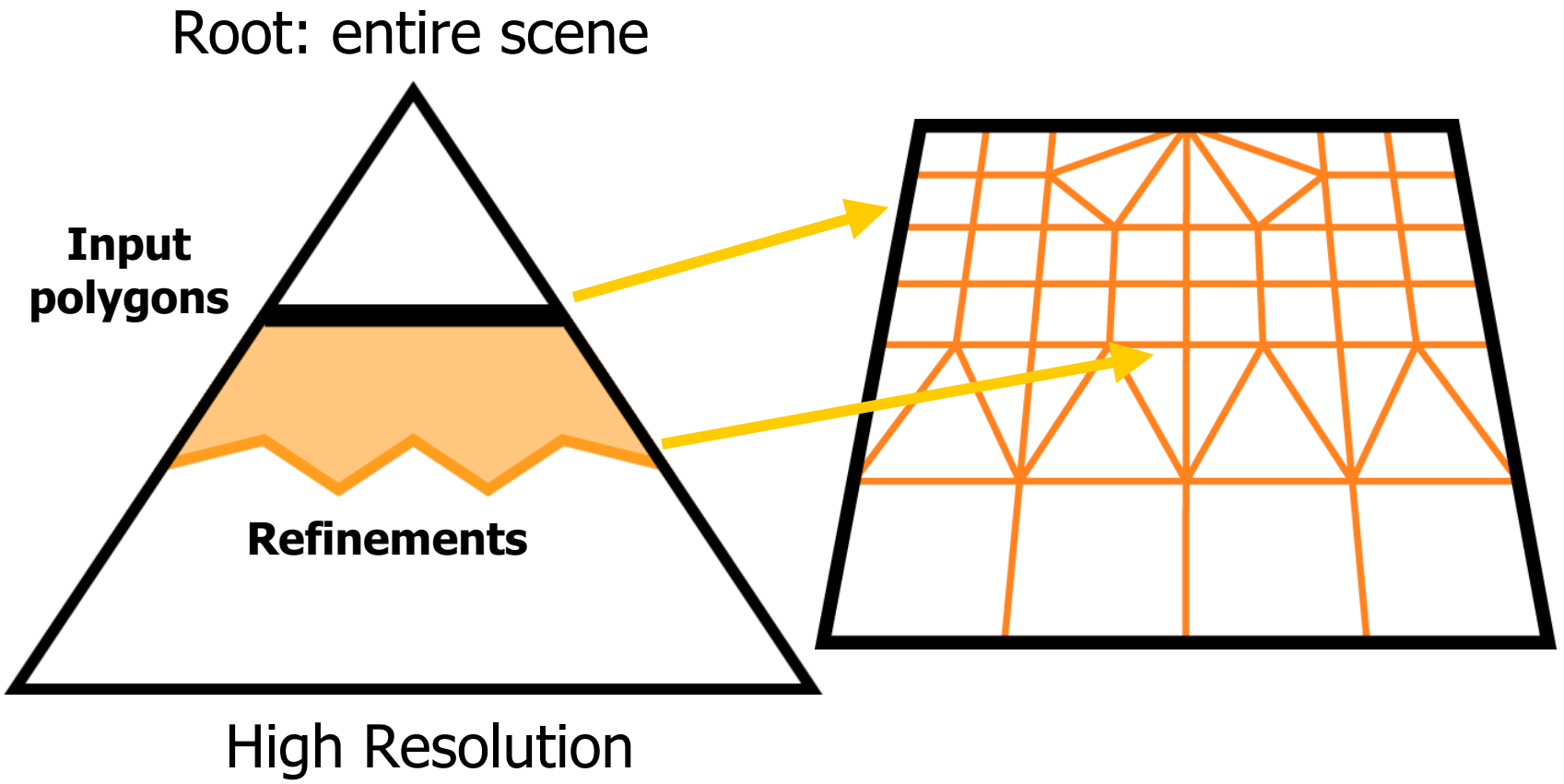
Progressive Radiosity [Cohen '88]

- Reorder computation
- Repeatedly shoot element with most unshot radiosity: can see results improving
- Still $O(n^2)$ speed, but $O(n)$ memory

Hierarchical Radiosity

- [Hanrahan '91]
- Use hierarchical mesh (quadtree)
  - **Coarse level:** unimportant interactions
  - **Fine level:** Interactions between close surfaces
- $O(k^2 + n)$ time and space complexity
  - k is the number of *input polygons*
  - n is the number of *elements* used by the solution
- k^2 is a problem for $k > 1000$ polygons

Refinement for Hier. Rad.

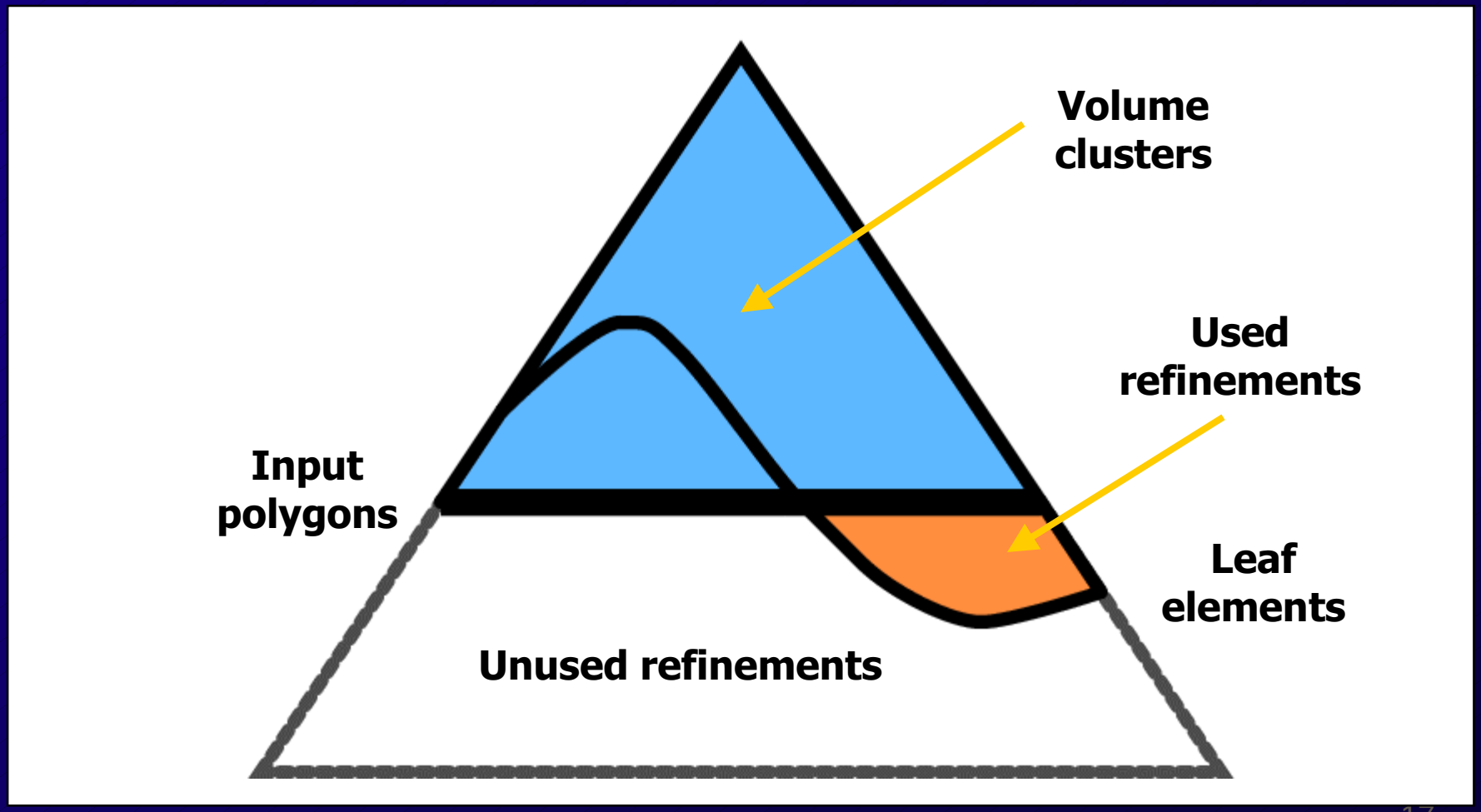


Hierarchical Radiosity with Volume Clustering

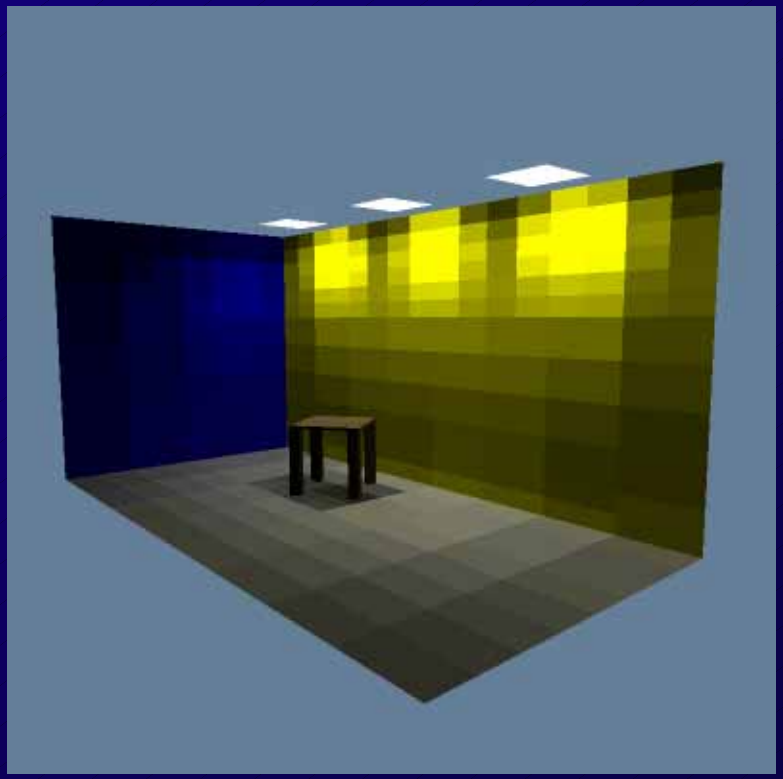
Constructs a complete scene hierarchy

- [Smits '94, Sillion '94]
- Adds volume clusters above input polygons (octree)
- Completes the hierarchy
- Algorithm is $O(k \log k + n)$
- $k \log k$ is a problem for k > 100,000

