Photorealism

- Ray Tracing
- Texture Mapping
- Radiosity

Photorealism -- Taking into Account Global Illumination

- Light can arrive at surfaces indirectly
- This light called global illumination
- To now we've approximated it with a constant, diffuse ambient term
  - This is wrong
- Need to take into account all the multiply reflected light in the scene
- Two different approaches:
    - Ray Tracing -- specularly reflected light
    - Radiosity -- diffusely reflected light

Photorealism: Ray Tracing

- See CS-460/560 Notes at:

http://www.cs.binghamton.edu/~reckert/460/raytrace.htm
http://www.cs.binghamton.edu/~reckert/460/texture.htm

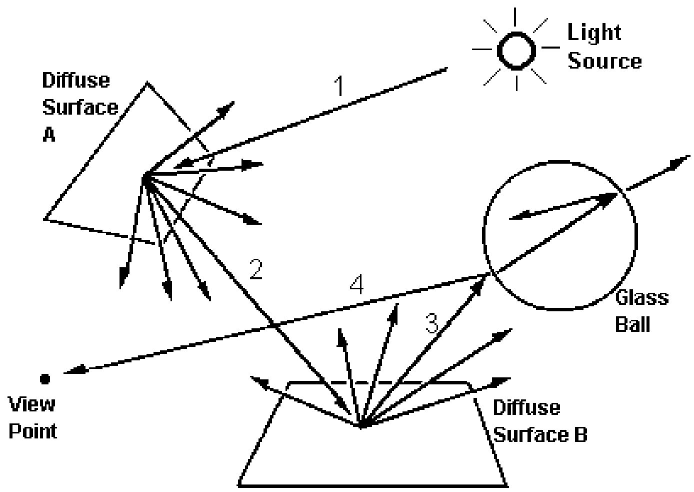
- Persistence of Vision Ray Tracer (free):

  http://povray.org/

Ray Tracing

- What is seen by viewer depends on:
  - rays of light that arrive at his/her eye
- So to get "correct" results:
  - Follow all rays of light from all light sources
  - Each time one hits an object, compute the reflected color/intensity
  - Store results for those that go through projection plane pixels into observer's eye
  - Paint each pixel in the resulting color

Forward Ray Tracing--Follow ray from source to viewpoint



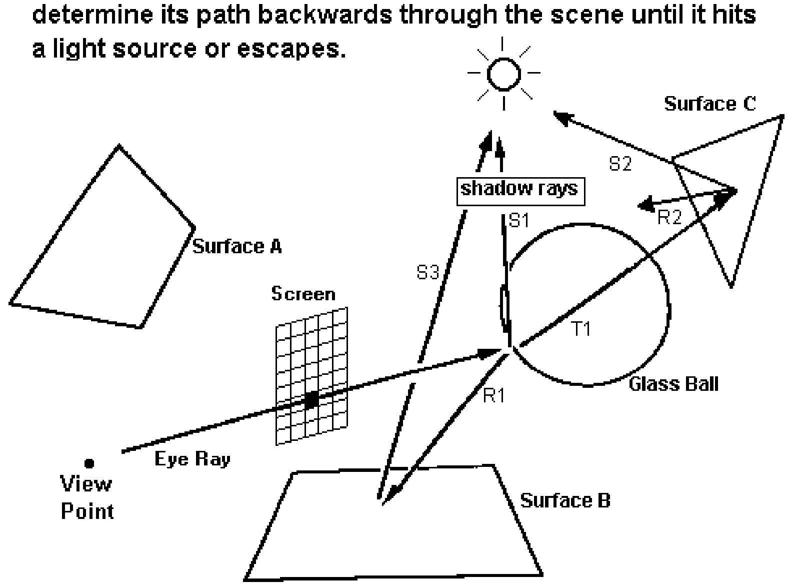
Forward Ray Tracing

- Infinite number of rays from each source
- At each intersection with an object
  - could have an infinite number of reflected rays
- Completely intractable
- Would take geological times to compute

