University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2010

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Lighting/Shading IV, Advanced Rendering I

Week 7, Fri Mar 5

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2010

News

- midterm is Monday, be on time!
- HW2 solutions out

Clarify: Projective Rendering Pipeline

coordinate system point of view!

glVertex3f(x,y,z)

object **OCS** → **O2W** **modeling transformation** → world **WCS** → **W2V** **viewing transformation** → viewing **VCS** → **V2C** alter w **projection transformation** → clipping **CCS** → **C2N** / w **perspective division** → normalized device **NDCS** → **N2D** **viewport transformation** → device **DCS**

glTranslatef(x,y,z)
glRotatef(a,x,y,z)
....

gluLookAt(...)

glFrustum(...)

glutInitWindowSize(w,h)
glViewport(x,y,a,b)

OCS - object coordinate system

WCS - world coordinate system

VCS - viewing coordinate system

CCS - clipping coordinate system

NDCS - normalized device coordinate system

DCS - device coordinate system

Clarify: OpenGL Example

coordinate system point of view!

object **OCS** → **modeling transformation** (**O2W**) → world **WCS** → **viewing transformation** (**W2V**) → viewing **VCS** → **projection transformation** (**V2C**) → clipping **CCS**

```
CCS   glMatrixMode( GL_PROJECTION );
      glLoadIdentity();
      gluPerspective( 45, 1.0, 0.1, 200.0 );
VCS   glMatrixMode( GL_MODELVIEW );
      glLoadIdentity();
      glTranslatef( 0.0, 0.0, -5.0 );   V2W
WCS   glPushMatrix()
      glTranslate( 4, 4, 0 );   W2O
OCS1  glutSolidTeapot(1);
      glPopMatrix();
      glTranslate( 2, 2, 0);   W2O
OCS2  glutSolidTeapot(1);
```

- transformations that are applied to object first are specified last

Coordinate Systems: Frame vs Point

read down: transforming between coordinate frames, from frame A to frame B

read up: transforming points, up from frame B coords to frame A coords

DCS display

D2N **N2D**

NDCS normalized device

N2V **V2N**

VCS viewing

V2W **W2V**

WCS world

W2O **O2W**

OCS object

Coordinate Systems: Frame vs Point

- is gluLookAt V2W or W2V? depends on which way you read!
  - coordinate frames: V2W
    - takes you from view to world coordinate frame
  - points/objects: W2V
    - transforms point from world to view coords

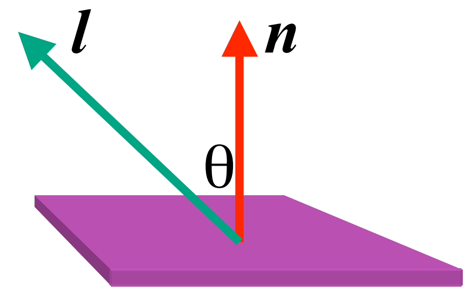
Homework

- most of my lecture slides use coordinate frame reading ("reading down")
  - same with my post to discussion group: said to use W2V, V2N, N2D
- homework questions asked you to compute for object/point coords ("reading up")

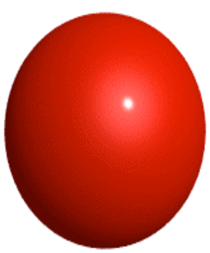
- correct matrix for question 1 is gluLookat
- enough confusion that we will not deduct marks if you used inverse of gluLookAt instead of gluLookAt!
  - same for Q2, Q3: no deduction if you used inverses of correct matices

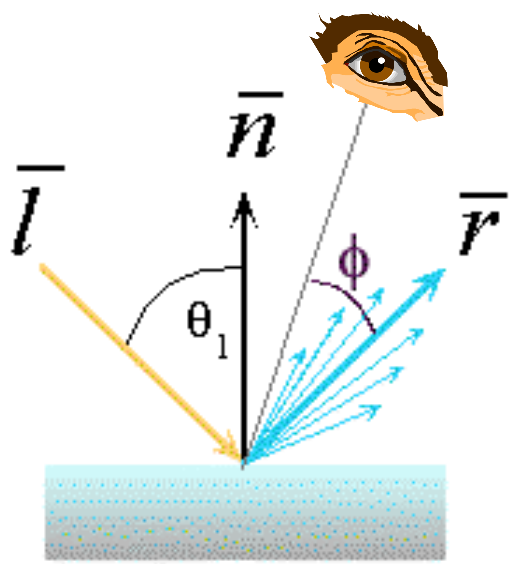
Review: Reflection Equations

$$I_{diffuse} = k_d \, I_{light} \, (\mathbf{n} \bullet \mathbf{l})$$



$$I_{specular} = k_s I_{light} (\mathbf{v} \bullet \mathbf{r})^{n_{shiny}}$$





2 (**N** (**N** · **L**)) – **L** = **R**

Review: Phong Lighting Model

- combine ambient, diffuse, specular components

$$\mathbf{I}_{\mathbf{total}} = \mathbf{k}_{\mathbf{a}}\mathbf{I}_{\mathbf{ambient}} + \sum_{i=1}^{\#\,lights} \mathbf{I}_{\mathbf{i}}\left(\mathbf{k}_{\mathbf{d}}(\mathbf{n} \bullet \mathbf{l}_{\mathbf{i}}) + \mathbf{k}_{\mathbf{s}}(\mathbf{v} \bullet \mathbf{r}_{\mathbf{i}})^{n_{shiny}}\right)$$

- commonly called *Phong lighting*
  - once per light
  - once per color component

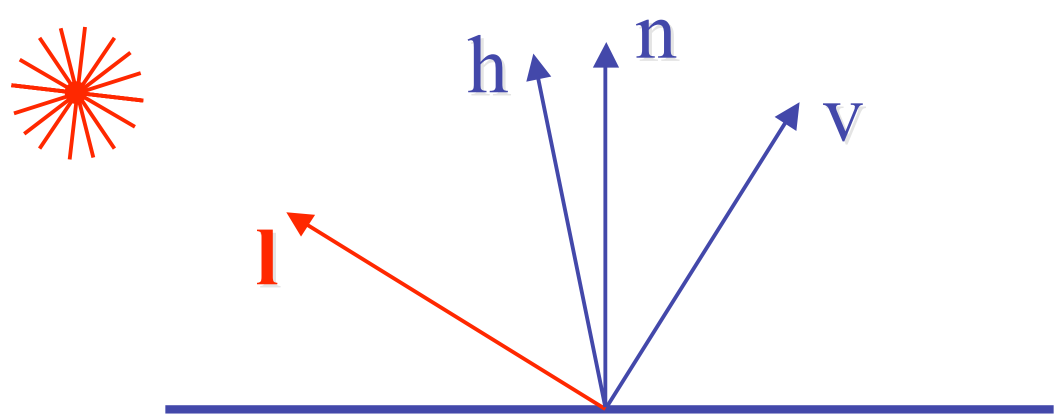
- reminder: normalize your vectors when calculating!
  - normalize all vectors: n,l,r,v

Review: Blinn-Phong Model

- variation with better physical interpretation
  - Jim Blinn, 1977

$$I_{out}(\mathbf{x}) = \mathbf{k_s}(\mathbf{h} \bullet \mathbf{n})^{n_{shiny}} \bullet I_{in}(\mathbf{x}); \text{with } \mathbf{h} = (\mathbf{l} + \mathbf{v})/2$$

- ***h***: halfway vector
  - h must also be explicitly normalized: h / |h|
  - highlight occurs when h near n