Volume Clustering



Hier. Radiosity Demo



Problems with HRVC

- Slow for complex scenes ($k >> n$)
  - Must push irradiance down to leaves when gathering, pull radiosity up when shooting
  - O(log$k$), and **all input polygons must be touched on each iteration**
- Approximation
  - Volume clusters approximate a cloud of unconnected polygons
  - Idea: We can do better for connected, largely smooth surfaces

My Focus

Working with large scanned models

- Large enough to make $k \log k$ a problem
- Observation
  - Most polygons are for high resolution detail
  - Don't affect radiosity computations much

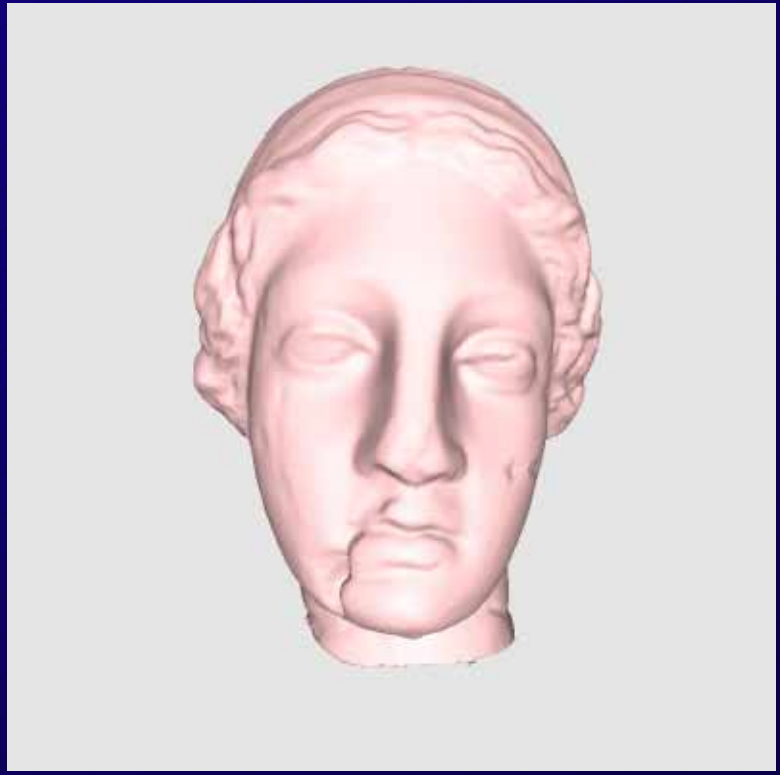
and with Multiresolution Models

- Allow you to adjust the resolution of the model at different places on the model

Detailed Models

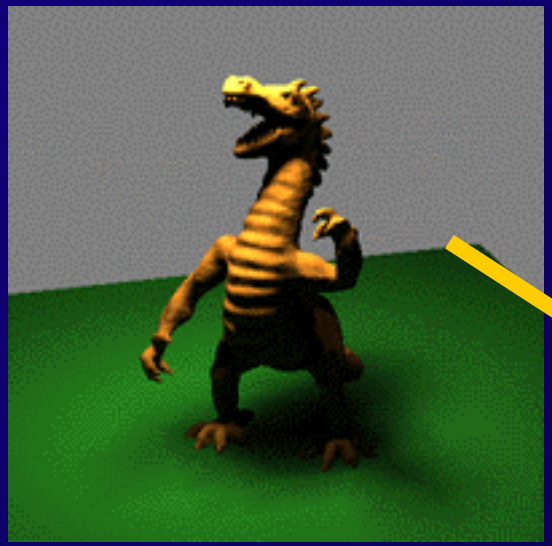
200,000 triangle model. Medium Resolution version(!)

Demo of a MR Model



Intuition

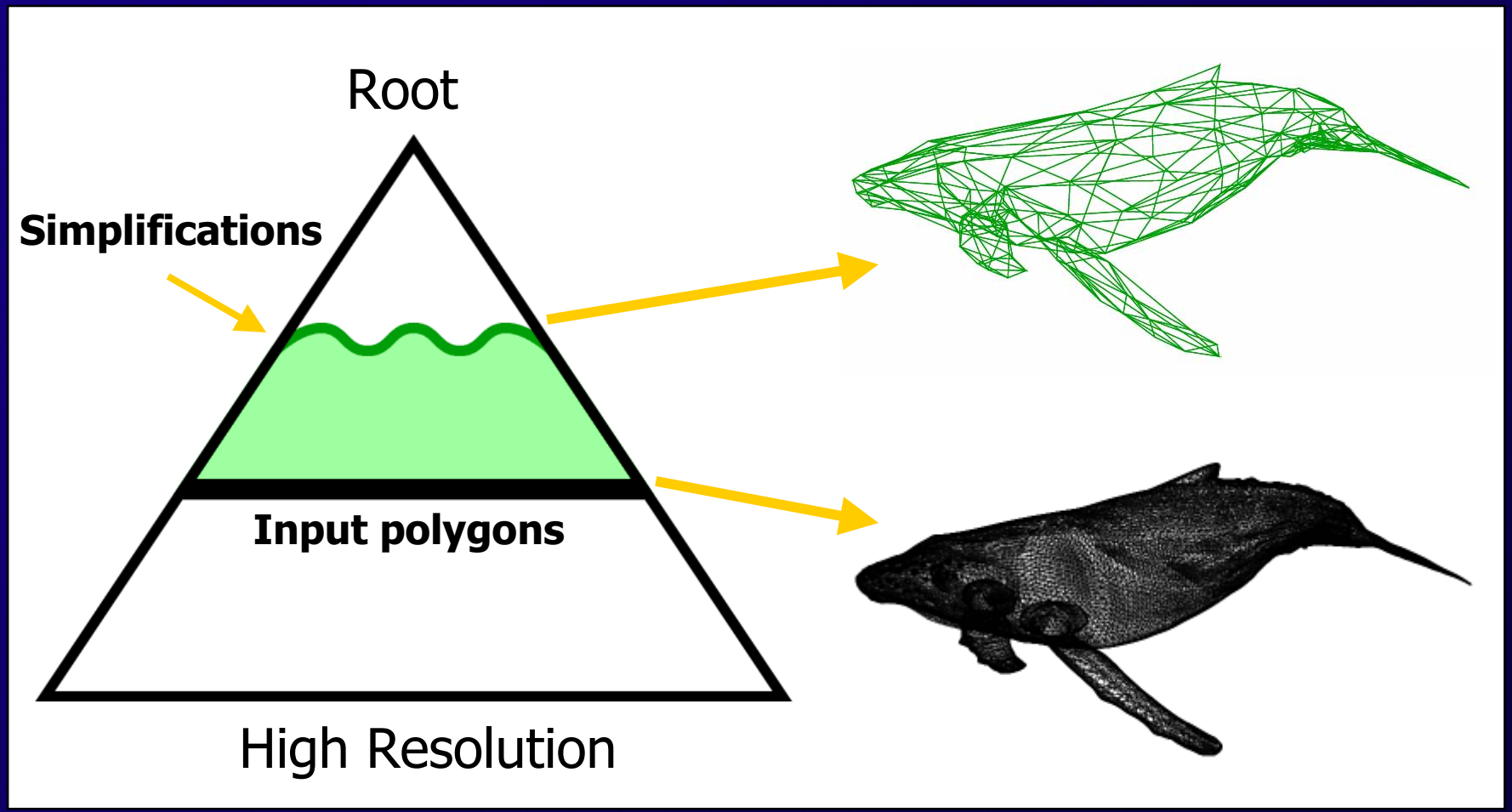
Instead of running radiosity on detailed model



