University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2007

Tamara Munzner

Advanced Rendering II

Week 7, Fri Mar 2

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2007

Reading for Last and This Time

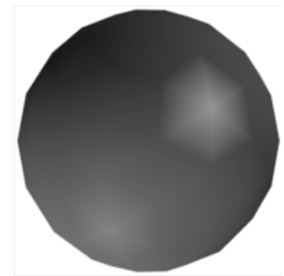
- FCG Chap 10 Ray Tracing
  - only 10.1-10.7
- FCG Chap 25 Image-Based Rendering

News

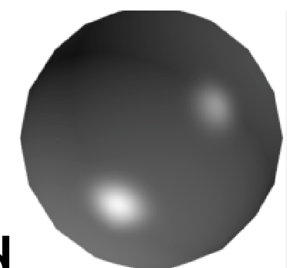
- signup sheet for P2 grading
  - Mon 11-12, 2-3, 5-5:30
  - Tue 11-1
  - Wed 11-12, 2-3, 5-5:30

Review: Shading Models

- flat shading
  - compute Phong lighting once for entire polygon



- Gouraud shading
  - compute Phong lighting at the vertices and interpolate lighting values across polygon
- Phong shading
  - compute averaged vertex normals
  - interpolate normals across polygon and perform Phong lighting across polygon



Review/Clarification: Specifying Normals

- OpenGL state machine
  - uses last normal specified
  - if no normals specified, assumes all identical
- per-vertex normals

```
glNormal3f(1,1,1);
glVertex3f(3,4,5);
glNormal3f(1,1,0);
glVertex3f(10,5,2);
```

- per-face normals

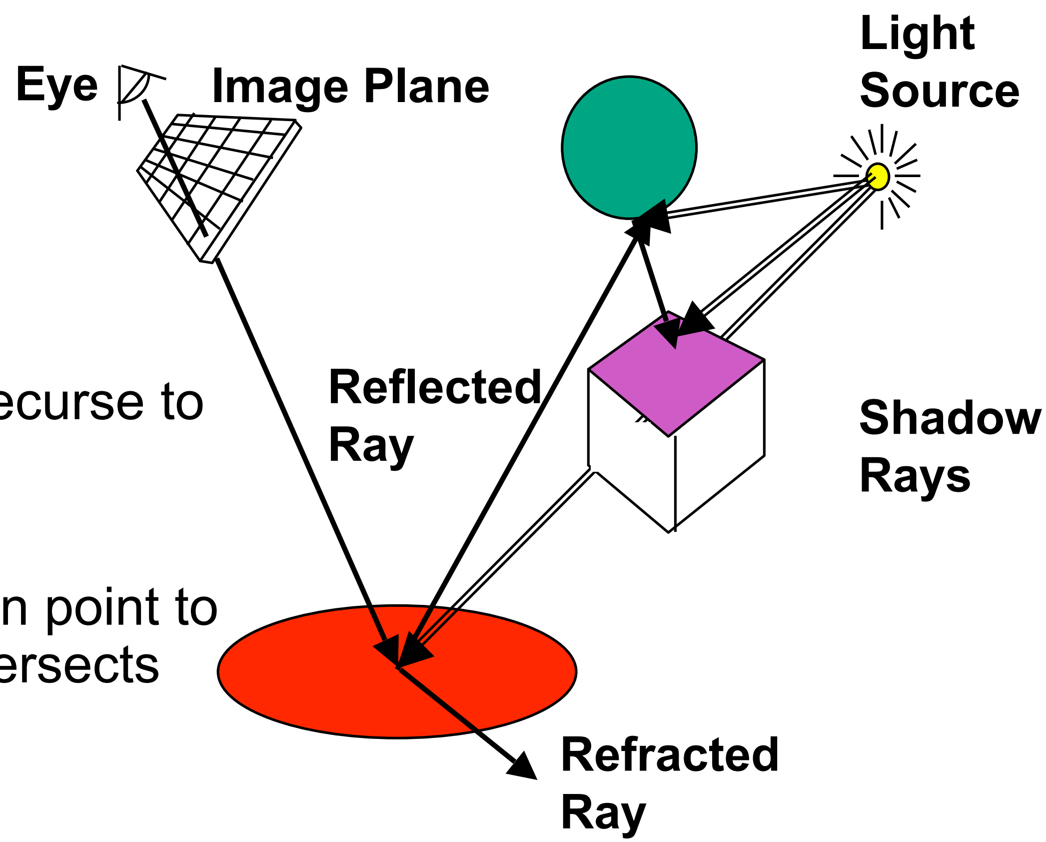
```
glNormal3f(1,1,1);
glVertex3f(3,4,5);
glVertex3f(10,5,2);
```

- normal interpreted as direction from vertex location
- can automatically normalize (computational cost)

```
glEnable(GL_NORMALIZE);
```

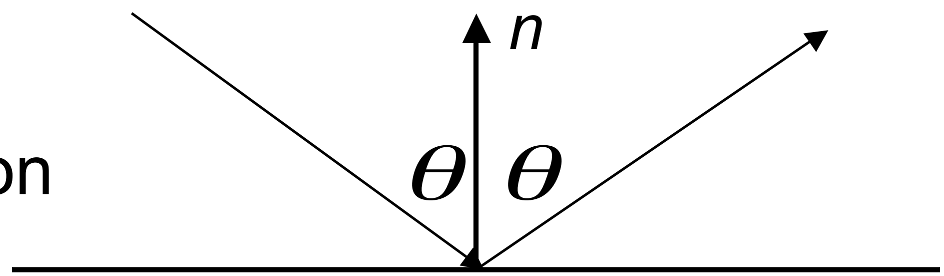
Review: Recursive Ray Tracing

- ray tracing can handle
  - reflection (chrome/mirror)
  - refraction (glass)
  - shadows
- one primary ray per pixel
- spawn secondary rays
  - reflection, refraction
    - if another object is hit, recurse to find its color
  - shadow
    - cast ray from intersection point to light source, check if intersects another object
  - termination criteria
    - no intersection (ray exits scene)
    - max bounces (recursion depth)
    - attenuated below threshold



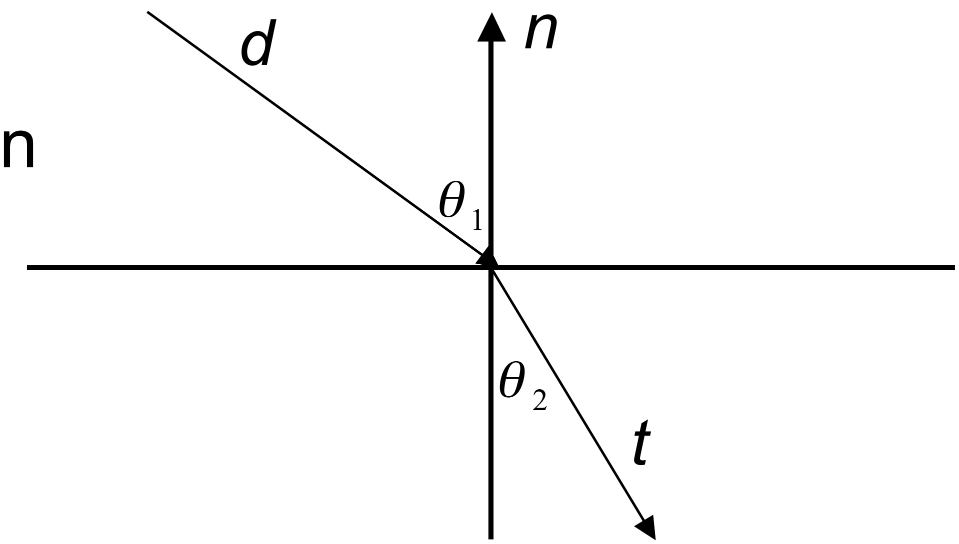
Review: Reflection and Refraction

- refraction: mirror effects
  - perfect specular reflection



- refraction: at boundary
- Snell's Law
  - light ray bends based on refractive indices c_1, c_2