Review: Lighting

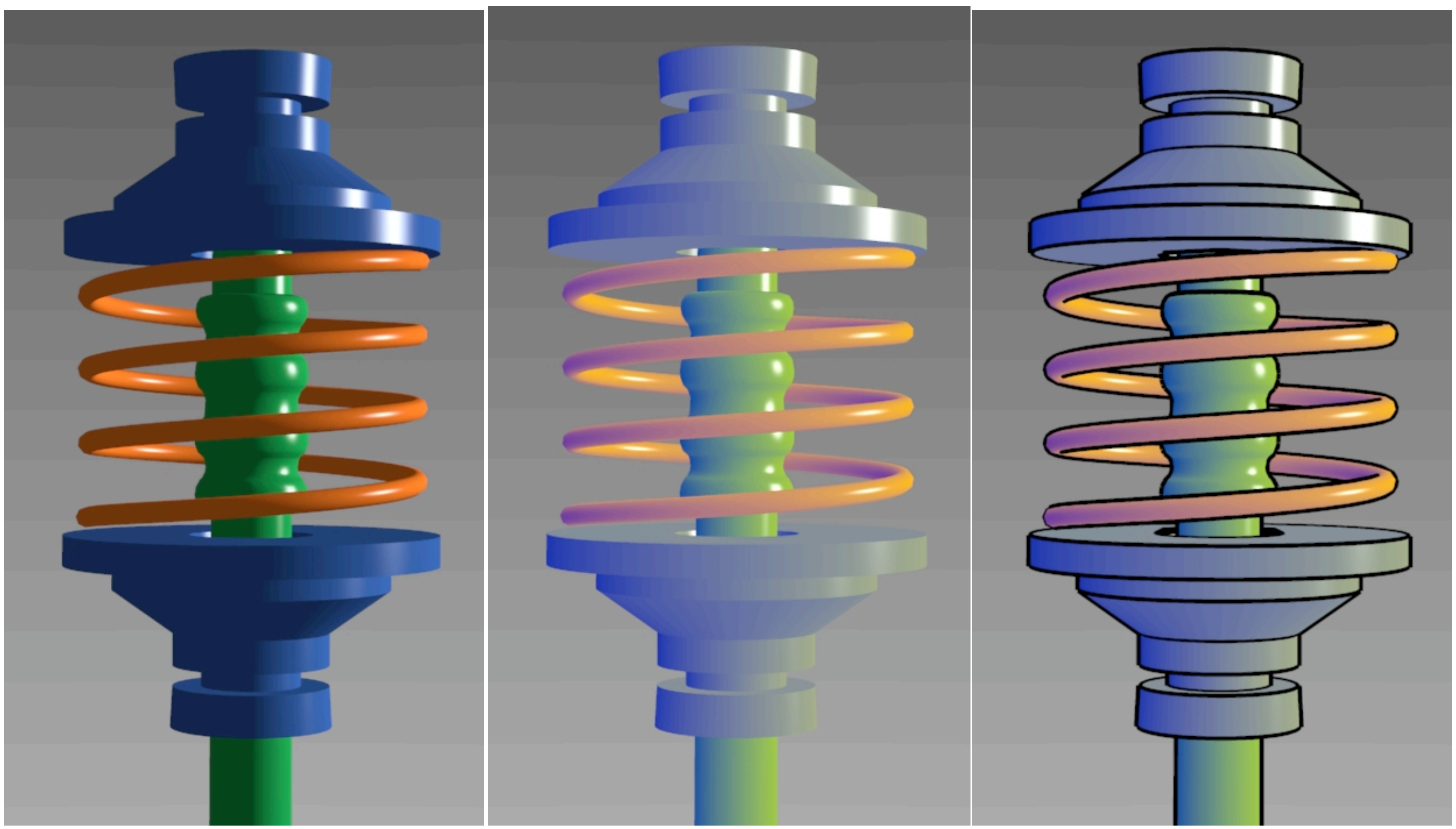
- lighting models
  - ambient
    - normals don’t matter
  - Lambert/diffuse
    - angle between surface normal and light
  - Phong/specular
    - surface normal, light, and viewpoint

Review: Shading Models Summary

- flat shading
  - compute Phong lighting once for entire polygon
- Gouraud shading
  - compute Phong lighting at the vertices
  - at each pixel across polygon, interpolate lighting values
- Phong shading
  - compute averaged vertex normals at the vertices
  - at each pixel across polygon, interpolate normals and compute Phong lighting

Non-Photorealistic Shading

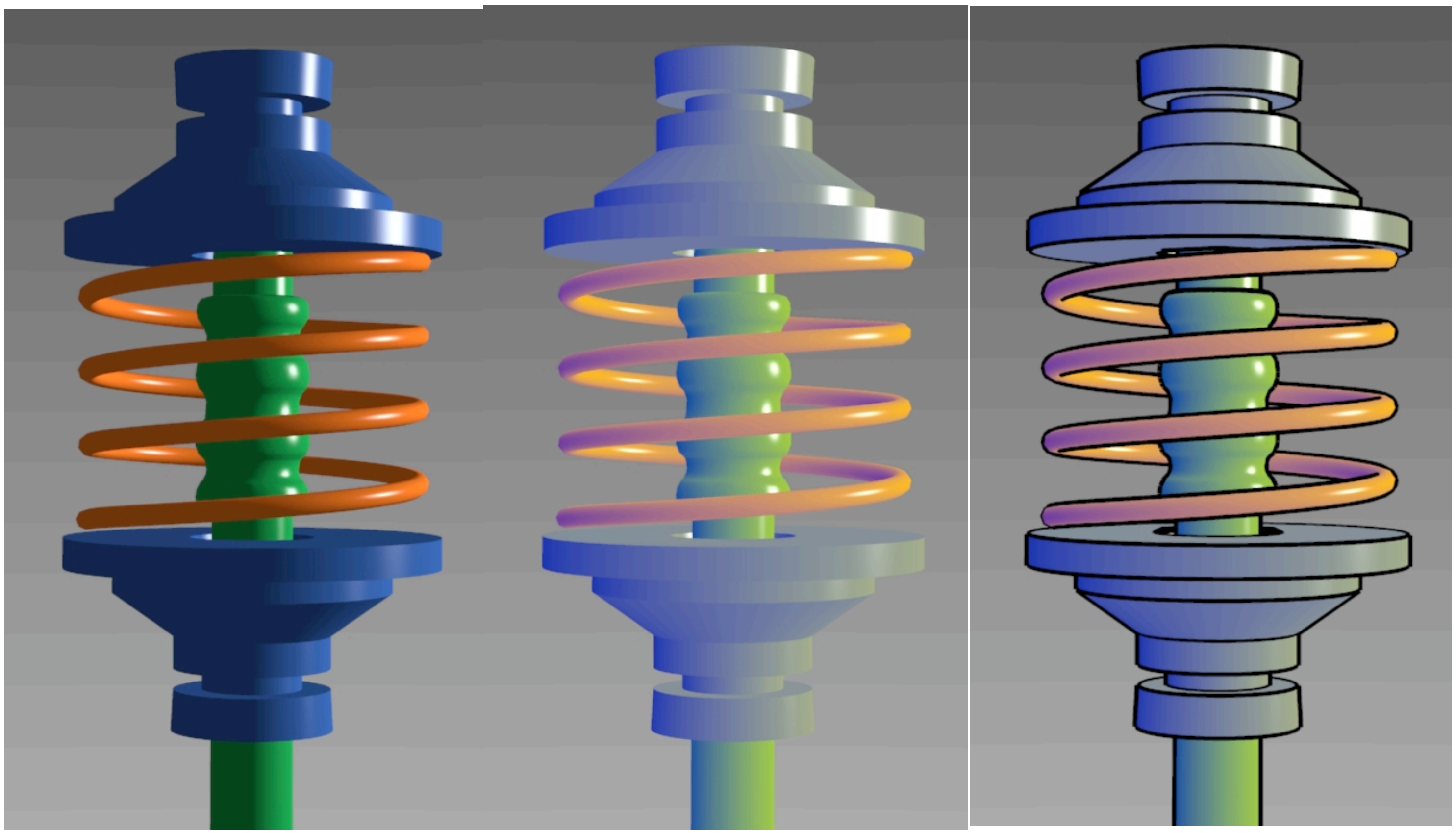
- cool-to-warm shading $k_w = \frac{1 + \mathbf{n} \cdot \mathbf{l}}{2}, c = k_w c_w + (1 - k_w) c_c$