Run radiosity on simplified model

Apply results to original model

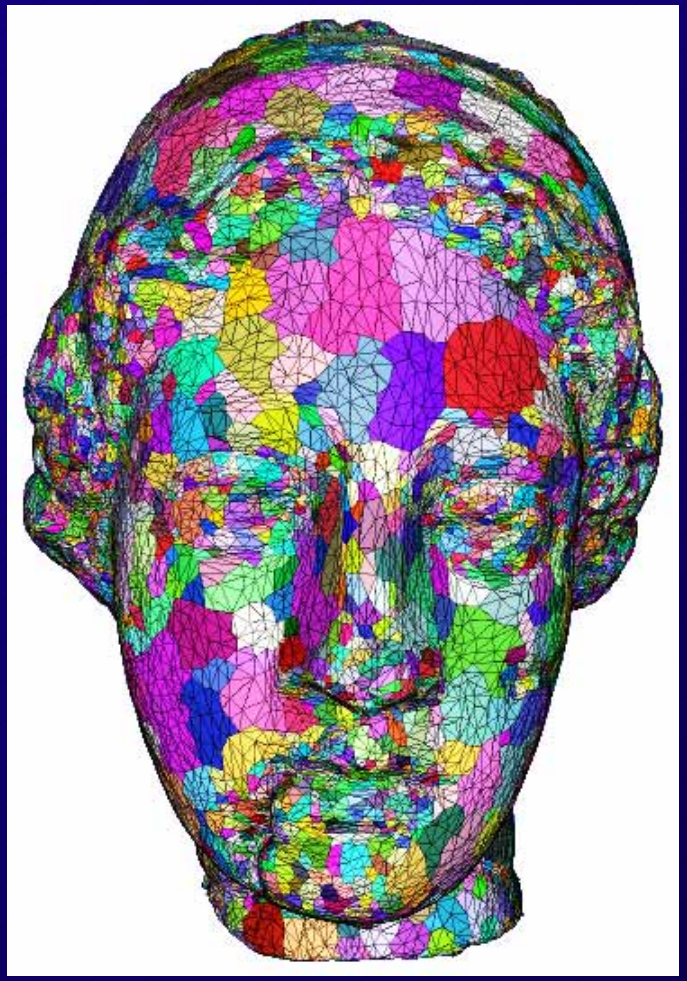
Simplification



Advantages

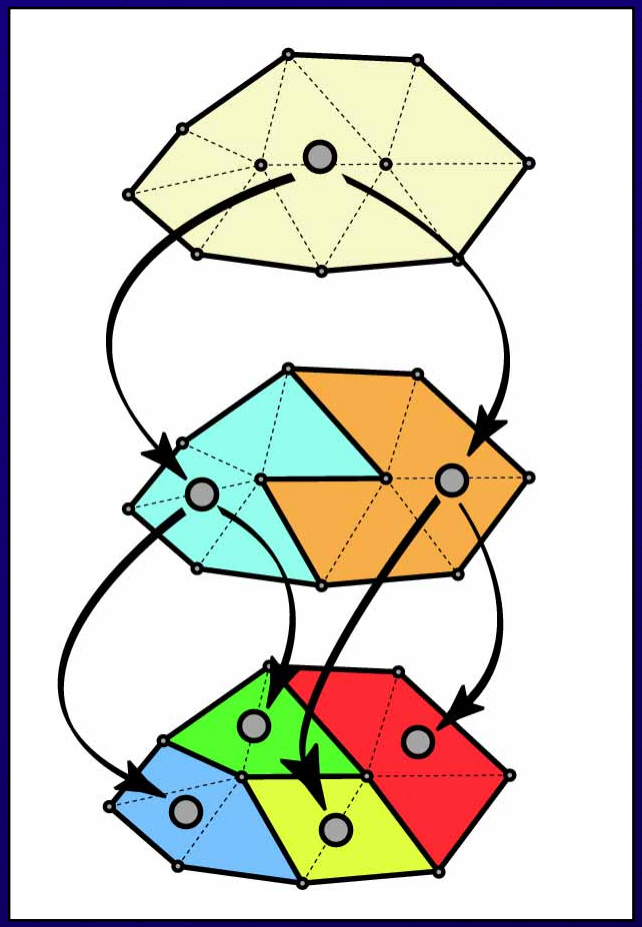
- No manual selection of simplification level
- Don't access each of the *k* input polygons during each iteration
- Don't store radiosity for each input polygon
- Multiresolution models are precalculated
  - Once for each new model acquired
  - Amortized over many scenes and renders

Face Clusters



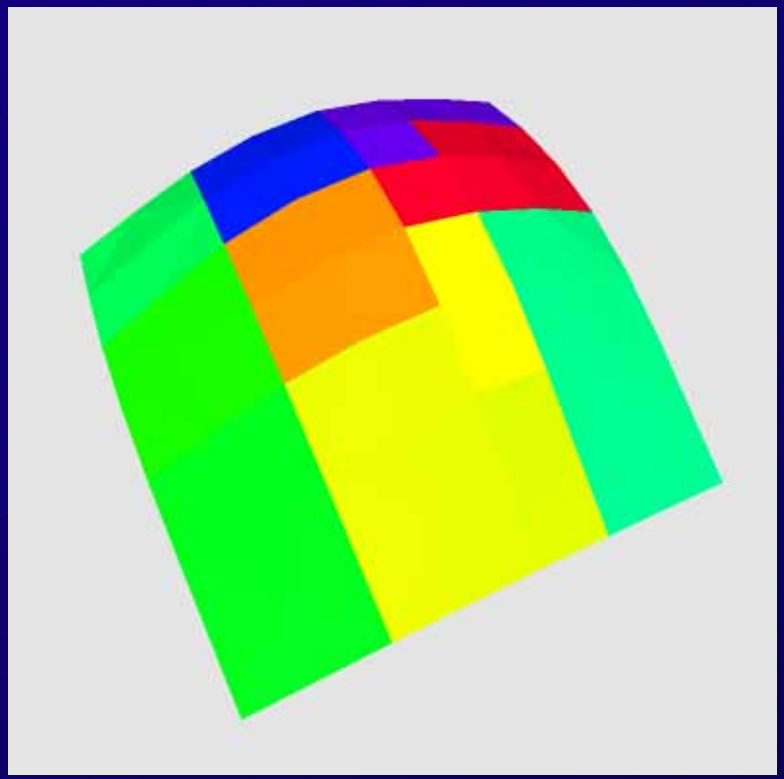
- Dual of standard multiresolution model
- Group faces rather than vertices
- Don’t change geometry of the model

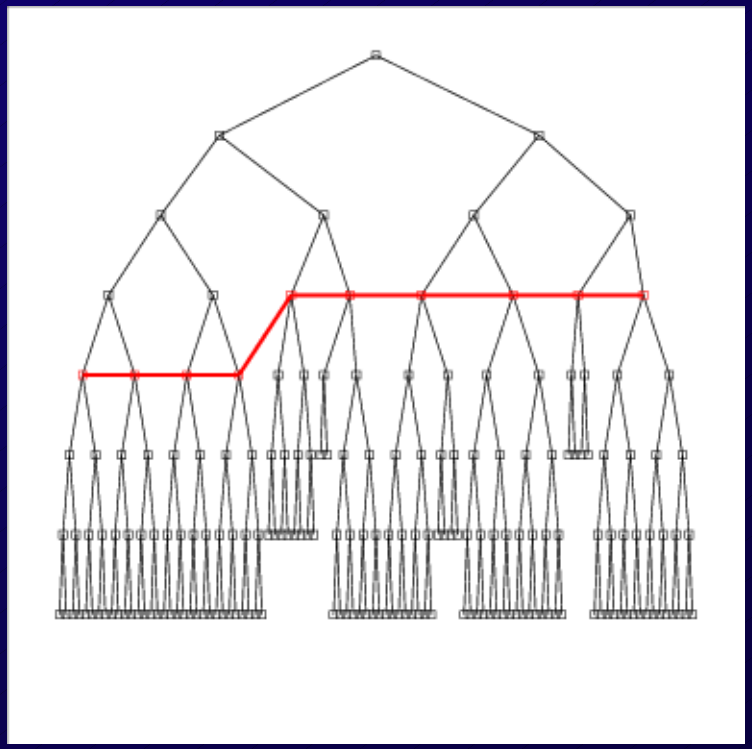
Face Cluster Hierarchies



- Iteratively merge face clusters
- Initial clusters each contain a single polygon
- Create links between two child clusters and their union
- Repeat until only root cluster left