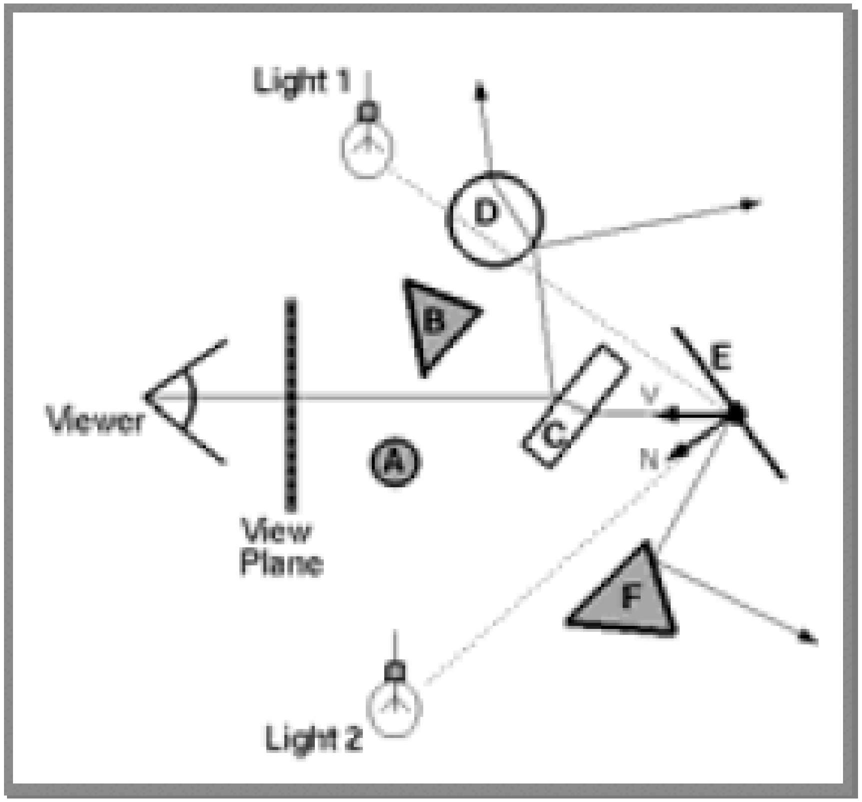
$$c_1 \sin\theta_1 = c_2 \sin\theta_2$$



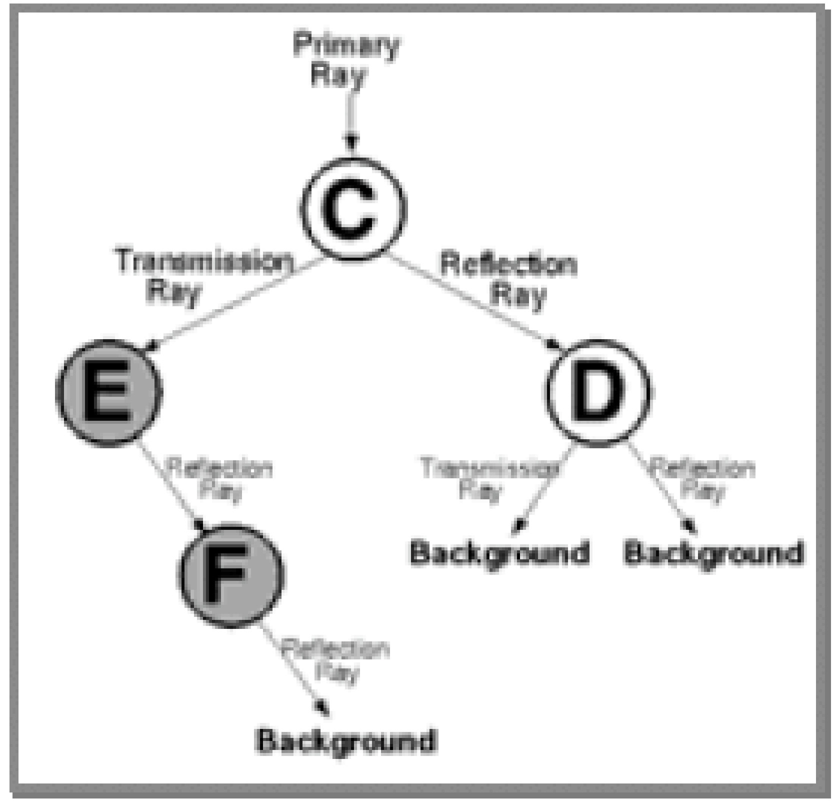
Advanced Rendering II

Ray Trees

- all rays directly or indirectly spawned off by a single primary ray



Ray traced through scene



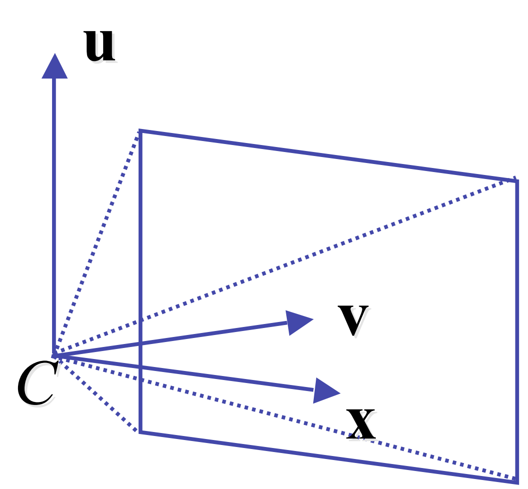
Ray tree

Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with *every* object

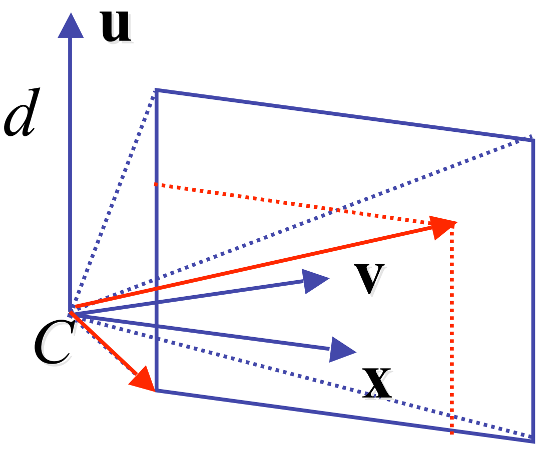
Ray Generation

- camera coordinate system
  - origin: C (camera position)
  - viewing direction: $\mathbf{v}$
  - up vector: $\mathbf{u}$
  - x direction: $\mathbf{x} = \mathbf{v} \times \mathbf{u}$
- note:
  - corresponds to viewing transformation in rendering pipeline
  - like gluLookAt



Ray Generation

- other parameters:
  - distance of camera from image plane: d
  - image resolution (in pixels): w, h
  - left, right, top, bottom boundaries in image plane: l, r, t, b



- then:
  - lower left corner of image: $O = C + d \cdot \mathbf{v} + l \cdot \mathbf{x} + b \cdot \mathbf{u}$
  - pixel at position i, j ($i=0..w-1$, $j=0..h-1$):

$$P_{i,j} = O + i \cdot \frac{r-l}{w-1} \cdot \mathbf{x} - j \cdot \frac{t-b}{h-1} \cdot \mathbf{u}$$

$$= O + i \cdot \Delta x \cdot \mathbf{x} - j \cdot \Delta y \cdot \mathbf{y}$$

Ray Generation

- ray in 3D space:

$$\mathrm{R}_{i,j}(t) = C + t \cdot (P_{i,j} - C) = C + t \cdot \mathbf{v}_{i,j}$$

where $t = 0 \ldots \infty$

Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with *every* object

Ray - Object Intersections

- inner loop of ray-tracing
  - must be extremely efficient
- task: given an object o, find ray parameter t, such that $\mathbf{R}_{i,j}(t)$ is a point on the object
  - such a value for t may not exist
- solve a set of equations
- intersection test depends on geometric primitive
  - ray-sphere
  - ray-triangle
  - ray-polygon