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 $(\mathbf{n_0} \cdot \mathbf{n_1}) \le \textit{threshold}$



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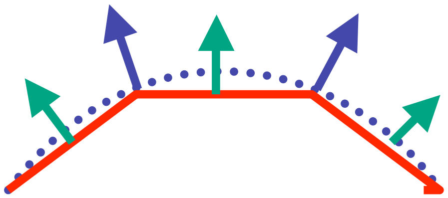
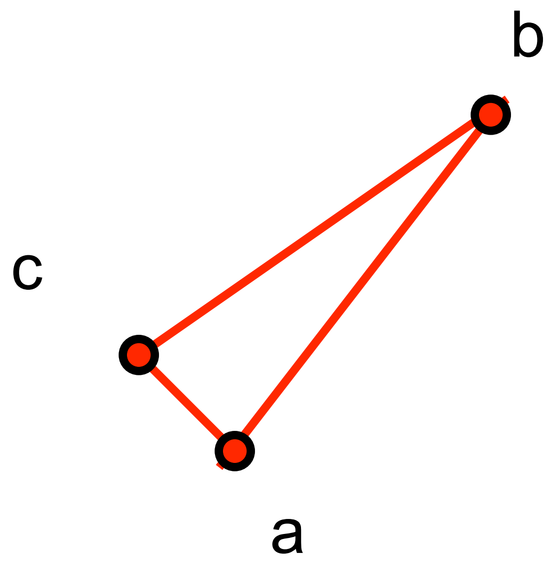
Computing Normals

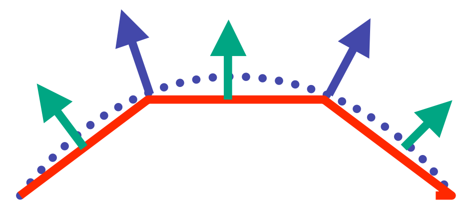
- per-vertex normals by interpolating per-facet normals
  - OpenGL supports both
- computing normal for a polygon

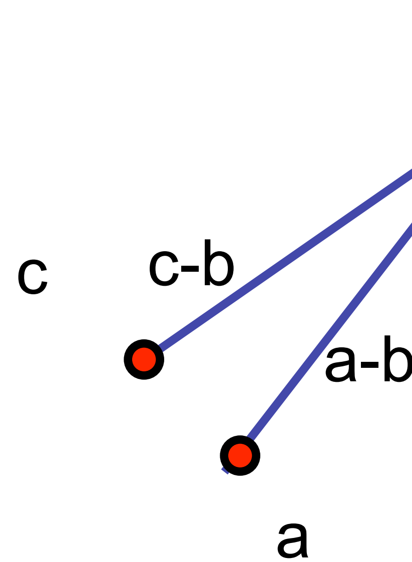




Computing Normals

- per-vertex normals by interpolating per-facet normals
  - OpenGL supports both
- computing normal for a polygon
  - three points form two vectors

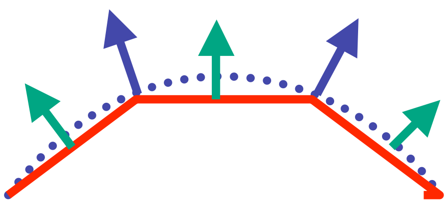


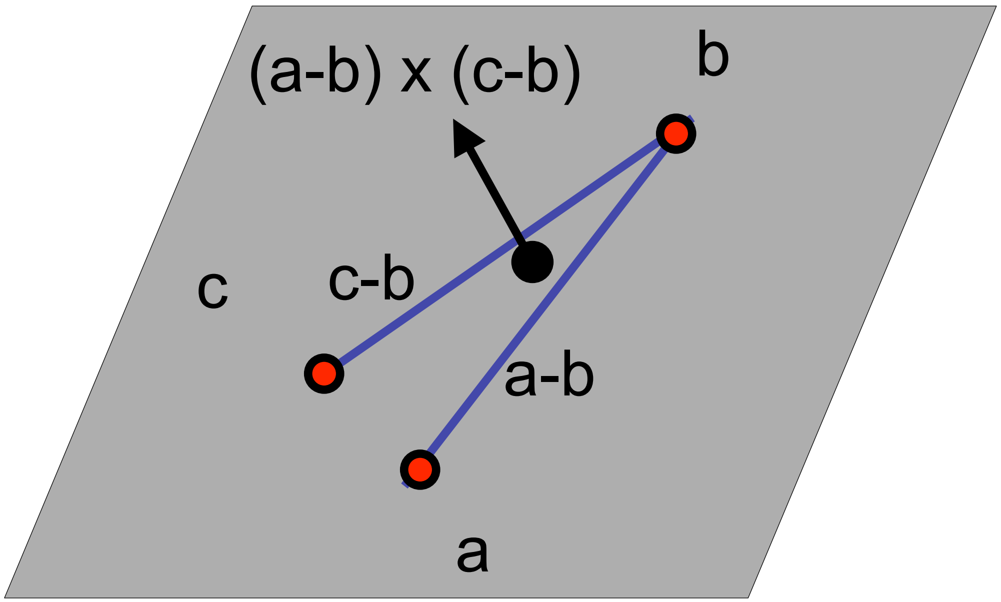


Computing Normals

- per-vertex normals by interpolating per-facet normals
  - OpenGL supports both
- computing normal for a polygon
  - three points form two vectors
  - cross: normal of plane gives direction
  - **normalize to unit length!**