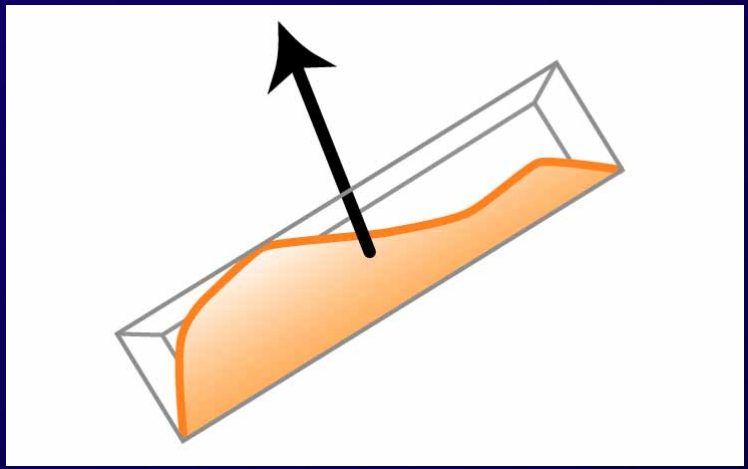
Face Cluster Demo



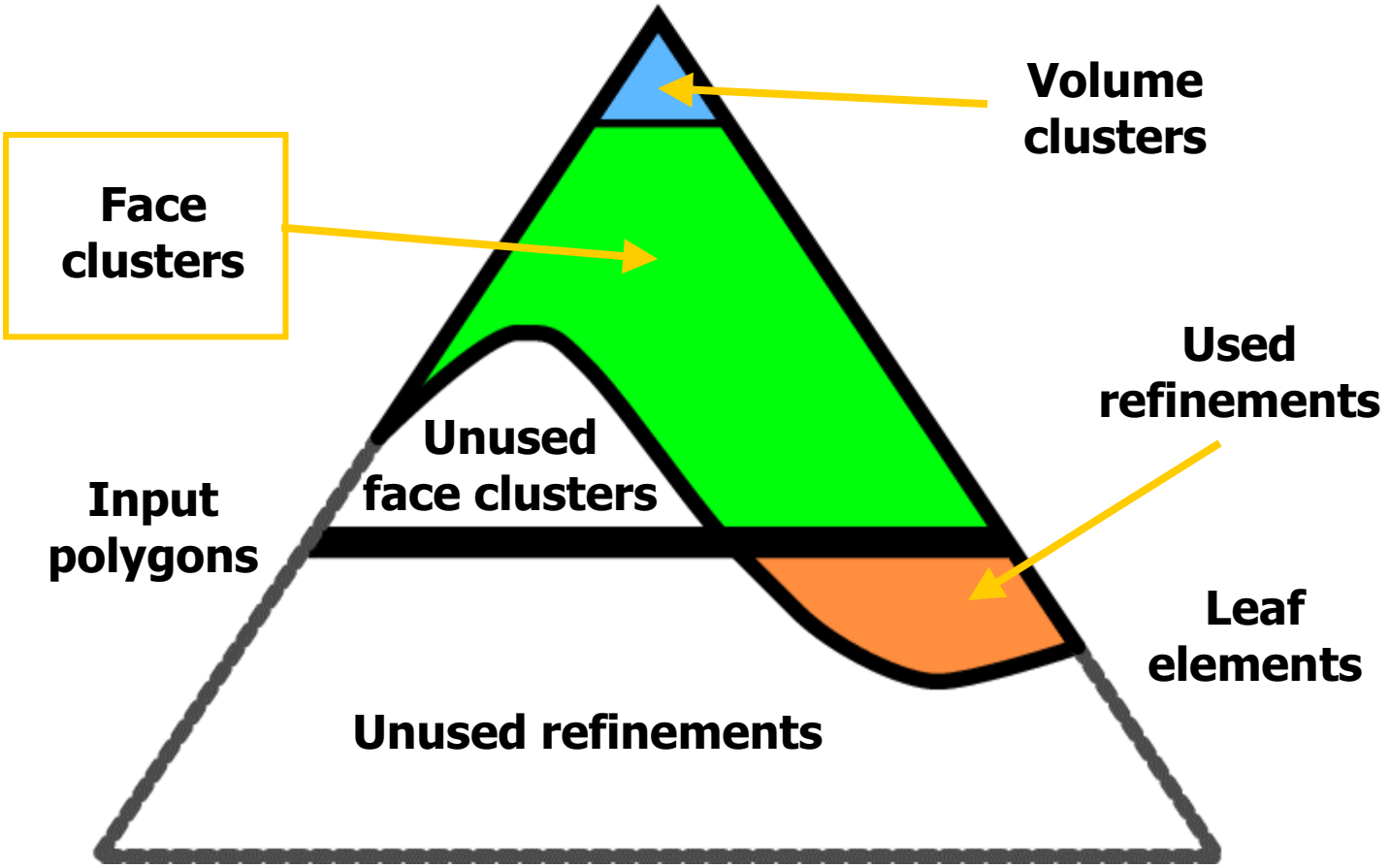


A Face Cluster

- An approximately planar region on the mesh
- Container for a set of connected faces
  - Oriented bounding box
  - Aggregate area-weighted normal
  - Pointers to the two child clusters that partition it



Radiosity with Face Clusters

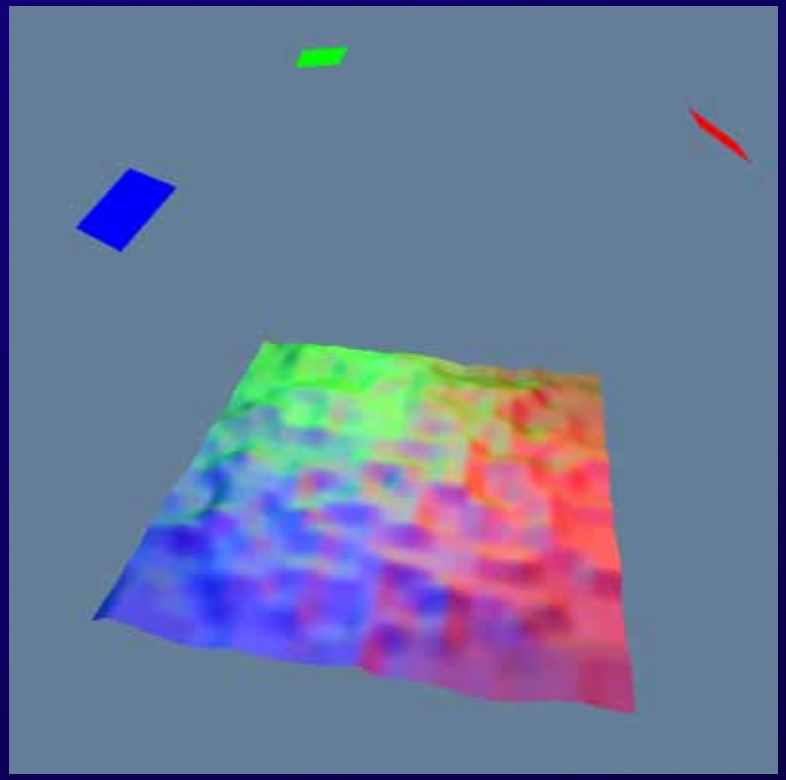


Building the Hierarchy

We use Garland's Quadric method

- Dual of edge-collapse simplification
  - Quadric error term measures distance to best-fit plane of face vertices, rather than distance to face planes of best-fit vertex.
- Most important properties
  - Produces clusters that are approximately planar
  - Tight *oriented* bounding box calculated via Principal Component Analysis
  - Add well-shaped term to get compact clusters

Radiator Demo



Vector Radiosity

Standard radiosity equation is scalar

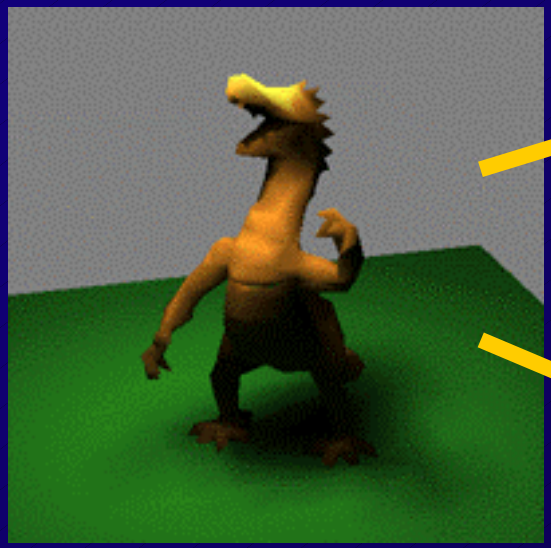
- Applied to face clusters it incorrectly ignores variation in local normals
- No obvious way of combining radiosities of two elements with different normals

Solution

- Recast radiosity equation in terms of *irradiance vector*

Why Vector Radiosity?