Backward Ray Tracing

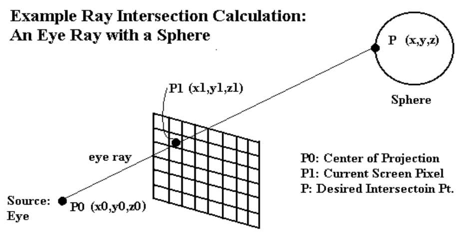
- Look <u>only</u> at rays observer sees
- Follow rays backwards from eye point through pixels on screen
  - "Eye" rays
- Check if they intersect objects
  - If so, can intersection point see a light source?
    - If so, compute intensity of reflected light
    - If not, point is in the shadow
  - If object has reflectivity/transparency
    - Follow reflected/transmission rays
    - Treat these rays as "eye" rays
    - So it's a recursive algorithm

Backward Ray Tracing--Follow Ray from Eye of viewer and determine its path backwards through the scene until it hits a light source or escapes.

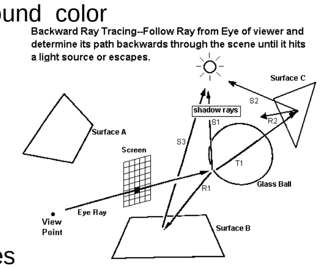


Recursive Ray Tracing Algorithm

```
depth = 0
for each pixel (x,y)
    Calculate direction from eyepoint to pixel
    TraceRay (eyepoint, direction, depth, *color)
    FrameBuf [x,y] = color
```




```
TraceRay (start_pt, direction_vector, recur_depth, *color)
  if (recur_depth > MAXDEPTH)    color = Background  color
  else
    // Intersect ray with all objects
    // Find int. point that is closest to start_point
          // Hidden surface removal is built in
    if (no intersection)    color = Background_color
    else
      // Send out shadow rays toward light sources
        local_color = contribution of illumination model at int. pt.
      // Calculate direction of reflection ray
        TraceRay (int_pt, refl_dir., depth+1, *refl_color)
      // Calculate direction of transmitted ray
        TraceRay (int_pt., trans_dir., depth+1, *trans_color)
      color = Combine (local_color, refl_color, trans_color)
```



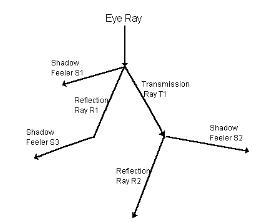
Combining Color from Reflection Ray

- Add attenuated reflected color intensity to local color intensity:

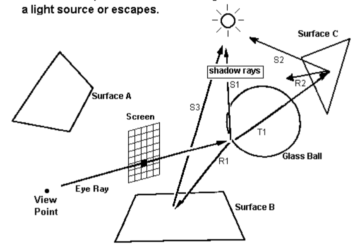
  color = local_color + k * refl_color

  - here refl_color is I(r,g,b) - color returned by reflection ray
  - local_color is I(r,g,b) - color computed by illumination model at intersection point
  - k is an attenuation factor (<1)

The Ray Tree for the above Scene



Backward Ray Tracing--Follow Ray from Eye of viewer and determine its path backwards through the scene until it hits a light source or escapes.



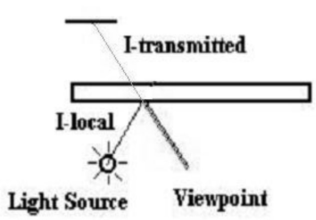
Combining Color from Transmission Ray

- Observer sees a mixture of light reflected off surface and light transmitted through surface
- So combine colors (interpolate)

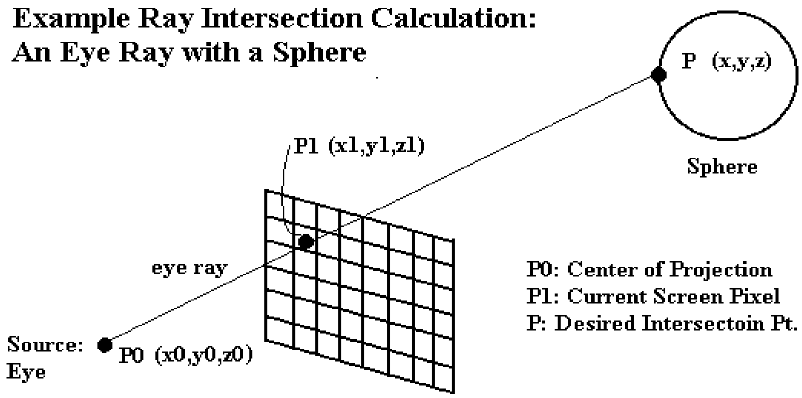
  $I(r,g,b) = k'*I_{local}(r,g,b) + (1 - k')*I_{transmitted}(r,g,b)$