  - which side is up?
    - convention: points in counterclockwise order





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);
```

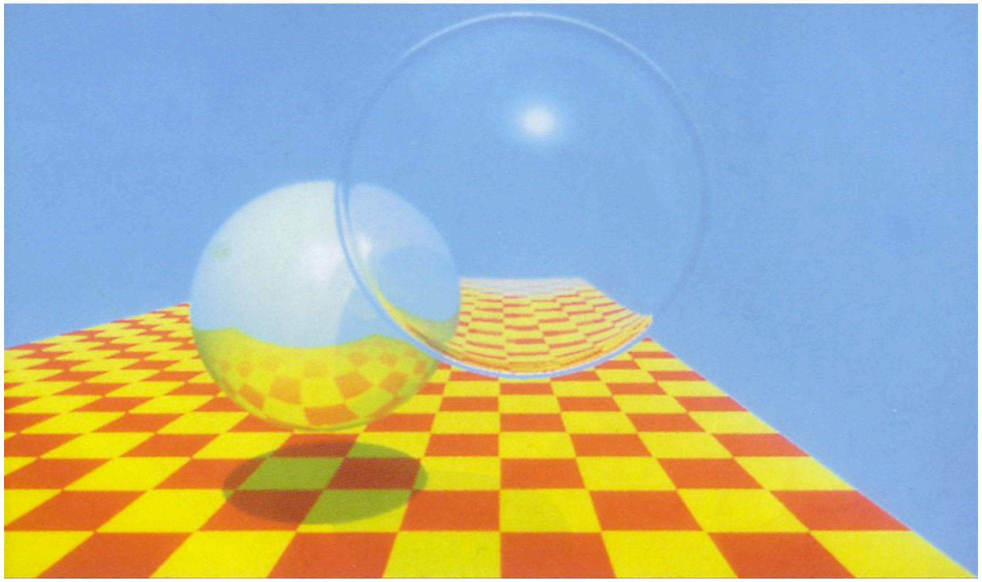
Advanced Rendering

Global Illumination Models

- simple lighting/shading methods simulate local illumination models
  - no object-object interaction
- global illumination models
  - more realism, more computation
  - leaving the pipeline for these two lectures!
- approaches
  - ray tracing
  - radiosity
  - photon mapping
  - subsurface scattering

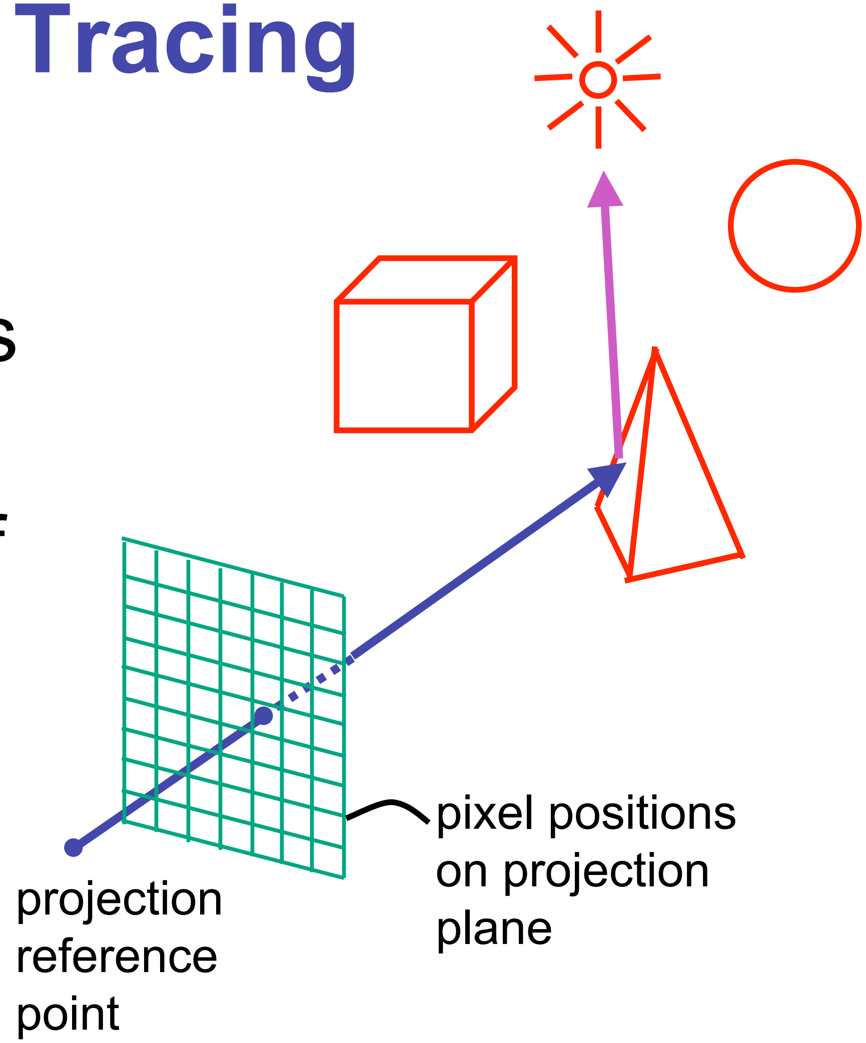
Ray Tracing

- simple basic algorithm
- well-suited for software rendering
- flexible, easy to incorporate new effects
    - Turner Whitted, 1990



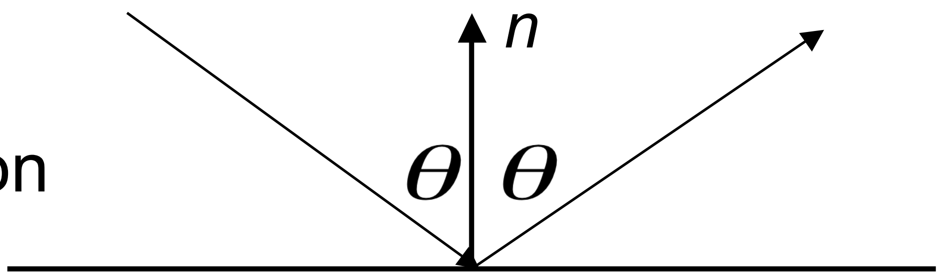
Simple Ray Tracing

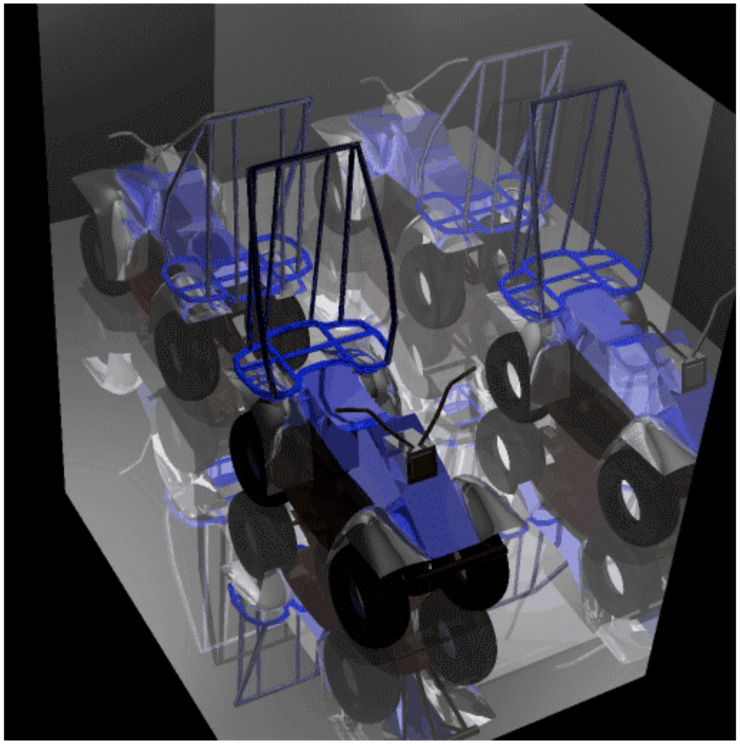
- view dependent method