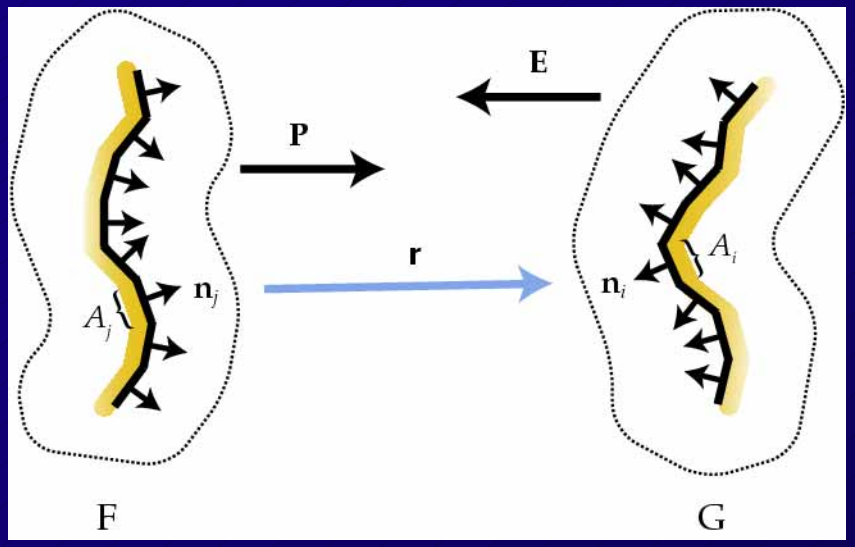
Leaf Elements



Scalar Radiosity

Vector Radiosity

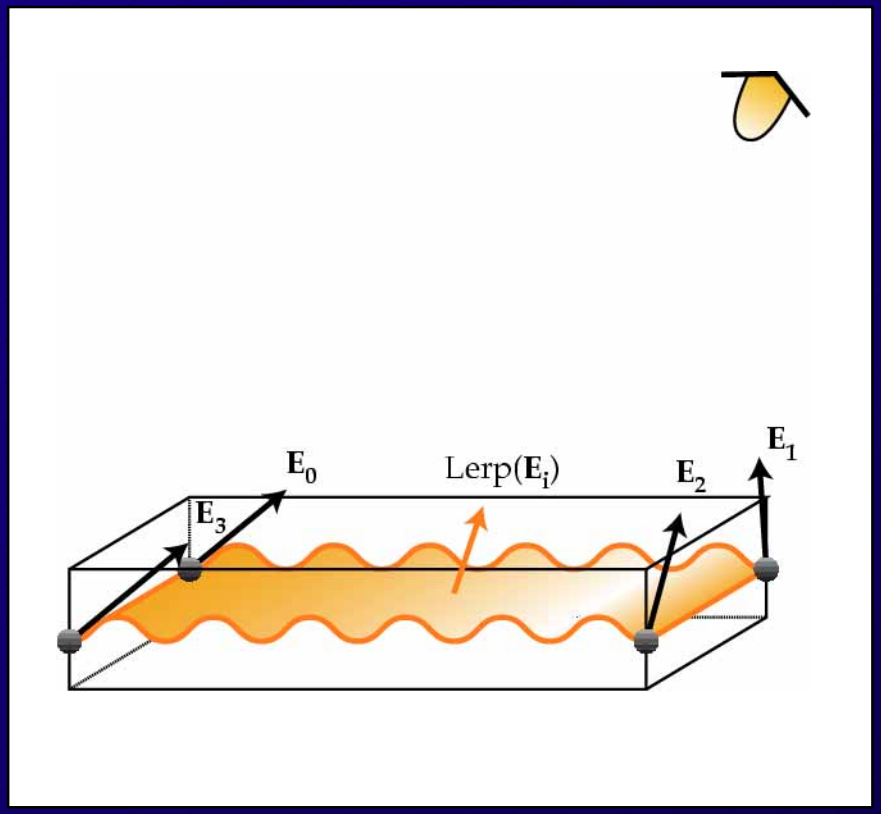
Gather in FCR



- Gather: process of transferring radiosity between elements
- Must be able to calculate *Visible Projected Area* quickly

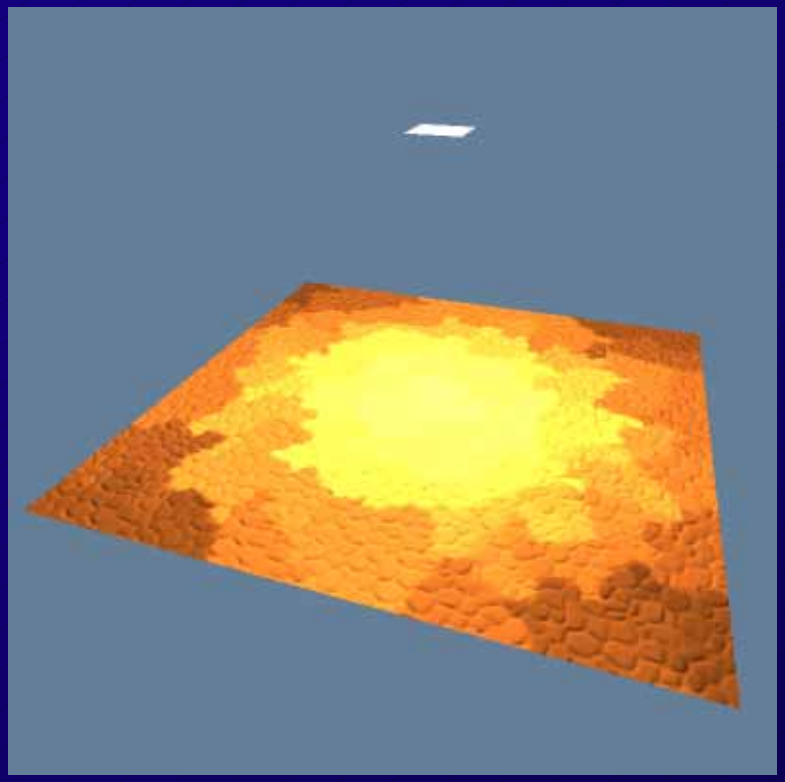
- Developed methods of bounding VPA **without sampling visibility**

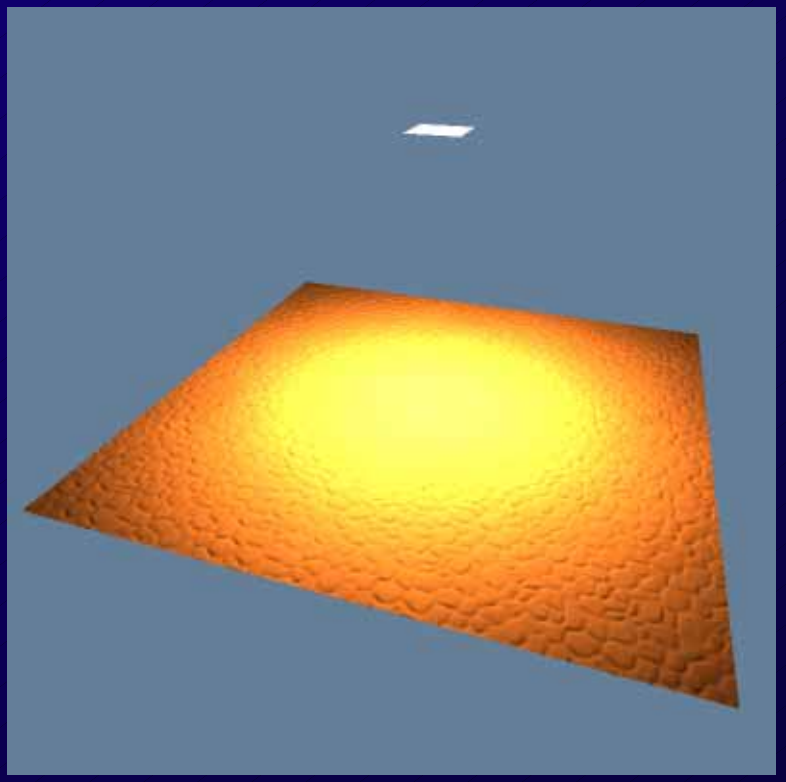
Vector Interpolation



- Can get inter-cluster discontinuities, same as with constant radiosity basis function
- Can fix by resampling irradiance vector at corners of the cluster, and interpolating
- Final pass only

Vector Interpolation



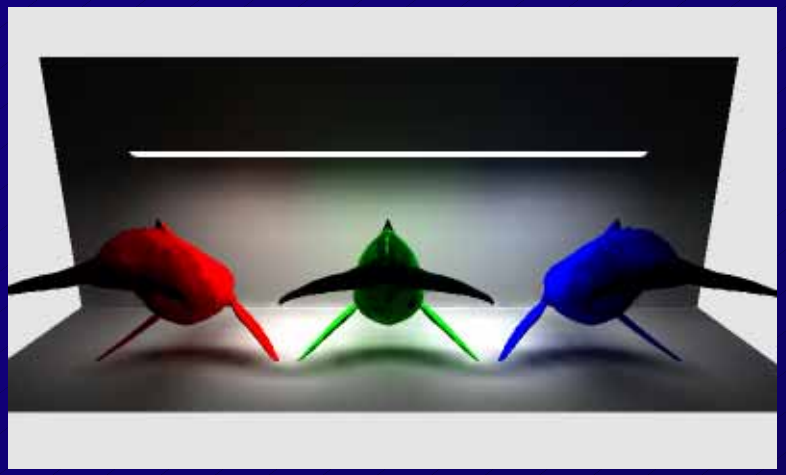


Same clusters: without & with interpolation

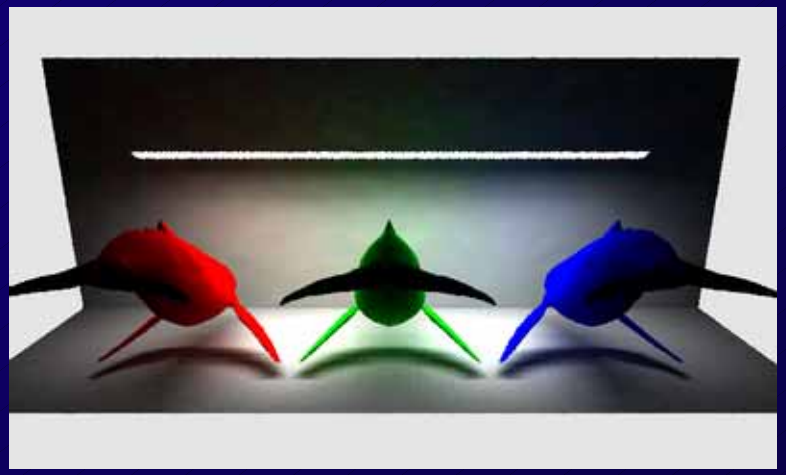
Algorithm Summary

- Construct face cluster hierarchy file for each new model. $k \log k$ (Approx. linear in k)
- Create scene from models
- Read in scene description, add root face cluster nodes to a volume cluster hierarchy
- Run gather/push-pull/refine solver. Sub-linear in k ***Dominant***
- Propagate radiosity solution to leaves of all models, write to disk. Linear in k