Ray Intersections: Spheres

- spheres at origin
  - implicit function

$$S(x, y, z) : x^2 + y^2 + z^2 = r^2$$

  - ray equation

$$\mathrm{R}_{i,j}(t) = C + t \cdot \mathbf{v}_{i,j} = \begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix} + t \cdot \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} c_x + t \cdot v_x \\ c_y + t \cdot v_y \\ c_z + t \cdot v_z \end{pmatrix}$$

Ray Intersections: Spheres

- to determine intersection:
  - insert ray $\mathbf{R}_{i,j}(t)$ into $S(x,y,z)$:

$$(c_x + t \cdot v_x)^2 + (c_y + t \cdot v_y)^2 + (c_z + t \cdot v_z)^2 = r^2$$

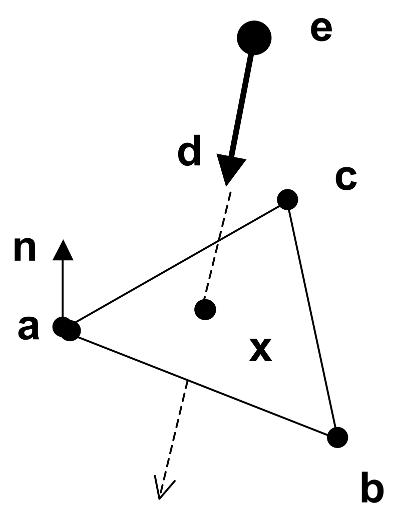
  - solve for t (find roots)
    - simple quadratic equation

Ray Intersections: Other Primitives

- implicit functions
  - spheres at arbitrary positions
    - same thing
  - conic sections (hyperboloids, ellipsoids, paraboloids, cones, cylinders)
    - same thing (all are quadratic functions!)
- polygons
  - first intersect ray with plane
    - linear implicit function
  - then test whether point is inside or outside of polygon (2D test)
  - for convex polygons
    - suffices to test whether point in on the correct side of every boundary edge
    - similar to computation of outcodes in line clipping (upcoming)

Ray-Triangle Intersection

- method in book is elegant but a bit complex
- easier approach: triangle is just a polygon
  - intersect ray with plane



$$\text{normal}: \mathbf{n} = (\mathbf{b} - \mathbf{a}) \times (\mathbf{c} - \mathbf{a})$$

$$\text{ray}: \mathbf{x} = \mathbf{e} + t\mathbf{d}$$

$$\text{plane}: (\mathbf{p} - \mathbf{x}) \cdot \mathbf{n} = 0 \Rightarrow \ \mathbf{x} = \frac{\mathbf{p} \cdot \mathbf{n}}{\mathbf{n}}$$

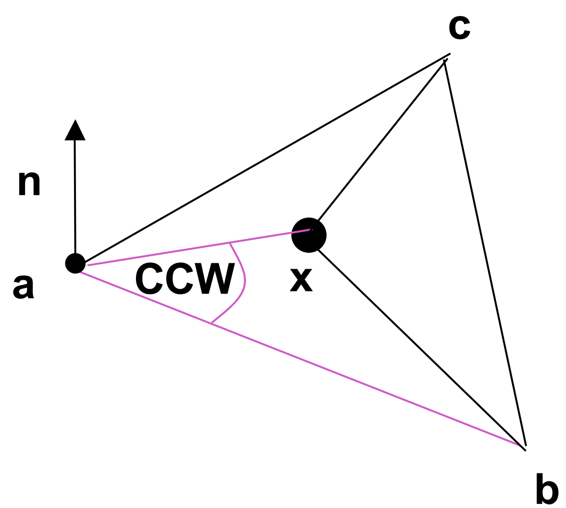
$$\frac{\mathbf{p} \cdot \mathbf{n}}{\mathbf{n}} = \mathbf{e} + t\mathbf{d} \Rightarrow t = -\frac{(\mathbf{e} - \mathbf{p}) \cdot \mathbf{n}}{\mathbf{d} \cdot \mathbf{n}}$$

$\mathbf{p}$ is $\mathbf{a}$ or $\mathbf{b}$ or $\mathbf{c}$

  - check if ray inside triangle

Ray-Triangle Intersection

- check if ray inside triangle
  - check if point counterclockwise from each edge (to its left)
  - check if cross product points in same direction as normal (i.e. if dot is positive)



$$(\mathbf{b}-\mathbf{a})\times(\mathbf{x}-\mathbf{a})\cdot\mathbf{n}\geq 0$$

$$(\mathbf{c}-\mathbf{b})\times(\mathbf{x}-\mathbf{b})\cdot\mathbf{n}\geq 0$$

$$(\mathbf{a}-\mathbf{c})\times(\mathbf{x}-\mathbf{c})\cdot\mathbf{n}\geq 0$$

  - more details at

http://www.cs.cornell.edu/courses/cs465/2003fa/homeworks/raytri.pdf

Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don’t have to test intersection with *every* object

Geometric Transformations

- similar goal as in rendering pipeline:
  - modeling scenes more convenient using different coordinate systems for individual objects
- problem
  - not all object representations are easy to transform
    - problem is fixed in rendering pipeline by restriction to polygons, which are affine invariant
  - ray tracing has different solution
    - ray itself is always affine invariant
    - thus: transform ray into object coordinates!

Geometric Transformations

- ray transformation
  - for intersection test, it is only important that ray is in same coordinate system as object representation
  - transform all rays into object coordinates
    - transform camera point and ray direction by <u>inverse</u> of model/view matrix
  - shading has to be done in world coordinates (where light sources are given)
    - transform object space intersection point to world coordinates
    - thus have to keep both world and object-space ray

Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with *every* object

Local Lighting

- local surface information (normal…)
  - for implicit surfaces $F(x,y,z)$=0: normal $\mathbf{n}(x,y,z)$ can be easily computed at every intersection point using the gradient

$$\mathbf{n}(x,y,z) = \begin{pmatrix} \partial F(x,y,z)/\partial x \\ \partial F(x,y,z)/\partial y \\ \partial F(x,y,z)/\partial z \end{pmatrix}$$

  - example:

$$F(x,y,z) = x^2 + y^2 + z^2 - r^2$$

$$\mathbf{n}(x,y,z) = \begin{pmatrix} 2x \\ 2y \\ 2z \end{pmatrix}$$

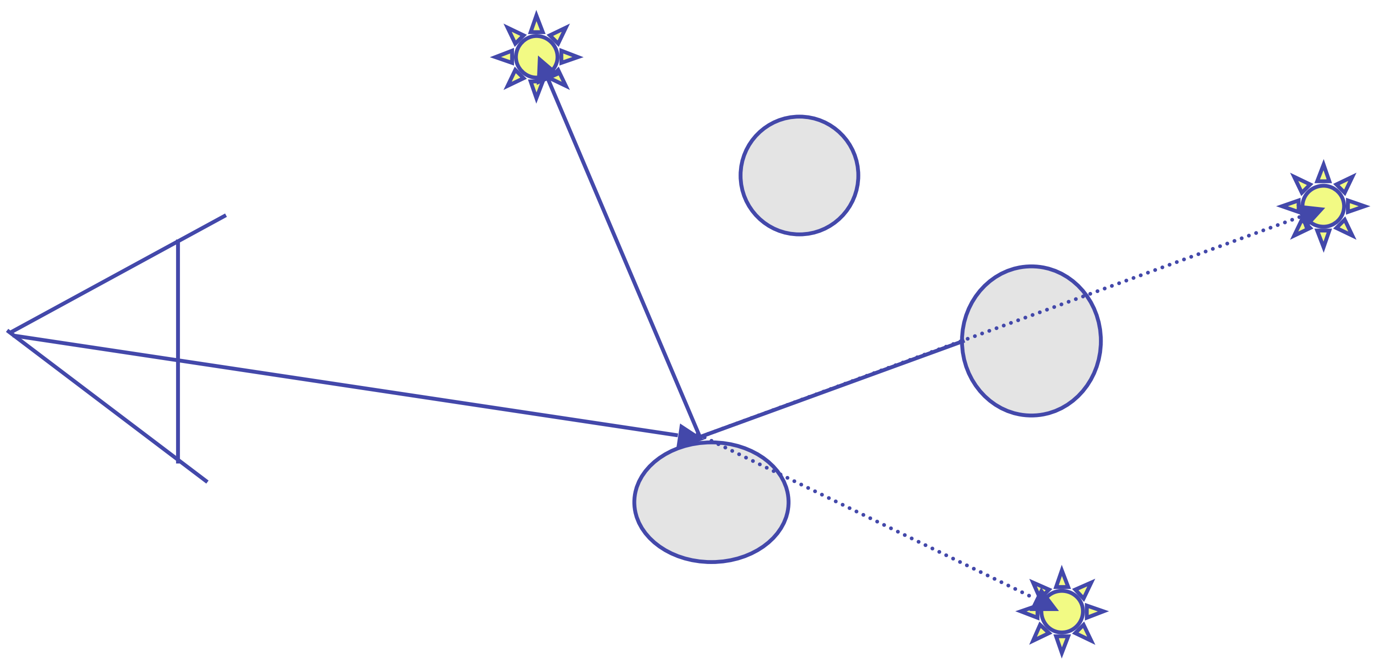
needs to be normalized!