  - cast a ray from viewer’s eye through each pixel
  - compute intersection of ray with first object in scene
  - cast ray from intersection point on object to light sources

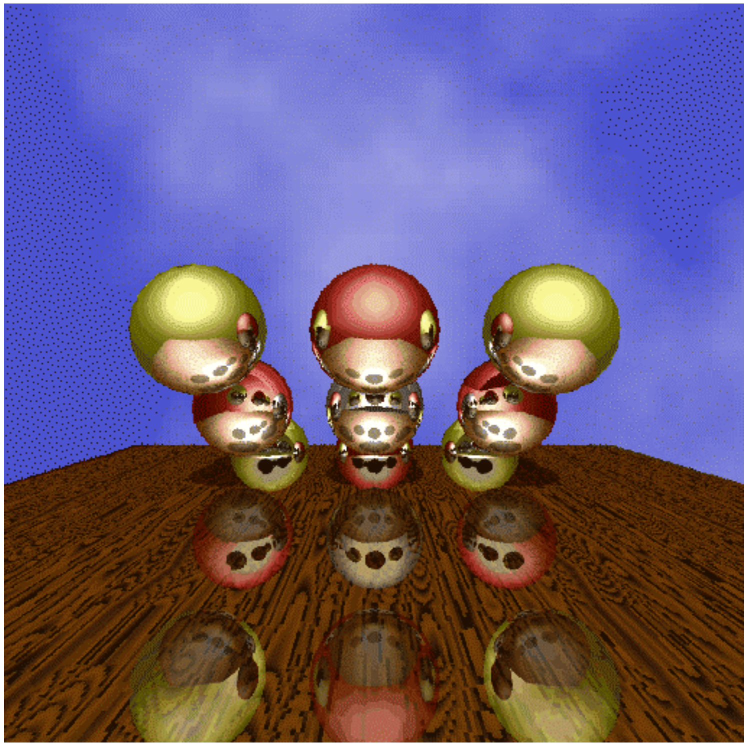


Reflection

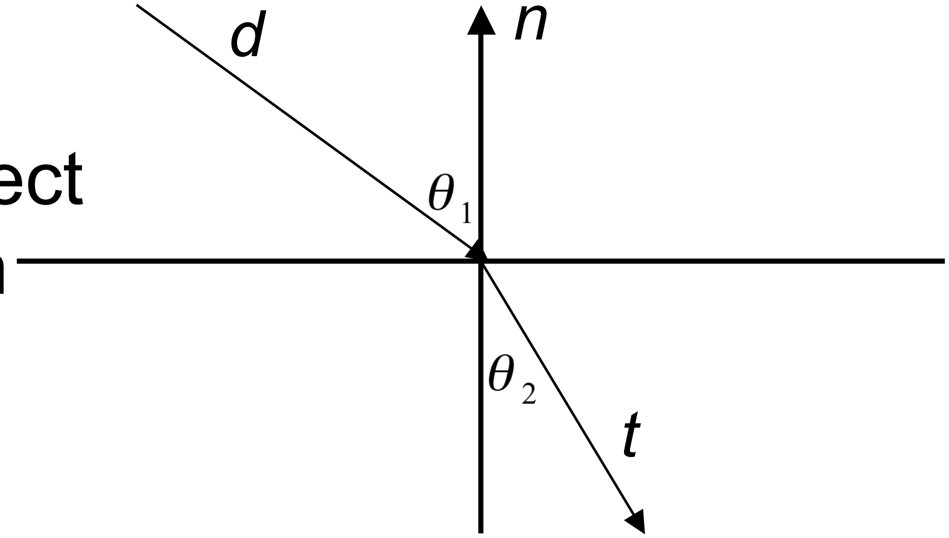
- mirror effects
  - perfect specular reflection



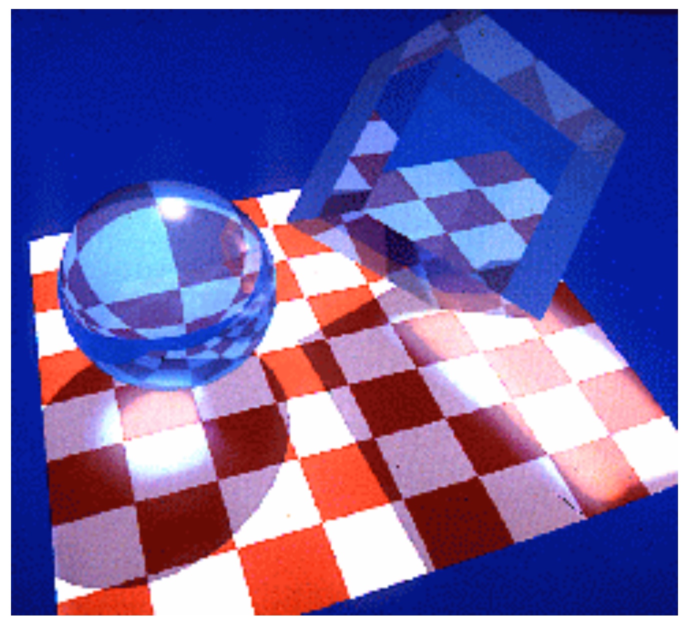




Refraction

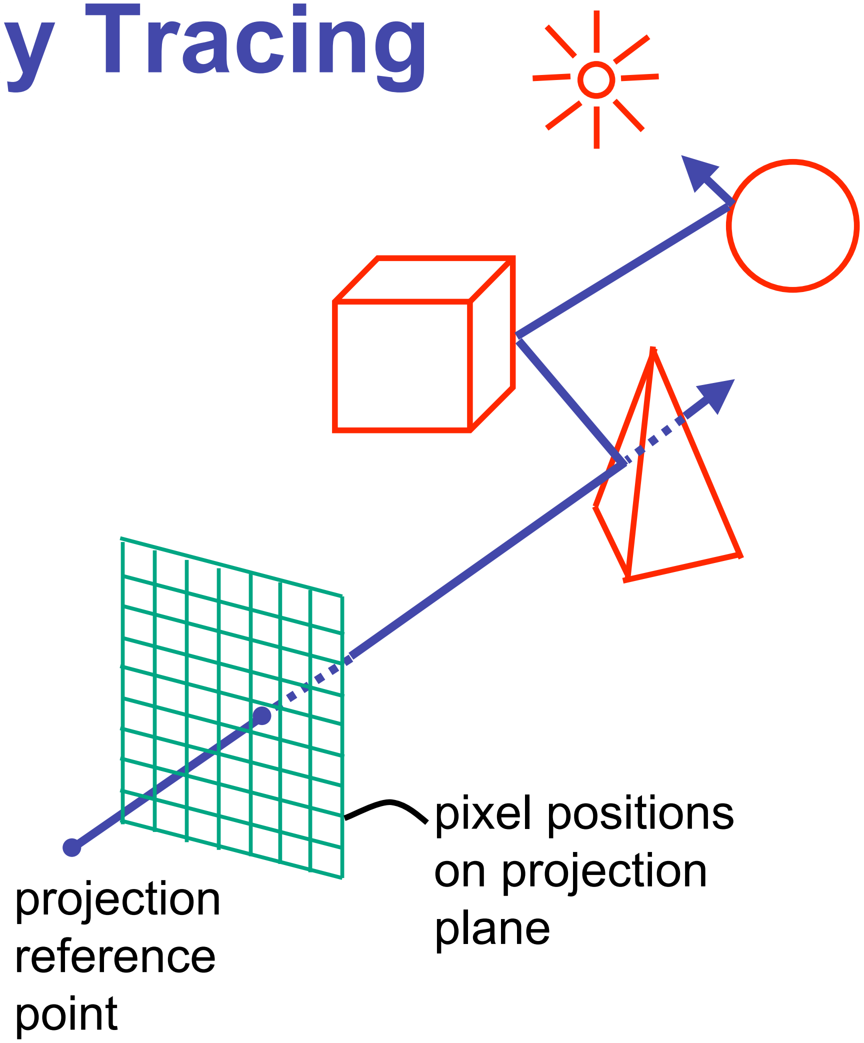


- happens at interface between transparent object and surrounding medium
  - e.g. glass/air boundary
- Snell's Law
  - $c_1 \sin\theta_1 = c_2 \sin\theta_2$
  - light ray bends based on refractive indices c_1, c_2



Recursive Ray Tracing

- ray tracing can handle
  - reflection (chrome/mirror)
  - refraction (glass)
  - shadows
- 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



Basic Algorithm