  k' is opacity factor coefficient

  k'=0 => perfectly transparent, k'=1 ==> perfectly opaque



Ray Tracing Intersection Calculations



Parametric Equations for Eye Ray:

$x = x0 + (x1-x0)*t$

$x = x0 + \Delta x*t$

$y = y0 + (y1-y0)*t$

$y = y0 + \Delta y*t$

$z = z0 + (z1-z0)*t$

$z = z0 + \Delta z*t$

Equation of a sphere of radius r, centered at (a,b,c)

$(x-a)^2 + (y-b)^2 + (z-c)^2 = r^2$

Substitute ray parametric equations:

$(x0+\Delta x*t-a)^2 + (y0+\Delta y*t-b)^2 + (z0+\Delta z*t-c)^2 = r^2$

Rearrange terms:

$(\Delta x^2+\Delta y^2+\Delta z^2)t^2 + 2[\Delta x(x0-a)+\Delta y(y0-b)+\Delta z(z0-c)]t$

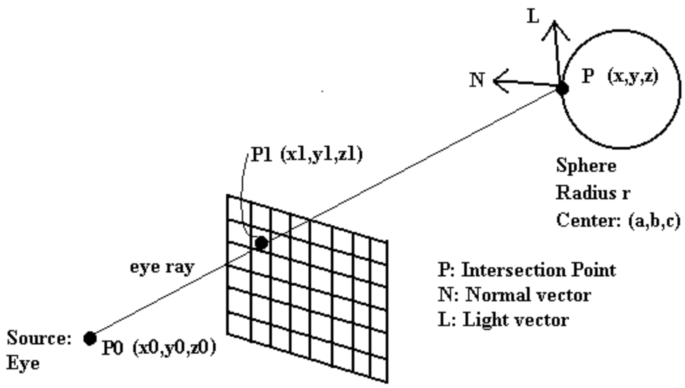
$+(x0-a)^2 + (y0-b)^2 + (z0-c)^2 - r^2 = 0$

This is a quadratic in parameter t

- Solution(s): value(s) of t where ray intersects sphere
- Three cases
  - No real roots ==> no intersection point
  - 1 real root ==> ray grazes sphere
  - 2 real roots ==> ray passes thru sphere
    - Select smaller t (closer to source)

Sphere Normal Computation

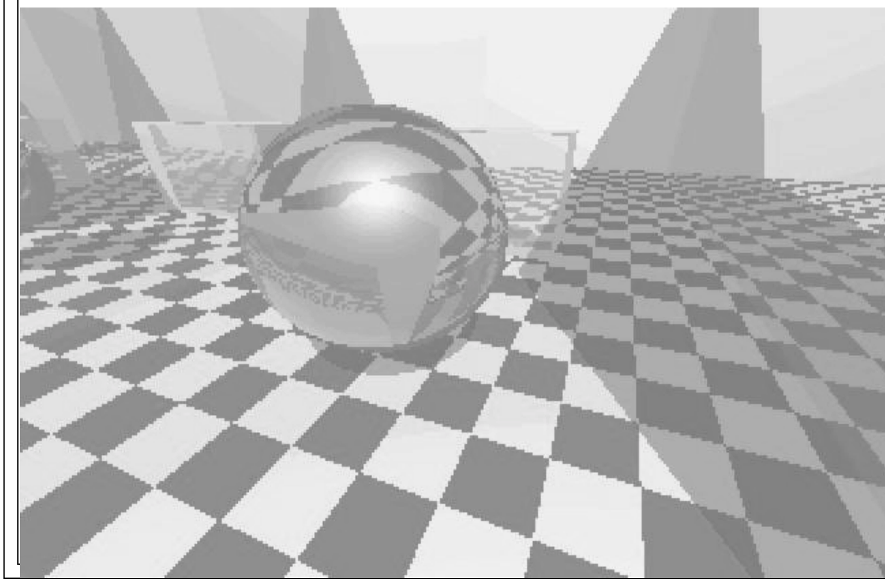
- To apply illumination model at intersection point P, need surface normal
- Can show: N = ((x-a)/r, (y-b)/r, (z-c)/r)