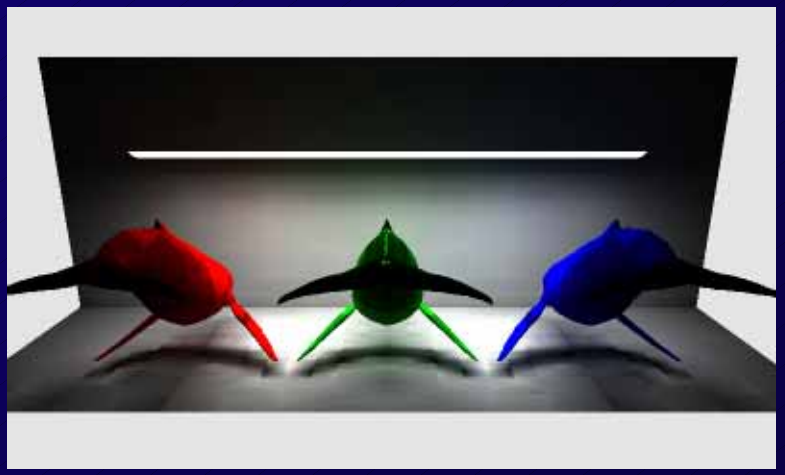
Results: Test Patch Whales



FCR, 127s



Radiance, 378s



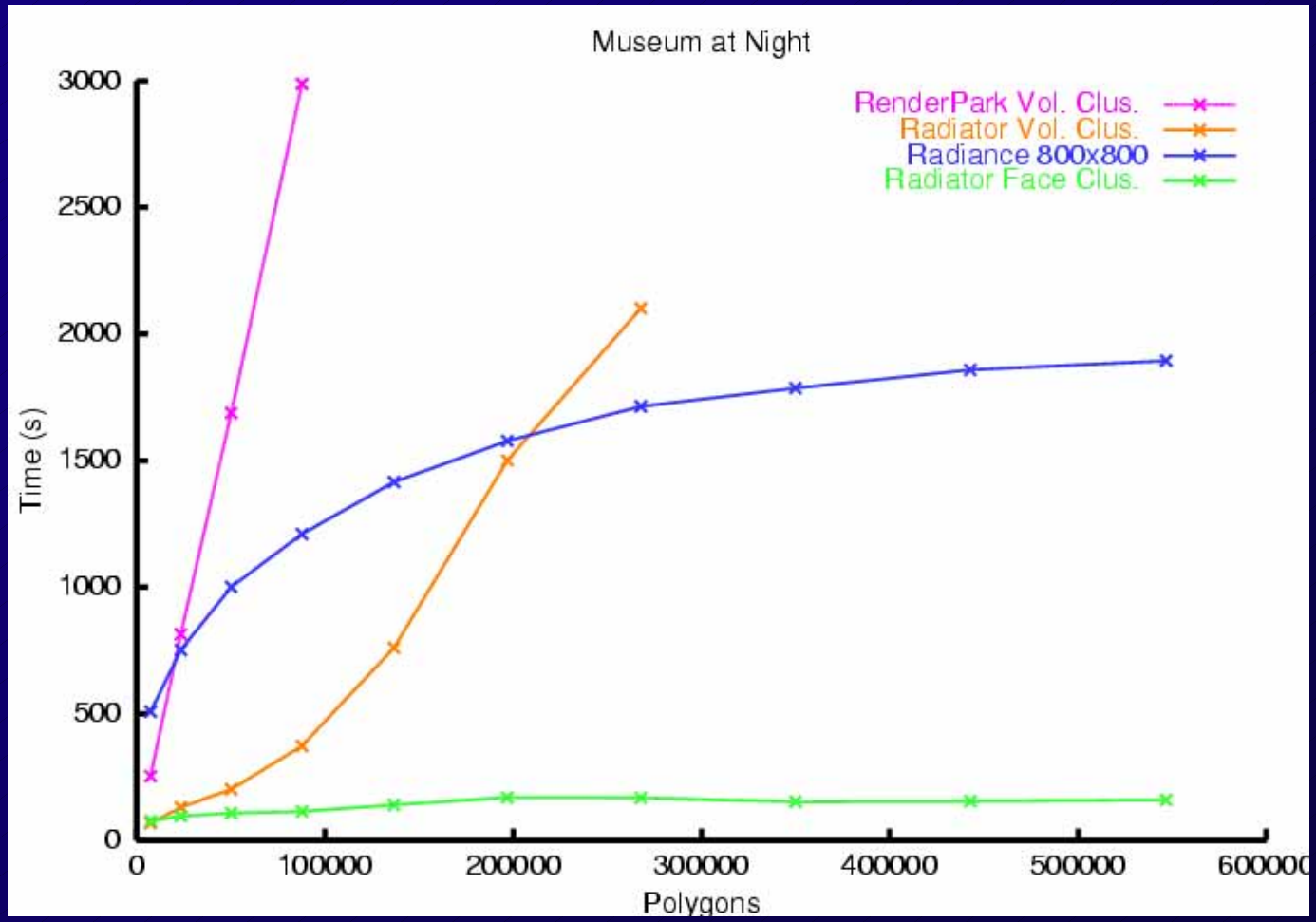
RenderPark, 2700s

Results: Complexity

Tested on several scene resolutions

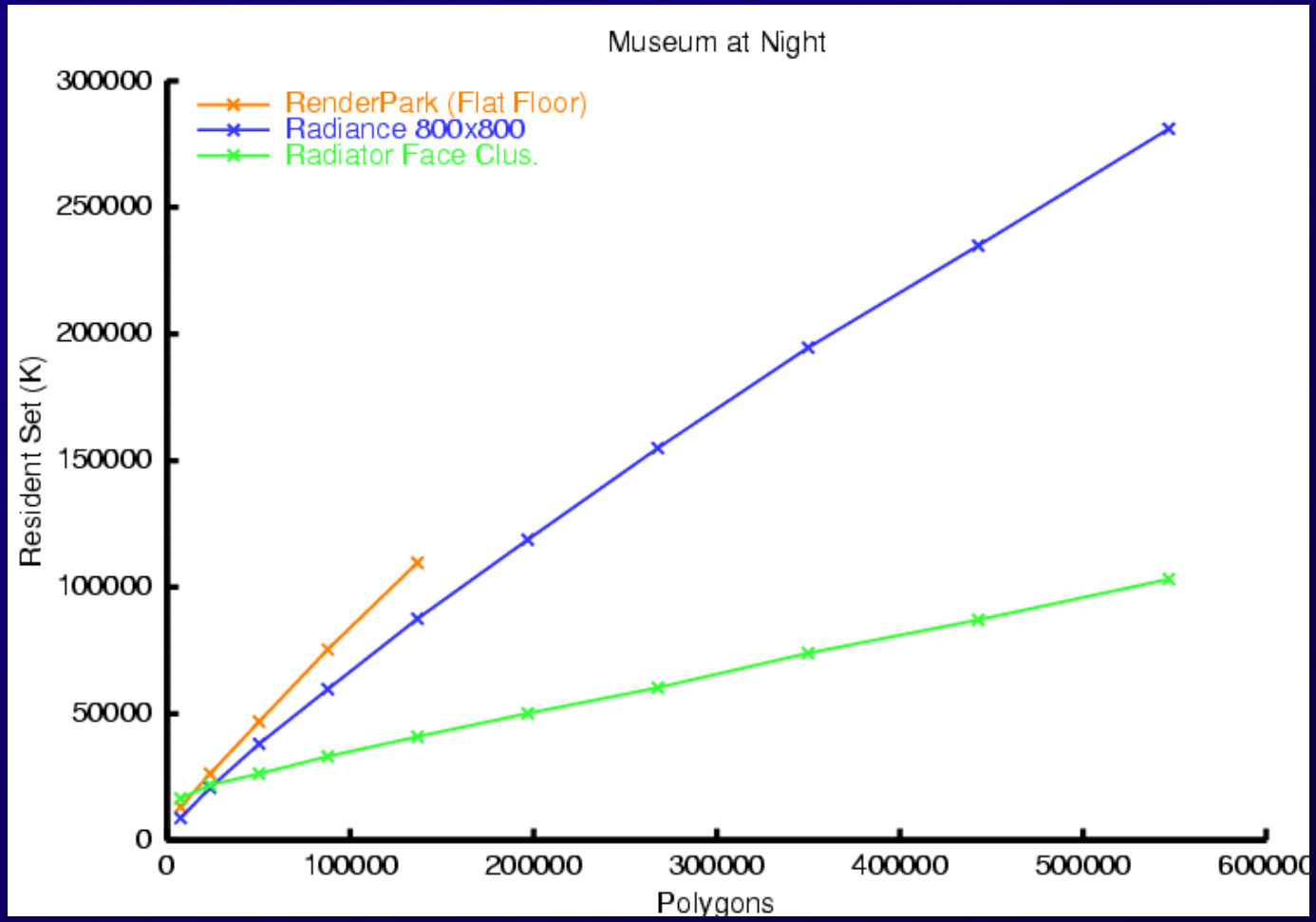
- Museum scene
- Medium-high illumination complexity (nighttime, daytime)
- 6 scanned models, implicit surface podium, displacement-mapped floor
- 550,000 polygons in maximum scene; lower-resolution ones generated by simplification