Local Lighting

- local surface information
  - alternatively: can interpolate per-vertex information for triangles/meshes as in rendering pipeline
    - now easy to use Phong shading!
      - as discussed for rendering pipeline
  - difference with rendering pipeline:
    - interpolation cannot be done incrementally
    - have to compute barycentric coordinates for every intersection point (e.g plane equation for triangles)

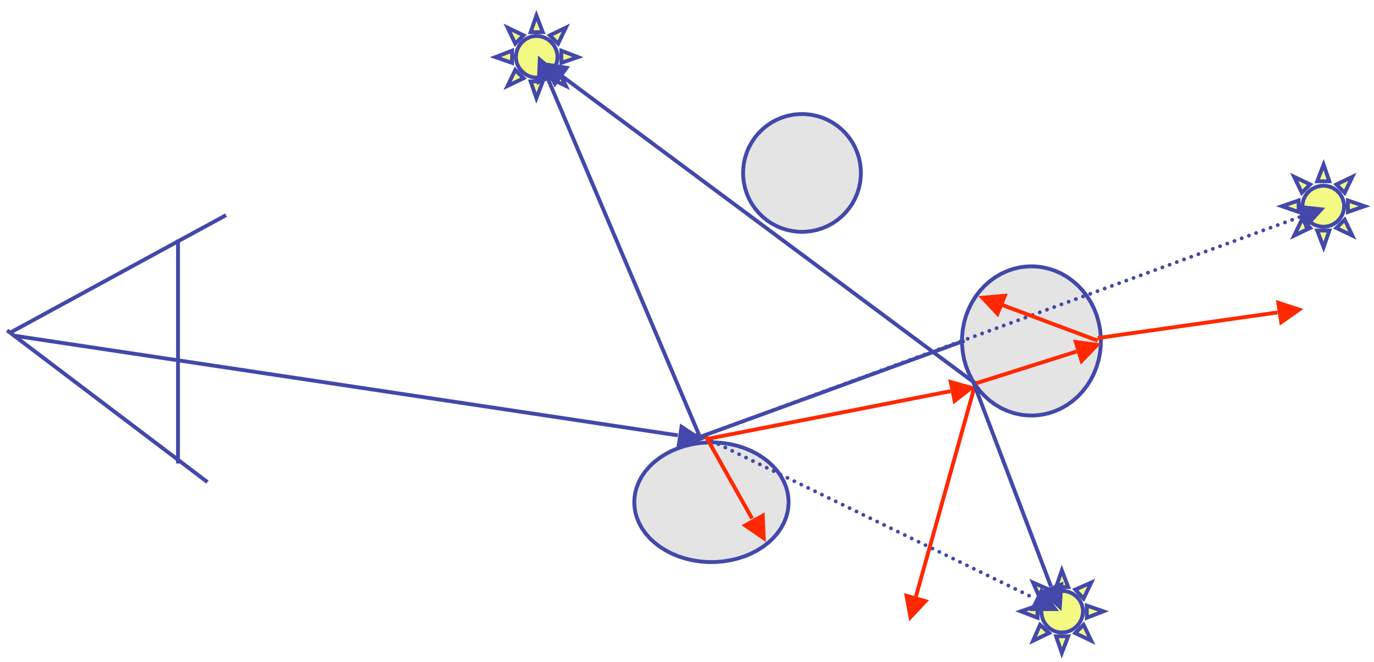
Global Shadows

- approach
  - to test whether point is in shadow, send out **shadow rays** to all light sources
    - if ray hits another object, the point lies in shadow



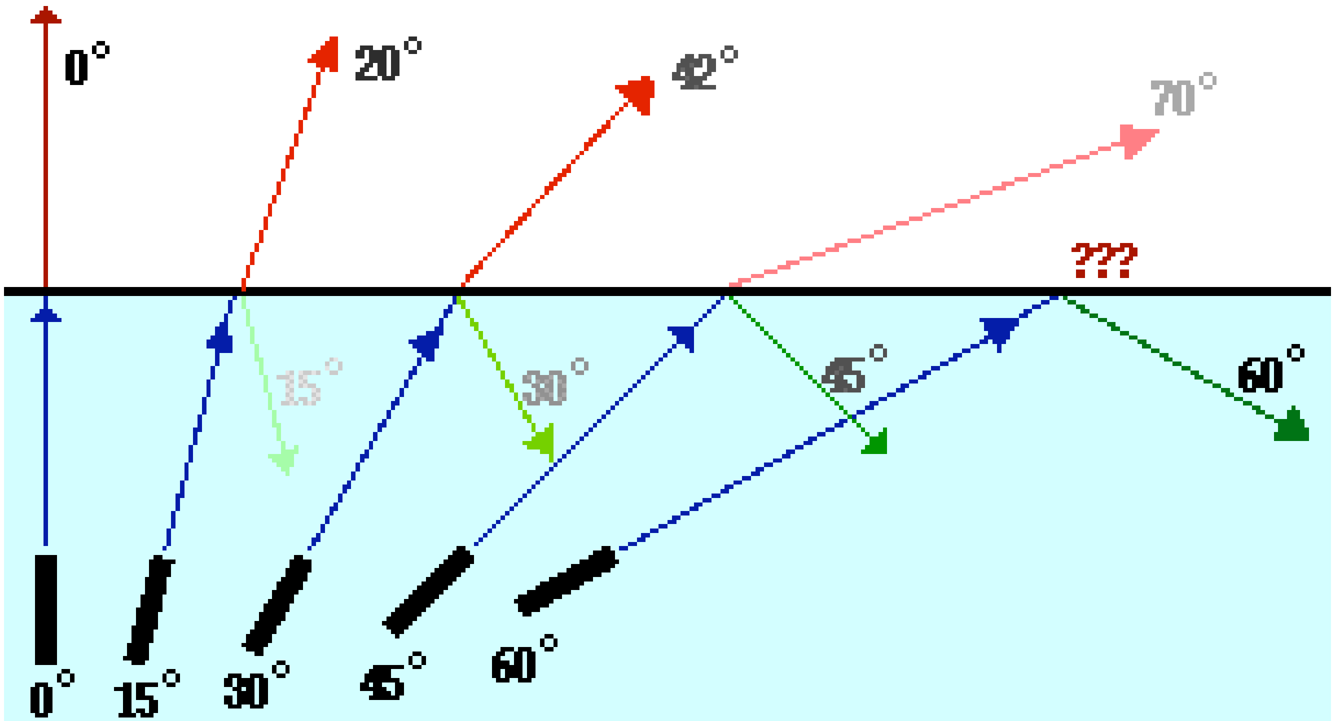
Global Reflections/Refractions

- approach
  - send rays out in reflected and refracted direction to gather incoming light
  - that light is multiplied by local surface color and added to result of local shading



Total Internal Reflection

As the angle of incidence increases from 0 to greater angles ...



...the refracted ray becomes dimmer (there is less refraction)

...the reflected ray becomes brighter (there is more reflection)

...the angle of refraction approaches 90 degrees until finally a refracted ray can no longer be seen.