Intersections with other Objects

- Handled in similar fashion
- May be difficult to come up with equations for their surfaces
- Sometimes approximation methods must be used to compute intersections of rays with surfaces

A Ray-Traced Image



Disadvantages of Ray Tracing

- Computationally intensive
  – But there are several acceleration techniques
- Bad for scenes with lots of diffuse reflection
  – But can be combined with other algorithms that handle diffuse reflection well
- Prone to aliasing
  – One sample per pixel
    - can give ugly artifacts
  – But there are anti-aliasing techniques

Persistence of Vision Ray Tracer

- POVRay free software
- Lots of capabilities
- Great for playing around with ray tracing
  - http://povray.org/

An Algorithm Animation of a Ray Tracer

Ray Tracing Algorithm Animator in VC++ (with David Goldman)

See:

http://www.cs.binghamton.edu/~reckert/3daape_paper.htm

Ray Tracing Algorithm Animation Java Applet and Paper (with Brian Maltzan)

See:

http://www.cs.binghamton.edu/~reckert/brian/index.html

Pattern/Texture Mapping

- Adding details or features to surfaces
  - (variations in color or texture)

General Texture Mapping

- Pattern Mapping Technique
  - Modulate surface color calculated by reflection model according to a pattern defined by a texture function
    - (“wrap” pattern around surface)
    - 2-D Texture function: T(u,v)
      - Define in a 2-D texture space (u,v)
      - Could be a digitized image
      - Or a procedurally-defined pattern

Inverse Pixel Mapping (Screen Scanning)

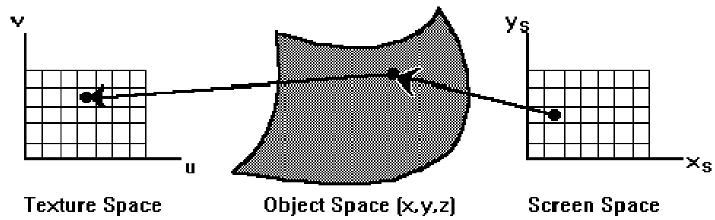
For each pixel on screen (xs, ys)

Compute pt (x,y,z) on closest surface projecting to pixel (e.g., ray tracing)

Determine color (e.g., apply illumination/reflection model)

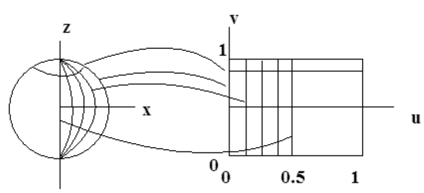
Compute (u,v) corresponding to (x,y,z) (inverse mapping)

Modulate color of (xs,ys) according to value of T(u,v) at (u,v)



Inverse Mapping a Sphere

- Lines of longitude: constant u, corresponds to theta
- Lines of latitude: constant v, corresponds to phi

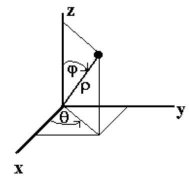


x=R sin(phi) cos(theta)
y=R sin(phi) sin(theta)
z=R cos(phi)

phi = arccos(z/R) = arccos(N.z)
theta = arccos(x/R sin(phi))
theta = (arccos(N.x/sin(phi))