Results: Solution Time



Same scene, progressively more polygons

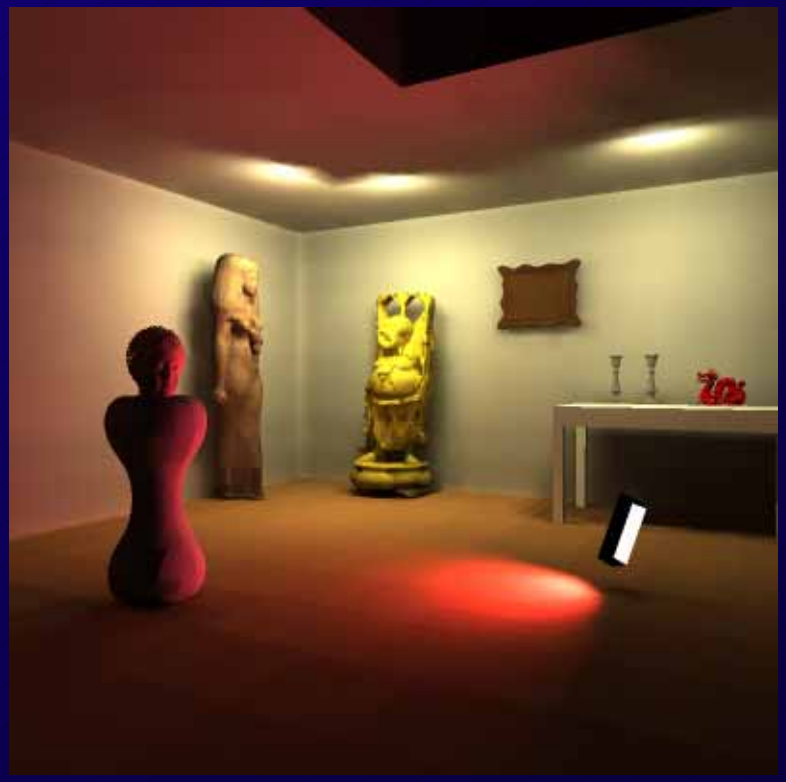
Results: Memory Use



Same scene, progressively more polygons

Results: Complexity

Face Cluster
Radiosity, 150s



Volume Clustering,
850s

Results: Large Scene

3,350,000 triangles

Time: 450s secs

Radiance, Progressive and HRVC would not fit in 1GB

Results: Large Scene

Conclusions

Face cluster hierarchies are highly effective for use with radiosity

- Sub-linear time in the number of input polygons, as opposed to 'previous best' of $O(k \log k)$
- After a point, solver is constant time
- Low memory usage
- Extremely detailed scenes

Contributions

- FCR helps make radiosity practical for general use
  - Runs on a laptop!
  - One of the most complex radiosity scenes simulated
- Three essential parts to making it work
  - Use of Face Clusters
  - Vector Radiosity
  - Tight visible area bounds for polygonal clusters
- Sped up Garland's cluster creation algorithm
- 80,000 lines of code available
  - http://www.cs.cmu.edu/~ajw/thesis-code

Future Work

- Better visibility sampling in final pass
- Extend bounded projected area to higher-order BRDFs (non-diffuse)
- Use of irradiance map to represent illumination

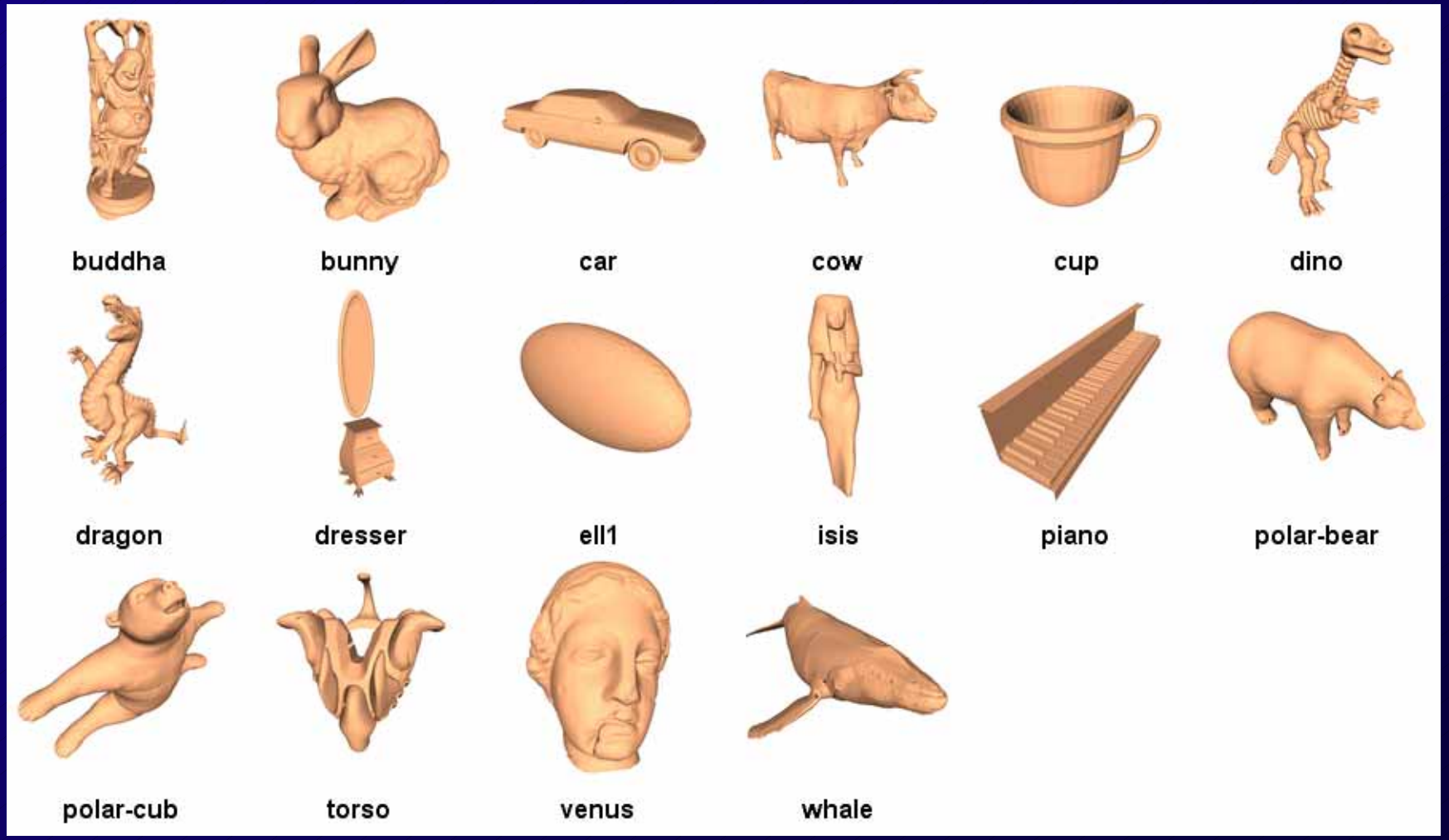
EXTRAS

Face Cluster Creation

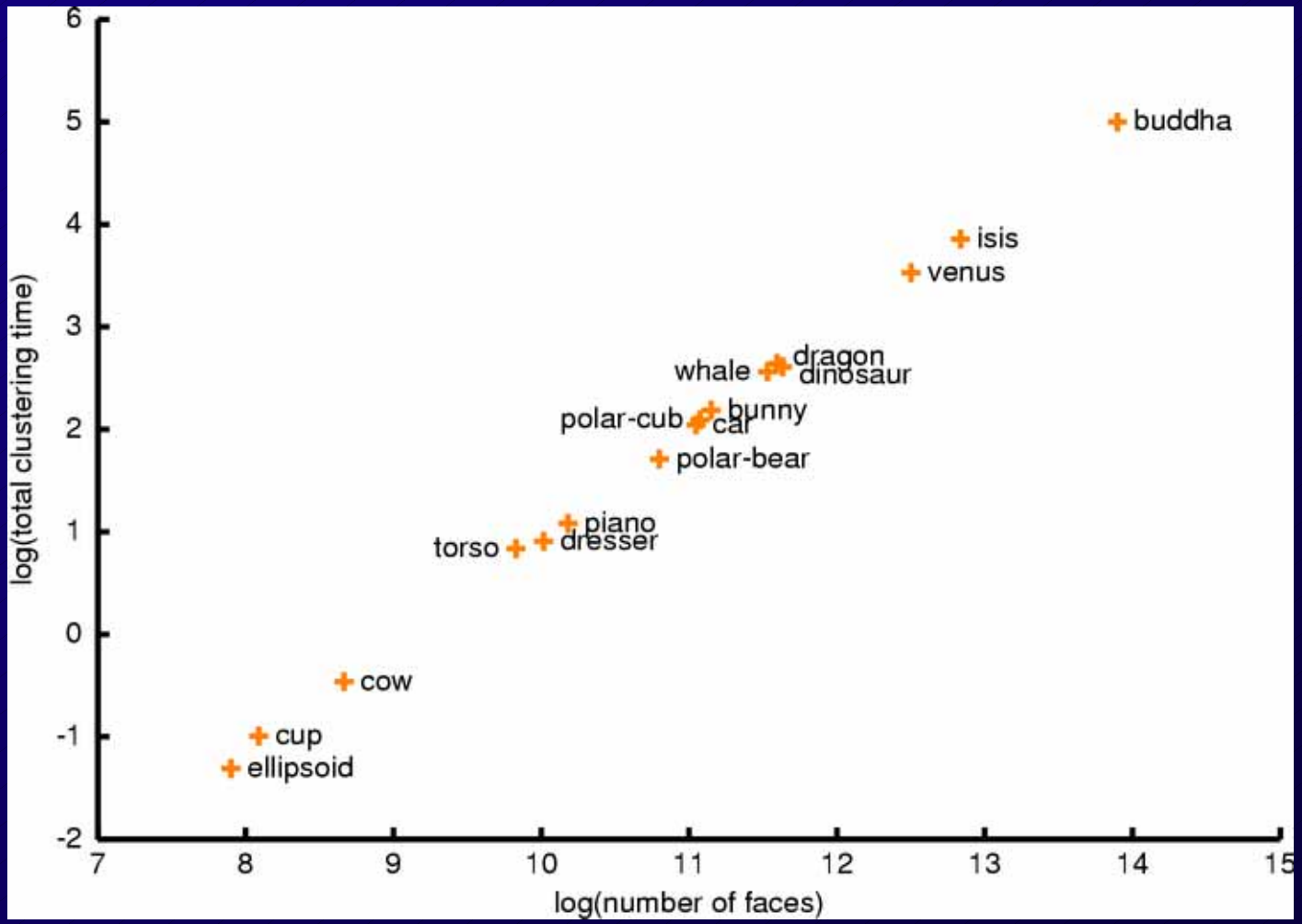
Modified & Extended Garland's method

- Existing code needed lots of memory
- Showed how balance was important to clustering time
- Created new, cheaper cost terms
- Improved stability and quality of bounding boxes