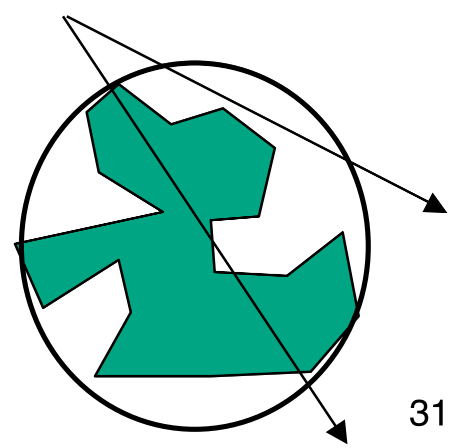
http://www.physicsclassroom.com/Class/refrn/U14L3b.html

Ray Tracing

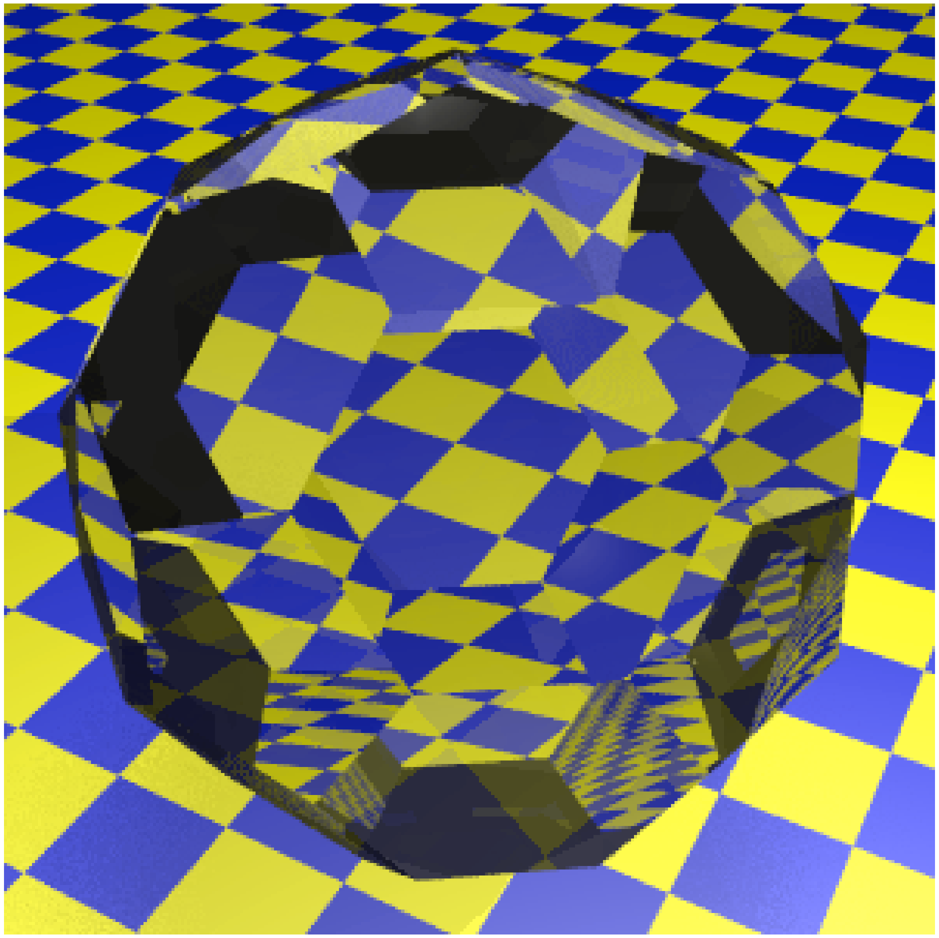
- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don’t have to test intersection with every object

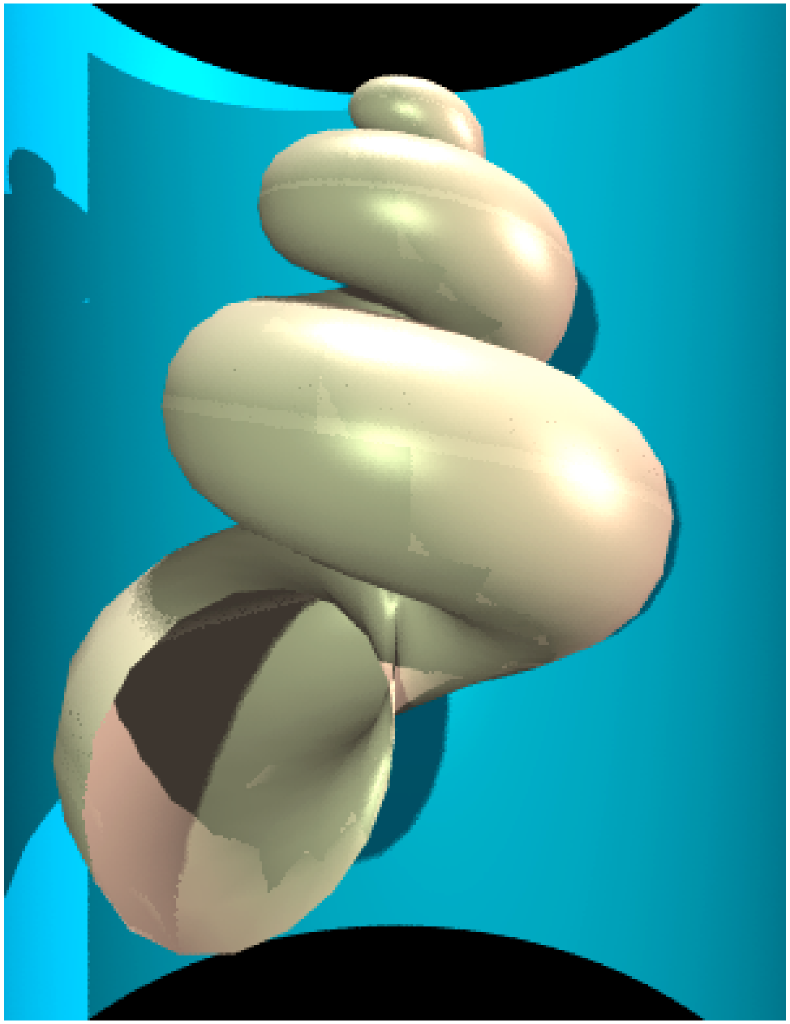
Optimized Ray-Tracing

- basic algorithm simple but very expensive
- optimize by reducing:
  - number of rays traced
  - number of ray-object intersection calculations
- methods
  - bounding volumes: boxes, spheres
  - spatial subdivision
    - uniform
    - BSP trees
- (more on this later with collision)



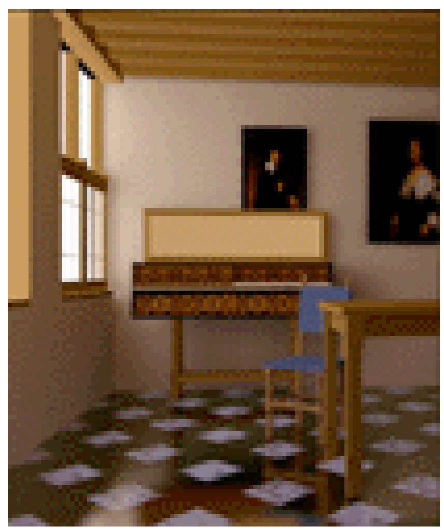
Example Images





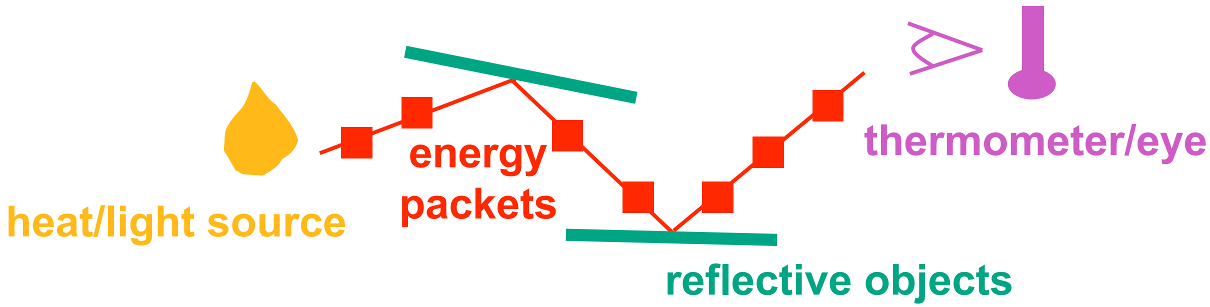
Radiosity

- radiosity definition
  - rate at which energy emitted or reflected by a surface
- radiosity methods
  - capture diffuse-diffuse bouncing of light
    - indirect effects difficult to handle with raytracing