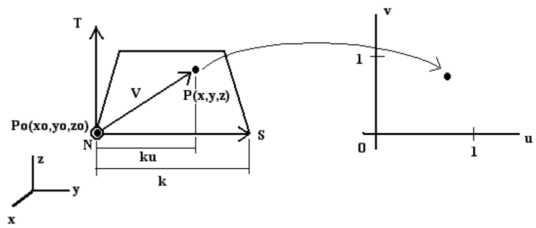
v = (pi-phi)/pi — phi=0, North Pole, v=1; phi=pi, South Pole, v=0

u = theta/2*pi if N.y is + — theta=0, u=0; theta=pi, u=0.5 (+y side)
u = 1-theta/2*pi if N.y is - — theta=pi, u =0.5; theta=0, u=1.0 (-y side)

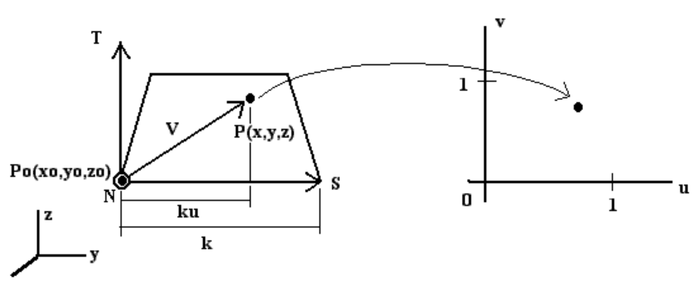


Ex: Inverse Mapping a Polygon

- Choose axis S (unit vector) along a polygon edge
  - will align with u-axis in texture space
- Choose a polygon vertex Po(xo,yo,zo)
  - will correspond to origin in texture space
- Choose a scaling factor k
  - k = max dimension of polygon
    - 0-k in object space --> 0-1 in texture space
- Want to map point P(x,y,z) on polygon to (u,v)



- Construct vector V = P - Po
- V·S = k*u, projection of P onto S
- So u = V·S/k
- Choose orthogonal axis T in polygon plane (T=NxS)
- v=V·T/k



There are lots of other Texture Mapping Techniques

See Section 10-17 of your text book

Radiosity Methods

- Alternative to ray tracing for handling global illumination
- Two kinds of illumination at each reflective surface
  - Local: from point sources
  - Global: light reflected from other surfaces in scene (multiple reflections)
  - Ray tracing handles specularly reflected global illumination
    - But not diffusely reflected global illumination

Radiosity Approach

- Compute global illumination
- All light energy coming off a surface is the sum of:
  - Light emitted by the surface
  - Light from other surfaces reflected off the surface
  - Divide scene into patches that are perfect diffuse reflectors...
    - Reflected light is non-directional
  - and/or emitters

Definitions

- Radiosity (B):
  - Total light energy per unit area leaving a surface patch per unit time--sum of emitted and reflected energy (Brightness)
- Emission (E):
  - Energy per unit area emitted by the surface itself per unit time (Surfaces having nonzero E are light sources)

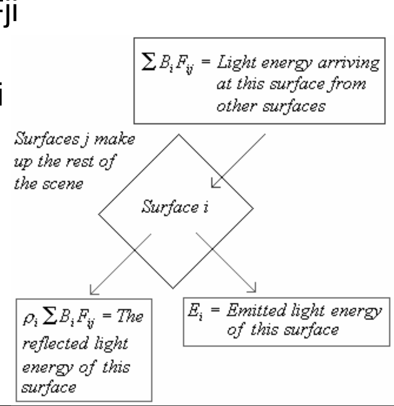
- <u>Reflectivity (ρ)</u>:
  - Fraction of light reflected from a surface (a number between 0 and 1)

- <u>Form Factor (Fij)</u>:
  - Fraction of light energy leaving patch i which arrives at patch j
    - Function only of geometry of environment