```
for every pixel pi {
    generate ray r from camera position through pixel pi
    for every object o in scene {
        if ( r intersects o )
            compute lighting at intersection point, using local
            normal and material properties; store result in pi
        else
            pi= background color
    }
}
```

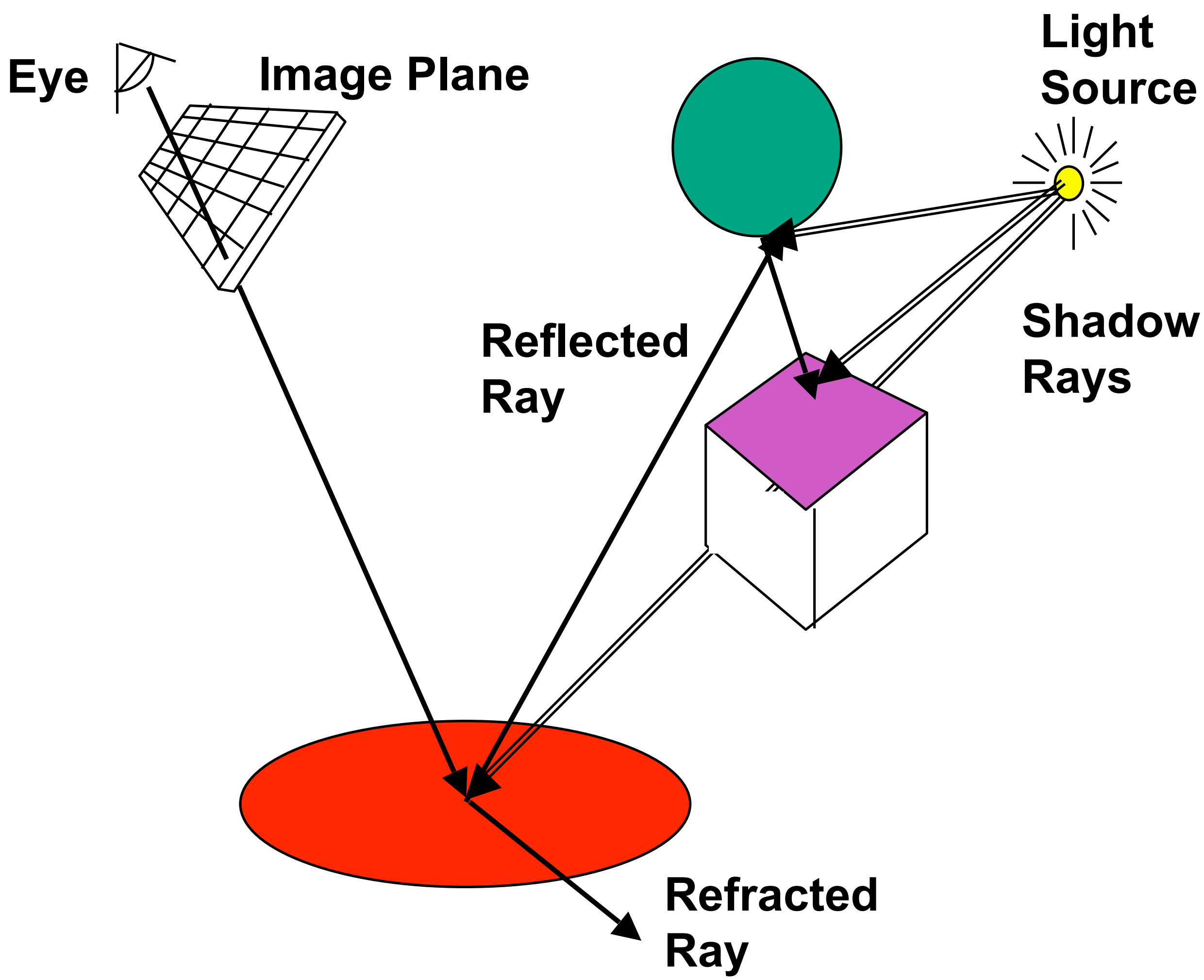
Basic Ray Tracing Algorithm