Radiosity

- illumination as radiative heat transfer

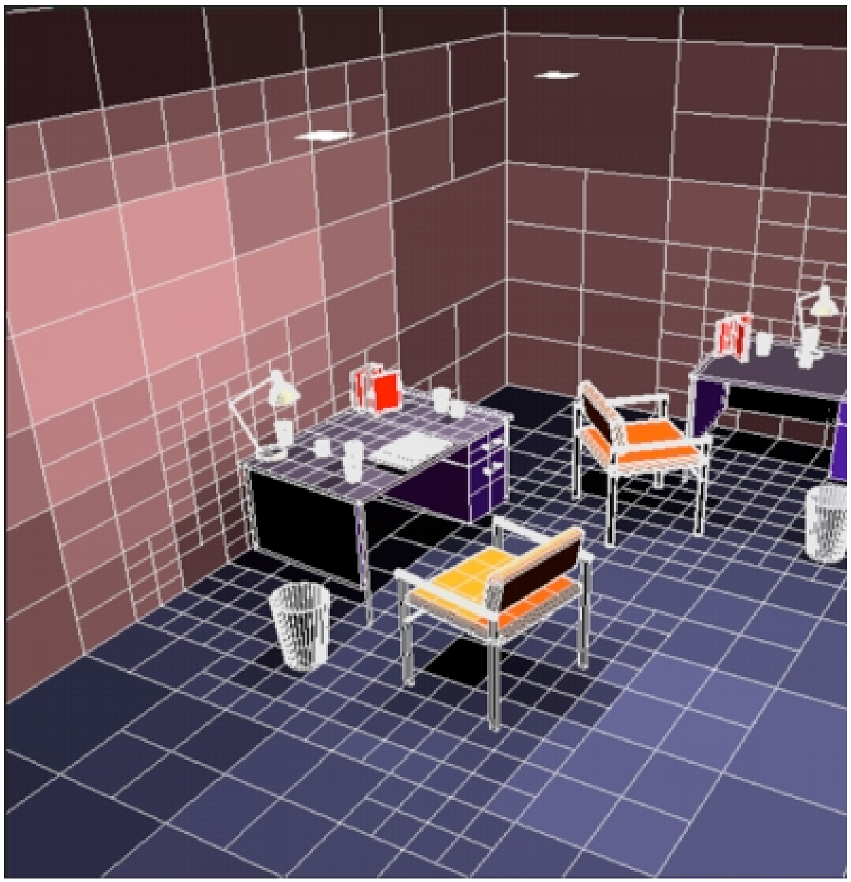


  - conserve light energy in a volume
  - model light transport as packet flow until convergence
  - solution captures diffuse-diffuse bouncing of light

- view-independent technique
  - calculate solution for entire scene offline
  - browse from any viewpoint in realtime

Radiosity

- divide surfaces into small patches
- loop: check for light exchange between all pairs
  - form factor: orientation of one patch wrt other patch (n x n matrix)



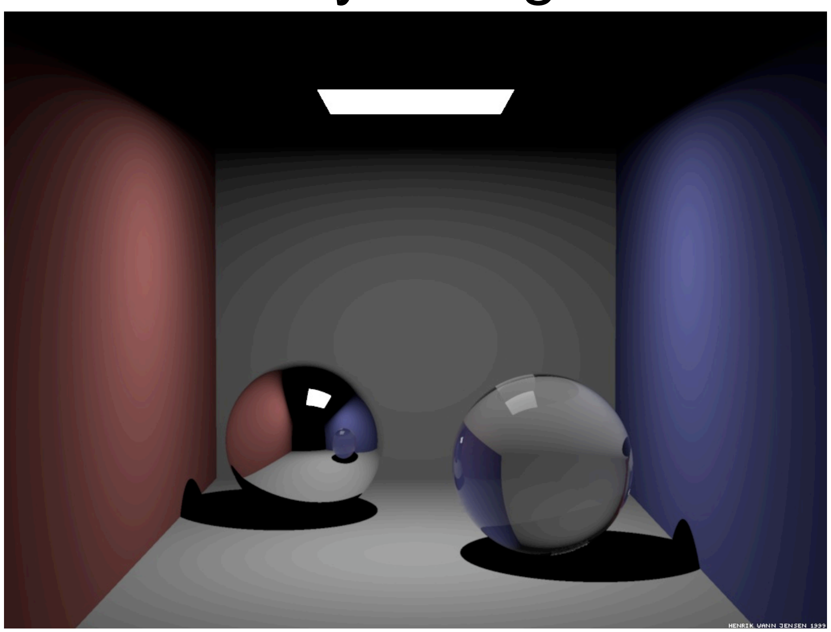
escience.anu.edu.au/lecture/cg/GlobalIllumination/Image/discrete.jpg

escience.anu.edu.au/lecture/cg/GlobalIllumination/Image/continuous.jpg

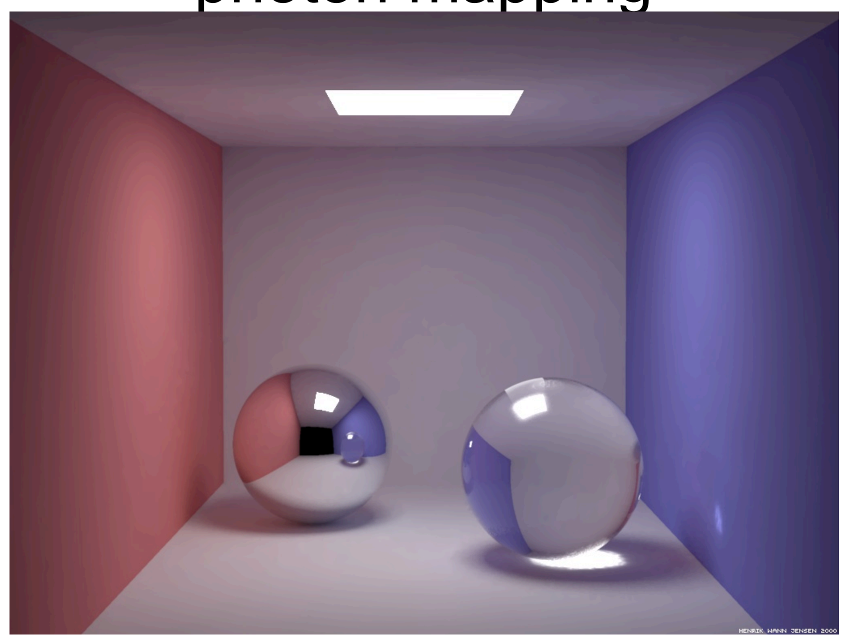
Better Global Illumination

- ray-tracing: great specular, approx. diffuse
  - view dependent
- radiosity: great diffuse, specular ignored
  - view independent, mostly-enclosed volumes
- photon mapping: superset of raytracing and radiosity
  - view dependent, handles both diffuse and specular well