- Conservation of energy for patch i:
  - Total energy out = Energy emitted + Sum of energy from other patches reflected by patch i:

$$Bi*Ai = Ei*Ai + \rho_i * \Sigma\, Bj*Aj*Fji$$

$$Bi = Ei + \rho_i * \Sigma_j (Bj*Aj/Ai)*Fji$$



- Principle of Reciprocity for Form Factors
  - Reversing role of emitters and receivers:
    - Fraction of energy emitted by one and received by other would be same as fraction of energy going the other way
    - Fij*Ai = Fji*Aj ==> Fji = (Ai/Aj) Fij
    - So:

$$B_i = E_i + \rho_i * \Sigma B_j * F_{ij}$$

$$B_i - \rho_i * \Sigma B_j * F_{ij} = E_i$$

    - Need to solve this system of equations for the radiosities Bi

Radiosity -- Matrix Formulation and Solution

Assume N patches

$F_{ii} = 0$ – Patch i receives no energy from itself

Rearranging and writing out the Radiosity equation:

$$\begin{bmatrix} 1 & -\rho_1 F_{12} & -\rho_1 F_{13} & \cdots & -\rho_1 F_{1N} \\ -\rho_2 F_{21} & 1 & -\rho_2 F_{23} & \cdots & -\rho_2 F_{2N} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ -\rho_N F_{N1} & -\rho_N F_{N2} & -\rho_N F_{N3} & \cdots & 1 \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \cdots \\ \cdots \\ B_N \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ \cdots \\ \cdots \\ E_N \end{bmatrix}$$

This is the matrix equation: $M B = E$

The E_i and ρ_i are known, and the form factors F_{ij} can be calculated so that the matrix elements M_{ij} can be determined. Since the ρ_i and F_{ij} are all less than or equal to zero, matrix M is diagonally dominant, so the Gauss-Seidel iteration method is guaranteed to converge after a few iterations.

Gauss-Seidel Solution

$B_1 + M_{12}B_2 + \ldots + M_{1N}B_N = E_1$
$M_{21}B_1 + B_2 + \ldots + M_{2N}BN = E_2$

....

$M_{i1}B_1 + M_{i2}B_2 + \ldots + B_i + \ldots + M_{iN}B_N = E_i$

....

Initial guess: $B_i^{(0)} = E_i$

Next iteration $B_i^{(1)} = E_i - (M_{i1}B_i^{(0)} + \ldots + M_{i,i-1}B_{i-1}^{(0)} + \ldots + M_{i,i+1}^{(0)} + \ldots + M_{iN}B_N^{(0)})$

Continue iterating until all the difference between $B_i^{(k+1)}$ and $B_i^{(k)}$ is small enough for all patches

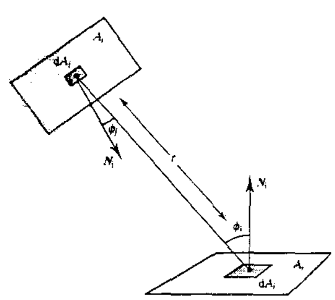
Notice that for each patch i we are "gathering" radiosity from all the other patches

Thus the scene is not finished until we have processed all patches--very time consuming.

Problem: getting form factors

Computing Form Factors

Form Factor Determination



The form factor F_{ij} from patch i to patch j is obtained in principle by by integrating over both patches:

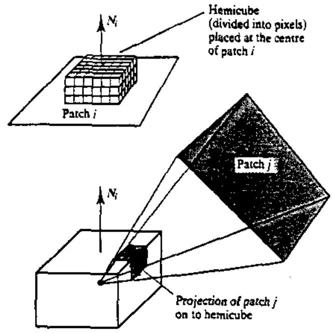
$$F_{A_iA_j} = F_{ij} = \frac{1}{A_i}\int_{A_i}\int_{A_j} \frac{\cos\phi_i \cos\phi_j}{\pi r^2}\, dA_j\, dA_i$$

But this is very difficult.

$\Delta FF = \Sigma (\cos \phi_i \cos \phi_j \Delta A_j) / (\pi r^2)$, approximately

Hemicube Approximation

The Hemicube Approximation



Calculate and store the delta form factors for each element of the hemicube.