```
RayTrace(r,scene)
obj := FirstIntersection(r,scene)
if (no obj)  return BackgroundColor;
else begin
    if ( Reflect(obj) ) then
       reflect_color := RayTrace(ReflectRay(r,obj));
    else
       reflect_color := Black;
   if ( Transparent(obj) ) then
       refract_color := RayTrace(RefractRay(r,obj));
    else
       refract_color := Black;
   return Shade(reflect_color,refract_color,obj);
end;
```

Algorithm Termination Criteria

- termination criteria
  - no intersection
  - reach maximal depth
    - number of bounces
  - contribution of secondary ray attenuated below threshold
    - each reflection/refraction attenuates ray

Ray Tracing Algorithm

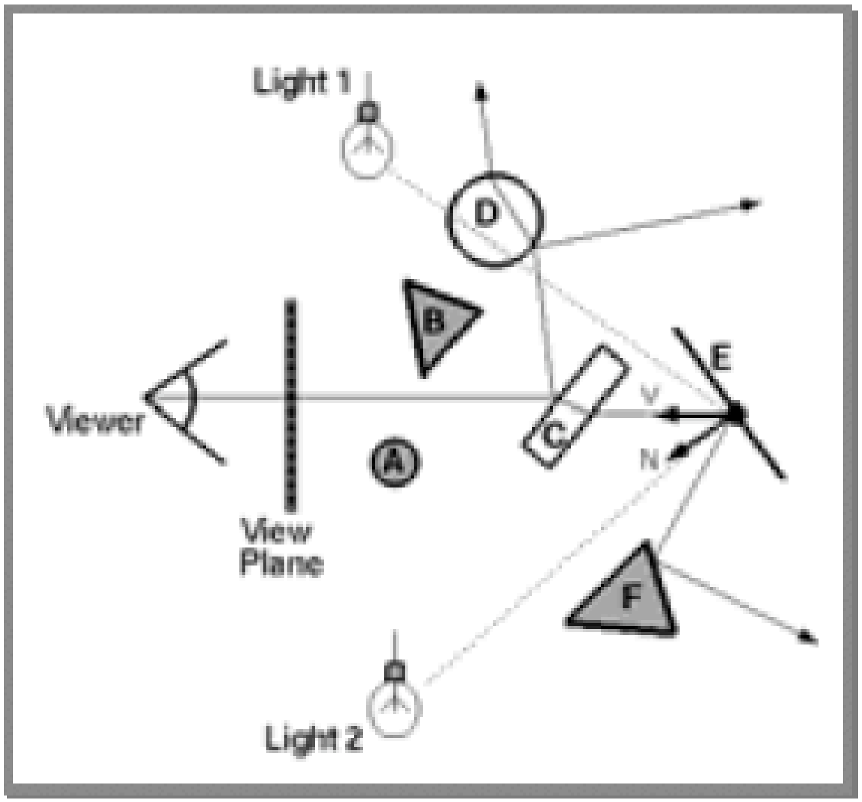


Ray-Tracing Terminology

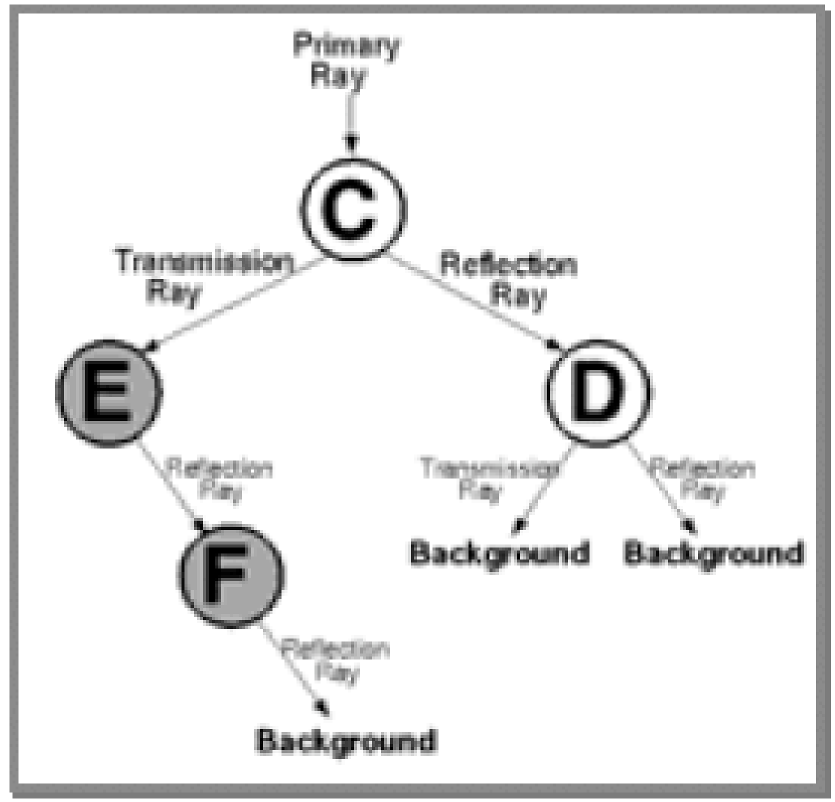
- terminology:
  - primary ray: ray starting at camera
  - shadow ray
  - reflected/refracted ray
  - ray tree: all rays directly or indirectly spawned off by a single primary ray
- note:
  - need to limit maximum depth of ray tree to ensure termination of ray-tracing process!

Ray Trees

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



Ray traced through scene



Ray tree

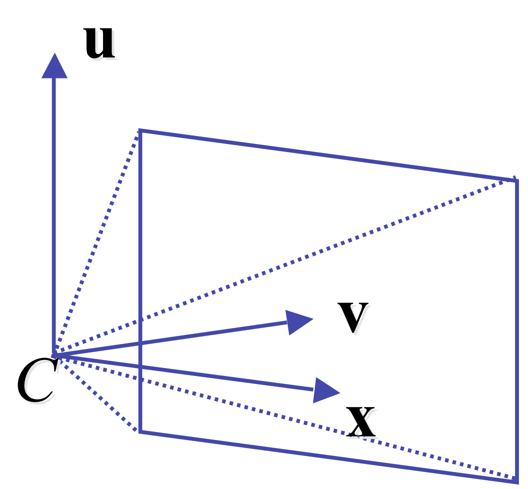
w.cs.virginia.edu/~gfx/Courses/2003/Intro.fall.03/slides/lighting_web/lighting.pdf

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