Test Models


buddha
bunny
car
cow
cup
dino
dragon
dresser
ell1
isis
piano
polar-bear
polar-cub
torso
venus
whale

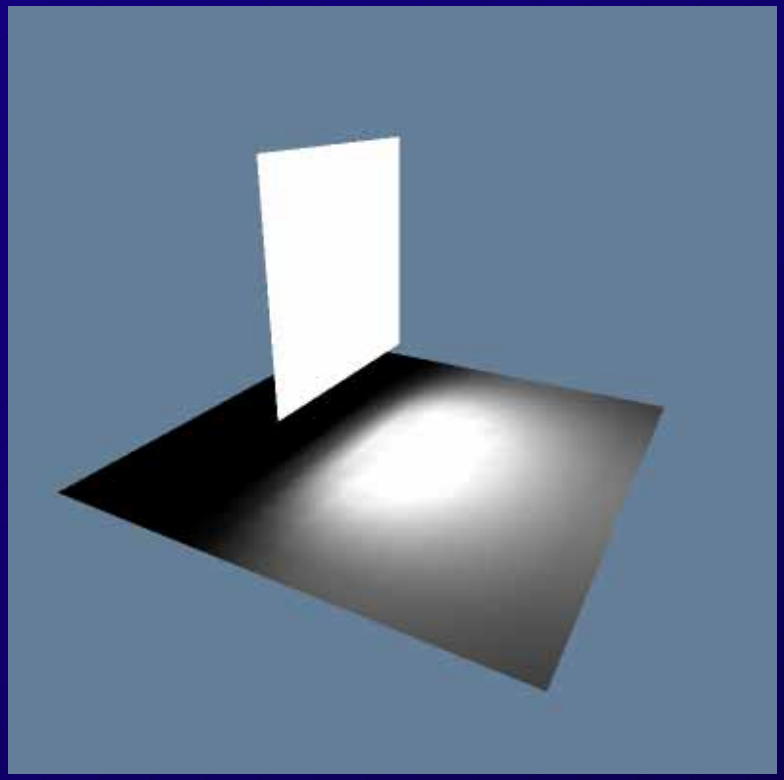
Clustering Times

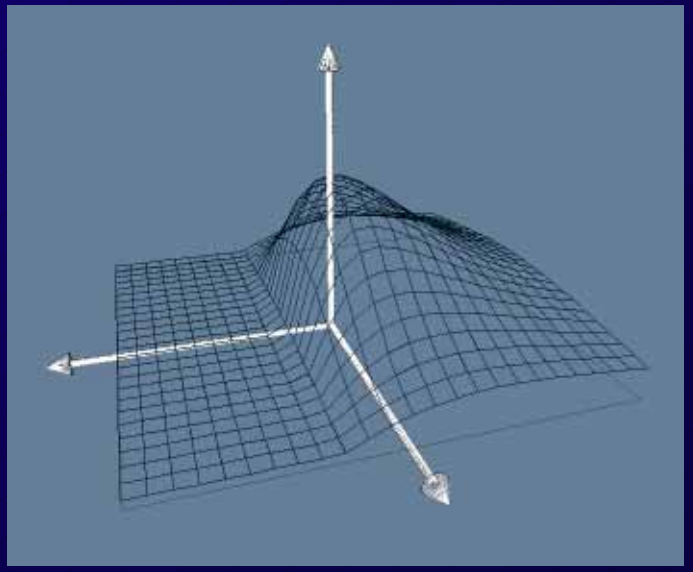


150s

1s

Integration for GI





State of the Art

Research

- Hierarchical/wavelet radiosity systems

High-quality: Lightscape, Lightworks

- Progressive radiosity, 1,000-100,000 polygon scenes
- Raytracing post-pass to add specular component, 2-3 hour renders is fine.

Virtual worlds

- Progressive radiosity, 10,000 polygon scenes
- Quick previews, 10 minute final renders.

Virtual Memory

- Face cluster files are written in breadth-first order, so get good memory locality
- Usually only small first section of the face cluster file used, so it's memory mapped

- Progressive Radiosity has good total memory use, but very poor locality. Hierarchical Radiosity thrashes better.

Details

- Visibility by ray casting, nested grids
- Fractional visibility used during simulation

Complexity

- O($s$log$s$), not O($k$log$k$), where s is the number of face cluster hierarchies.
- $s << k$
- Almost always, $s << n$
- Each face cluster hierarchy represents a separate polygon mesh
- Corresponds to a connected part of a model surface

Vector Radiosity Equations

$$E_i = \sum_j \frac{(\hat{\mathbf{n}}_i^T \hat{\mathbf{r}}_{ij})\,(\hat{\mathbf{r}}_{ji}^T \hat{\mathbf{n}}_j)}{\pi r_{ij}^2} v_{ij} A_j b_j$$

$$E_i \approx \hat{\mathbf{n}}_i^T \left[\frac{-\hat{\mathbf{r}}\hat{\mathbf{r}}^T}{\pi r^2} \sum_j \hat{\mathbf{n}}_j A_j b_j \right]$$

E **P**

$$\mathbf{E} = -\mathbf{m}\mathbf{m}^T\mathbf{P}$$

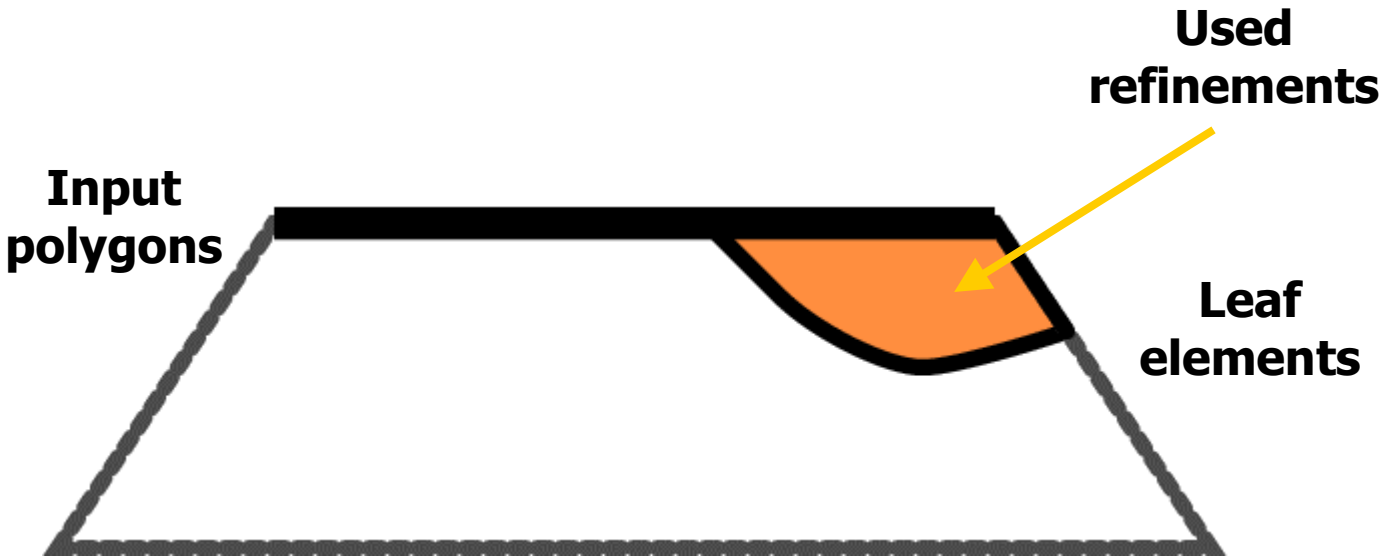
The Sky as a Light Source

Colour Bleeding

A Better Solution

- Combine simplification & radiosity algorithms
- Use multiresolution hierarchies of the models directly
- Adjust resolution on the fly to match that needed by the radiosity algorithm

Hierarchical Radiosity



Justification

- Simplest representation that captures the appropriate behaviour
- Minimises storage for each face cluster node
- We combine vectors hierarchically to represent complex radiosity distributions

Multiresolution Models

- Initially used edge-collapse models directly
  - These contain **vertex hierarchies**
- Switched to using dual of vertex hierarchy algorithm: *face cluster hierarchies*
  - It's easier to deal with **face hierarchies**