$$F_{ij} = \sum_q \Delta F_q$$

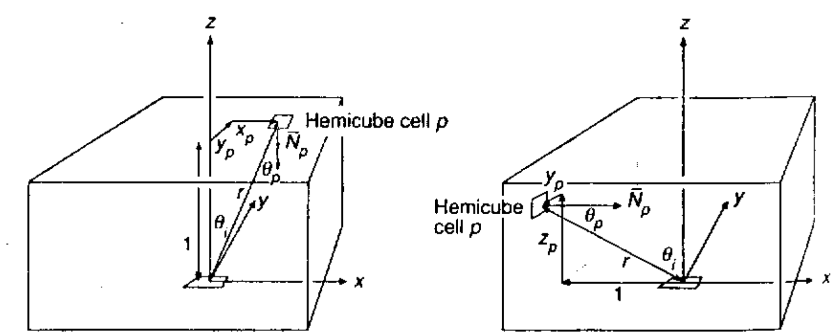
To calculate the form factor F_{ij}, build a hemicube centered on patch i and sum the delta form factors for those elements of the hemicube to which patch j projects.

Hemicube Pixel Computations

$\Delta F = \cos\theta_i * \cos\theta_p * \Delta A / (\pi * r^2)$

a. (top) $\Delta F = \Delta A / [\pi*(x^2 + y^2 + 1)^2]$

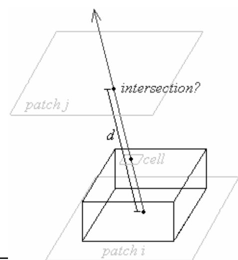
b. (sides) $\Delta F = z*\Delta A / [\pi*(y^2 + z^2 + 1)^2]$



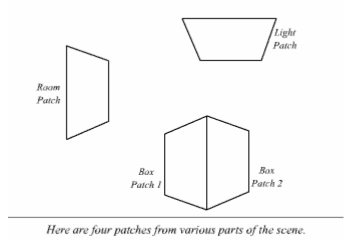
(a) (b)

Hemicube Form Factor Algorithm

Compute & strore all hemicube delta Form Factors: ΔFF[k]
Zero all the Form Factors: Fij
For all patches i
   Place unit hemicube at center of patch i
   For each cell k on hemicube
      dist[k] = infinity
      For each patch j (j != i)
         If line from origin through cell k intersects patch j
            compute distance d to intersection point
            if d < dist[k]
               dist[k] = d
               store j in item_buf [k]
   For each cell k on hemicube
      j = item_buf [k]
      Fij = Fij + ΔFF[k]



Video of Radiosity Form Factor Computation



Steps in Applying Radiosity Method

Summary of Steps:

Define a scene.

Divide scene into distinct patches.

Build a hemicube on each patch and calculate the delta form factors for cell on every hemicube.

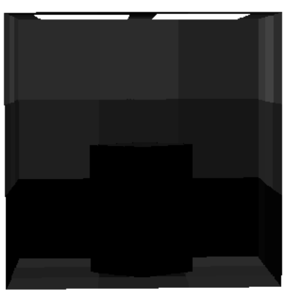
Calculate a form factor for every pair of patches in the scene.

Calculate the red, green, and blue radiosities for each patch.

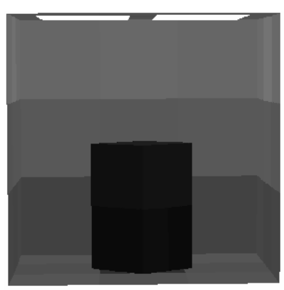
Map all radiosity values to a 0 - 255 color scale.

Apply Gouraud shading.

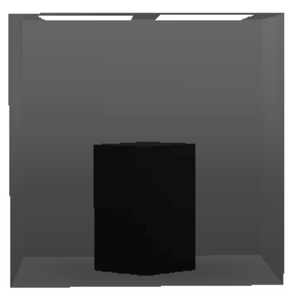
Three Simple Radiosity Images



After 1st Gauss-Seidel Iteration



No Gouraud Shading



Gouraud Shading

Radiosity Summary

- Good for scenes with lots of diffuse reflection
- Not good for scenes with lots of specular reflection
  - Complementary to Ray Tracing
  - But can be combined with Ray Tracing
- Very computationally intensive
  - Can take very long times for complex scenes
    - but once patch intensities are computed, scene “walkthroughs” are fast
  - Gauss-Seidel is very memory intensive
  - There are other approaches
    - Progressive Refinement