raytracing



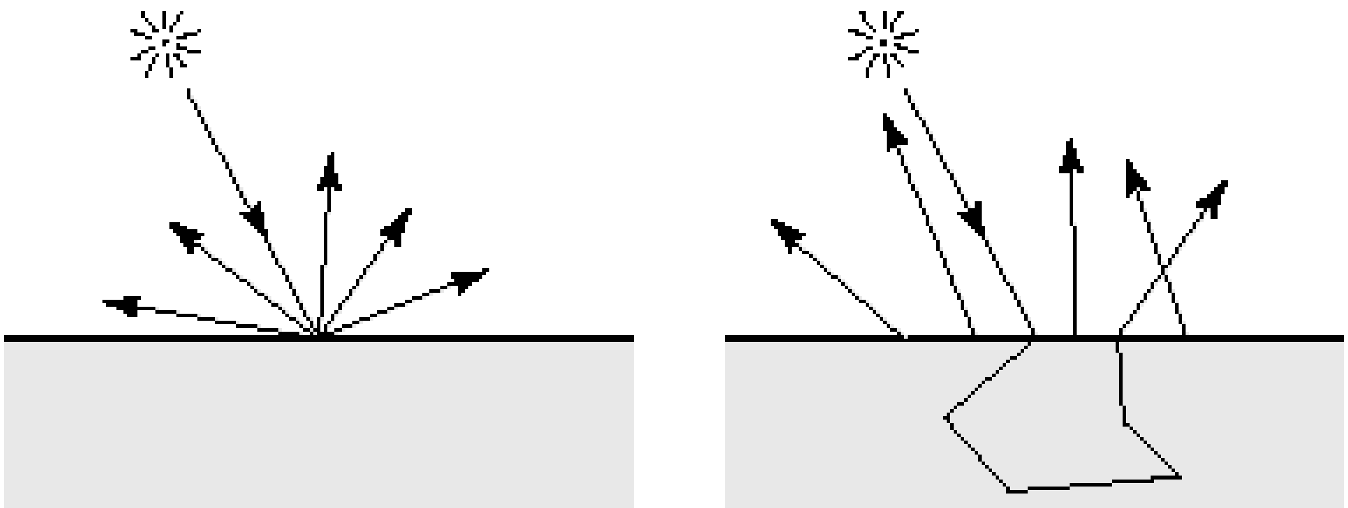
photon mapping



graphics.ucsd.edu/~henrik/images/cbox.html

Subsurface Scattering: Translucency

- light enters and leaves at *different* locations on the surface
  - bounces around inside
- technical Academy Award, 2003
  - Jensen, Marschner, Hanrahan



Subsurface Scattering: Marble

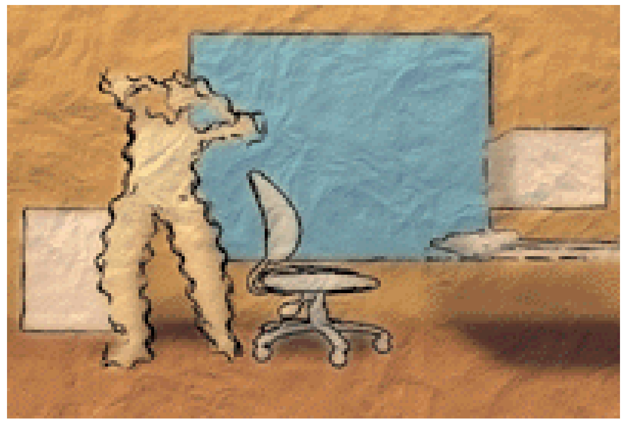
Subsurface Scattering: Milk vs. Paint

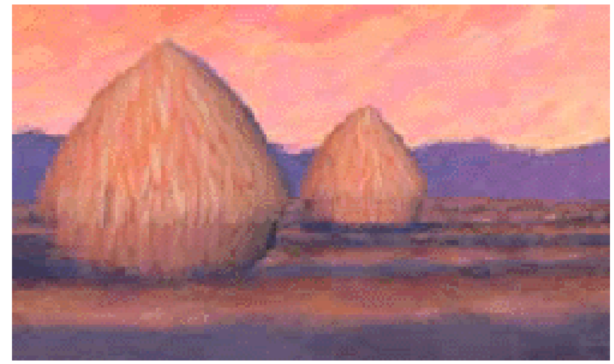
Subsurface Scattering: Skin

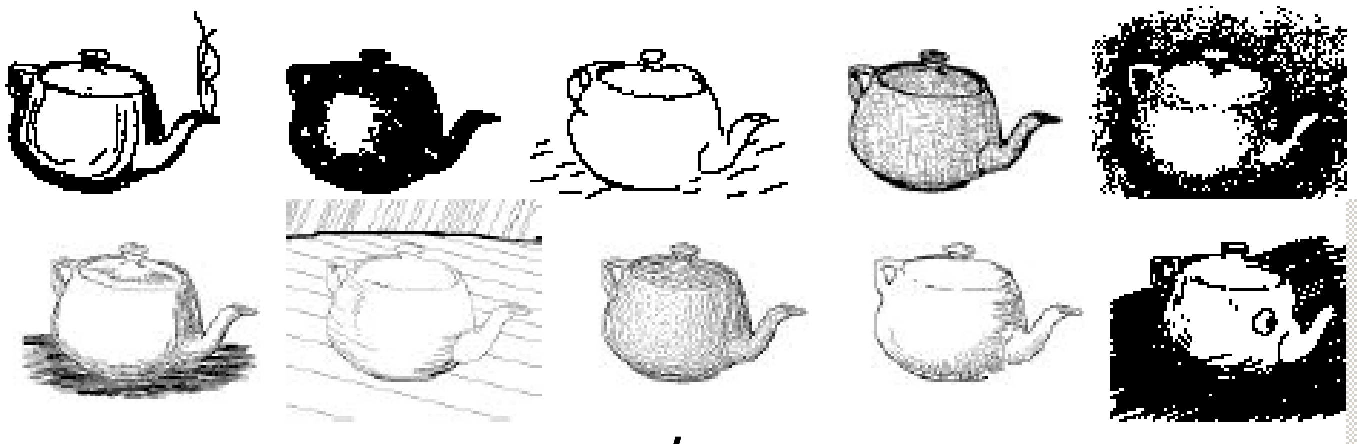
Subsurface Scattering: Skin

Non-Photorealistic Rendering

- simulate look of hand-drawn sketches or paintings, using digital models



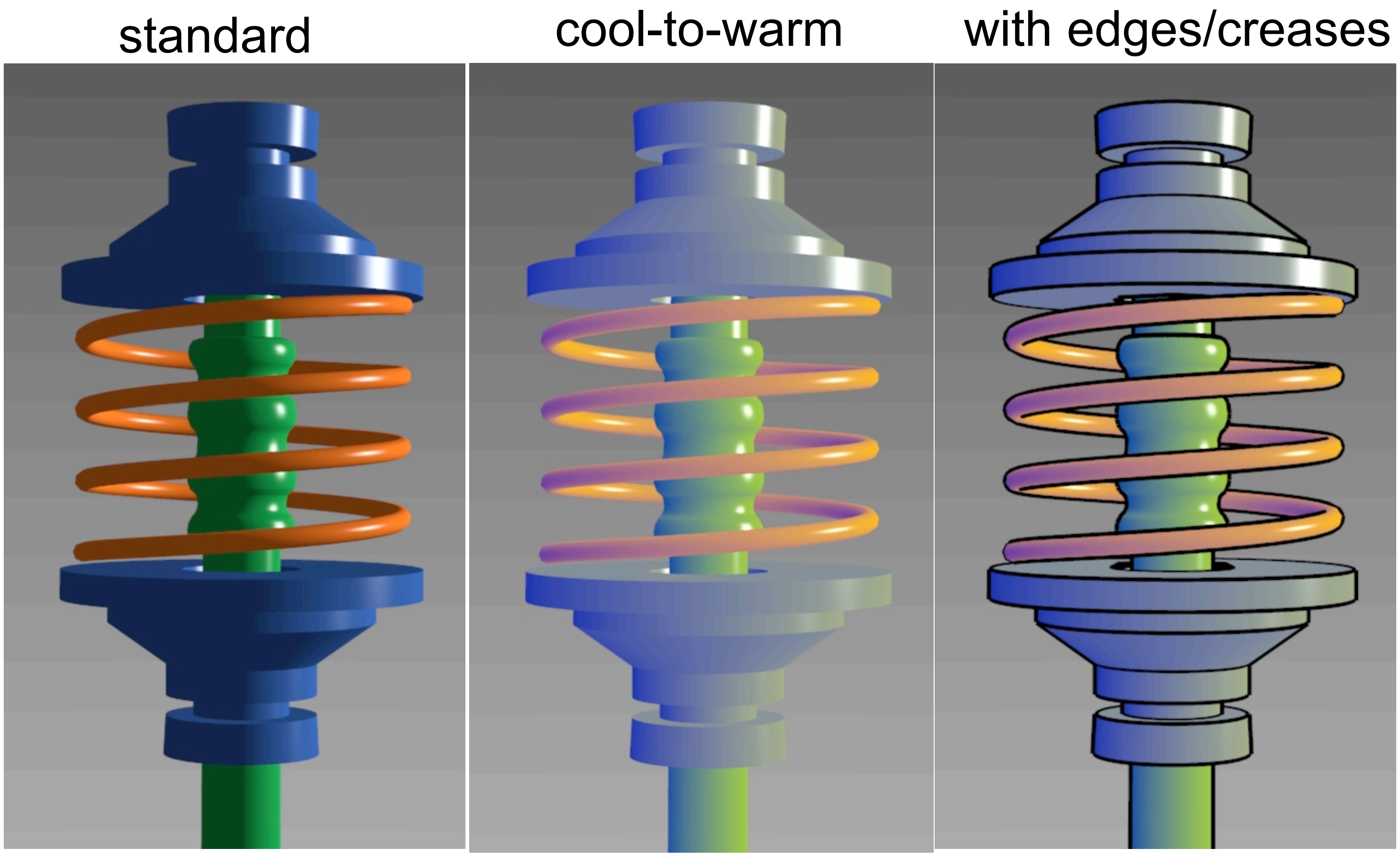




www.red3d.com/cwr/npr/

Non-Photorealistic Shading

- cool-to-warm shading $k_w = \dfrac{1 + \mathbf{n} \cdot \mathbf{l}}{2}, c = k_w c_w + (1 - k_w) c_c$

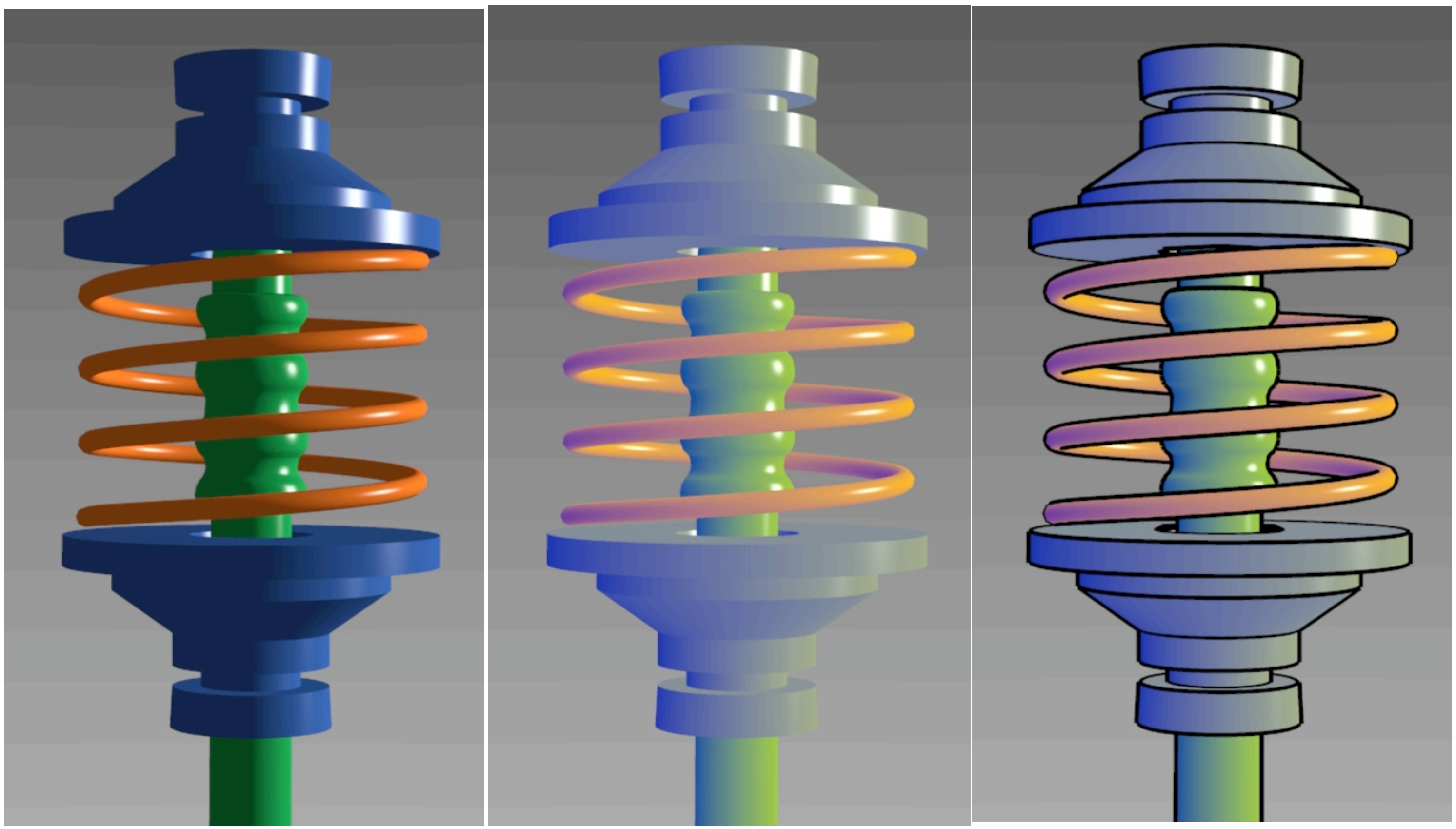


http://www.cs.utah.edu/~gooch/SIG98/paper/drawing.html

Non-Photorealistic Shading

- draw silhouettes: if $(\mathbf{e}\cdot\mathbf{n}_0)(\mathbf{e}\cdot\mathbf{n}_1) \le 0$, **e**=edge-eye vector
- draw creases: if $(\mathbf{n}_0 \cdot \mathbf{n}_1) \le \mathit{threshold}$

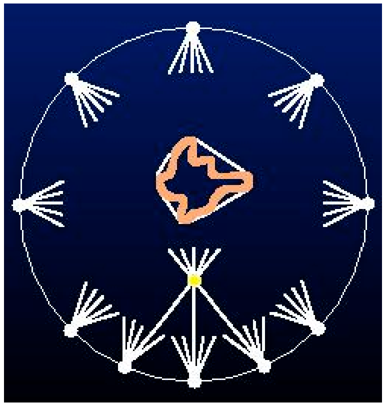
standard | cool-to-warm | with edges/creases



http://www.cs.utah.edu/~gooch/SIG98/paper/drawing.html

Image-Based Modelling and Rendering

- store and access only pixels
  - no geometry, no light simulation, ...
  - input: set of images
  - output: image from new viewpoint
    - surprisingly large set of possible new viewpoints
    - interpolation allows translation, not just rotation
      - lightfield, lumigraph: translate outside convex hull of object
      - QuickTimeVR: camera rotates, no translation
    - can point camera in or out



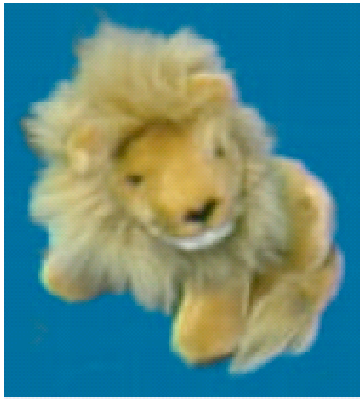


Image-Based Rendering

- display time not tied to scene complexity
  - expensive rendering or real photographs
- example: Matrix bullet-time scene
  - array of many cameras allows virtual camera to "freeze time"
- convergence of graphics, vision, photography
  - computational photography