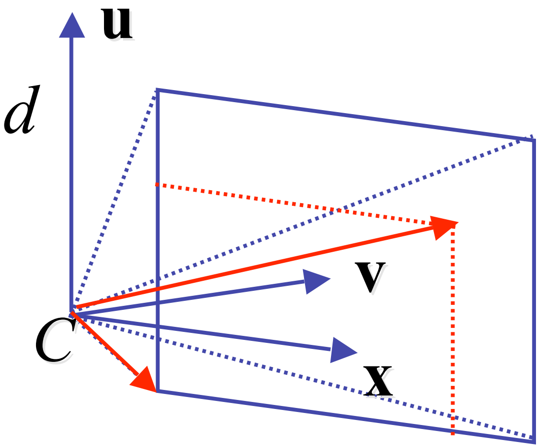
Ray Generation

- 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 $S(x,y,z)$:

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

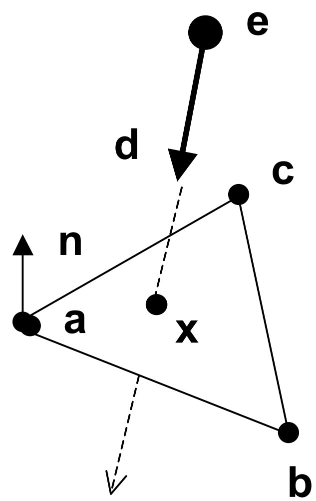
  - solve for t (find roots)
    - simple quadratic equation

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



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

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

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

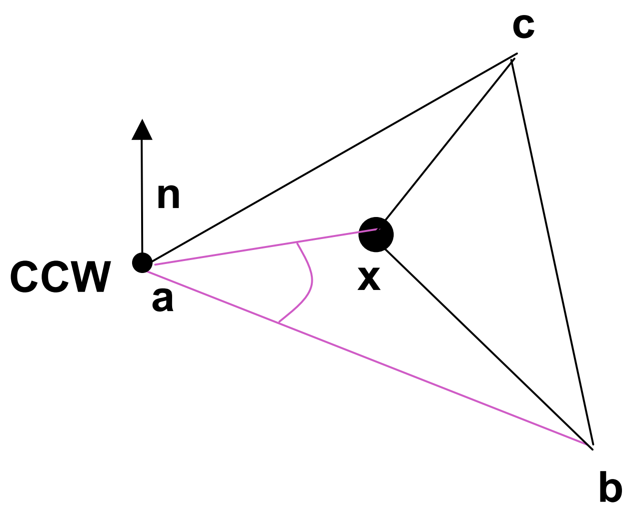
$$\frac{\mathbf{p} \cdot \mathbf{n}}{\mathbf{n}} = \mathbf{e} + t\mathbf{d} \Rightarrow t = -\frac{(\mathbf{e} - \mathbf{p}) \cdot \mathbf{n}}{\mathbf{d} \cdot \mathbf{n}}$$

$\mathbf{p}$ 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: $F(x,y,z) = x^2 + y^2 + z^2 - r^2$

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

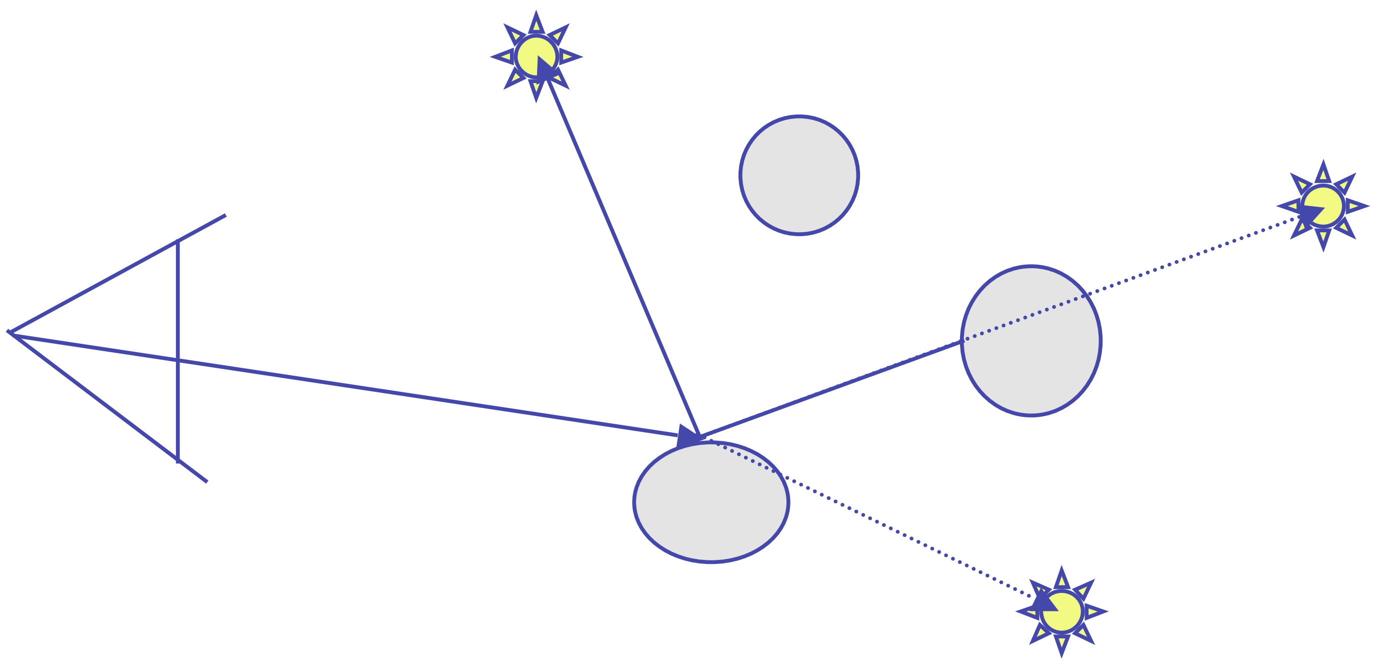
needs to be normalized!

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)

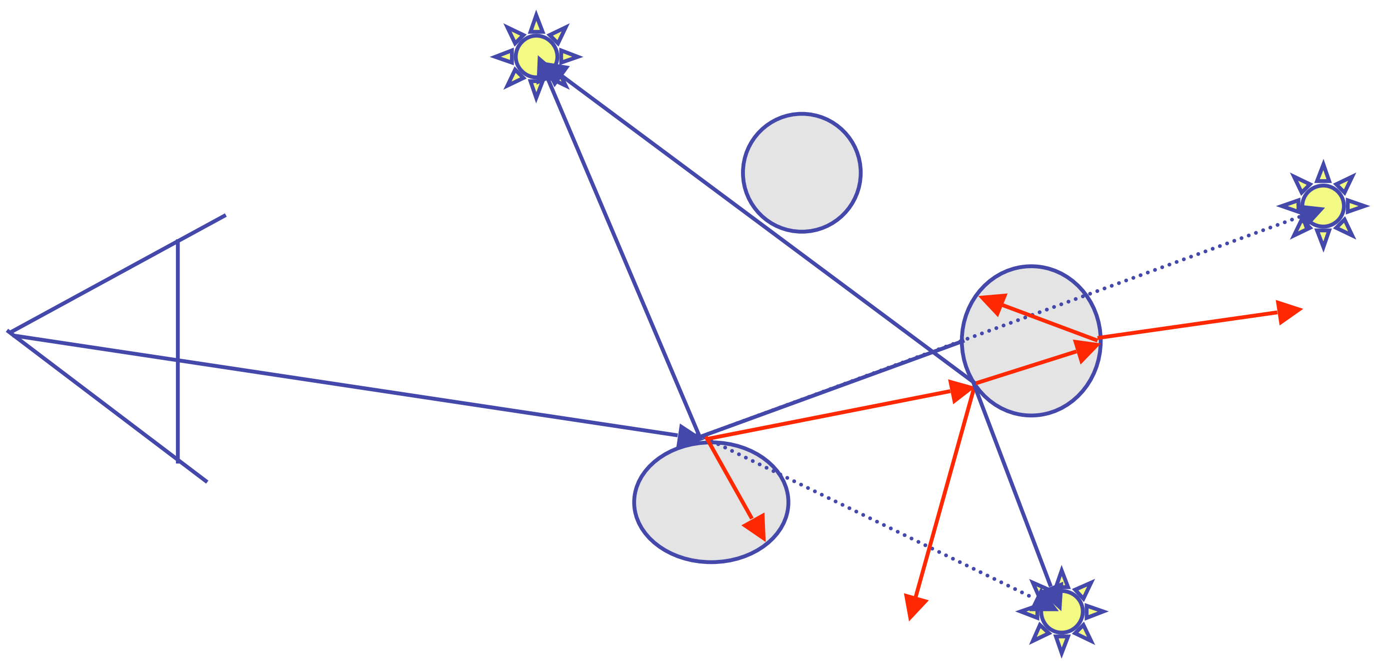
Global Shadows

- 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



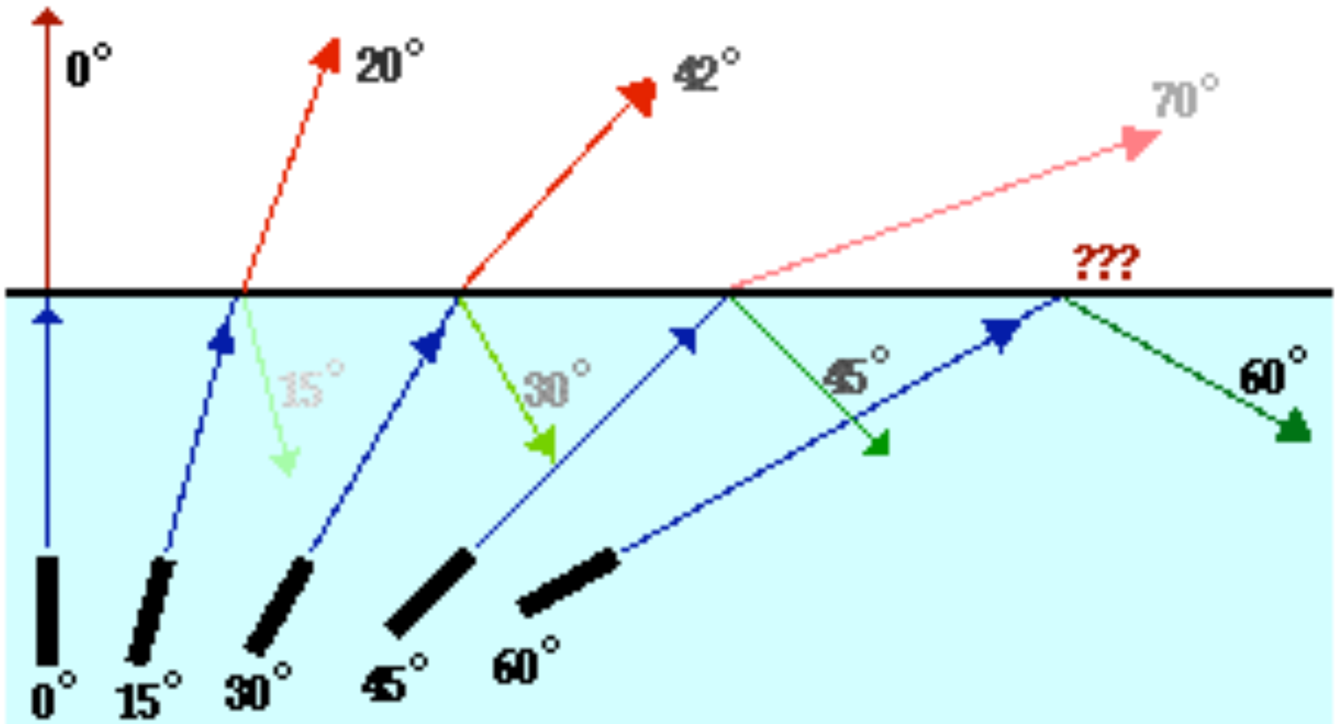
Global Reflections/Refractions

- 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.

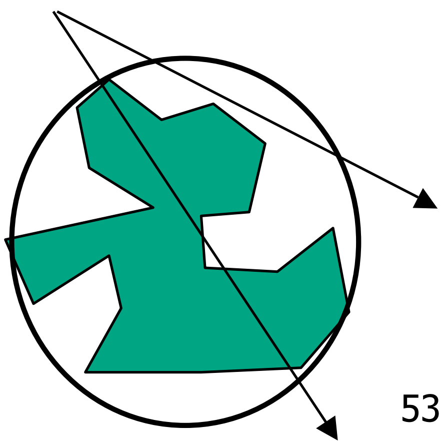
http://www.physicsclassroom.com/Class/refrn/U14L3b.html

Ray Tracing

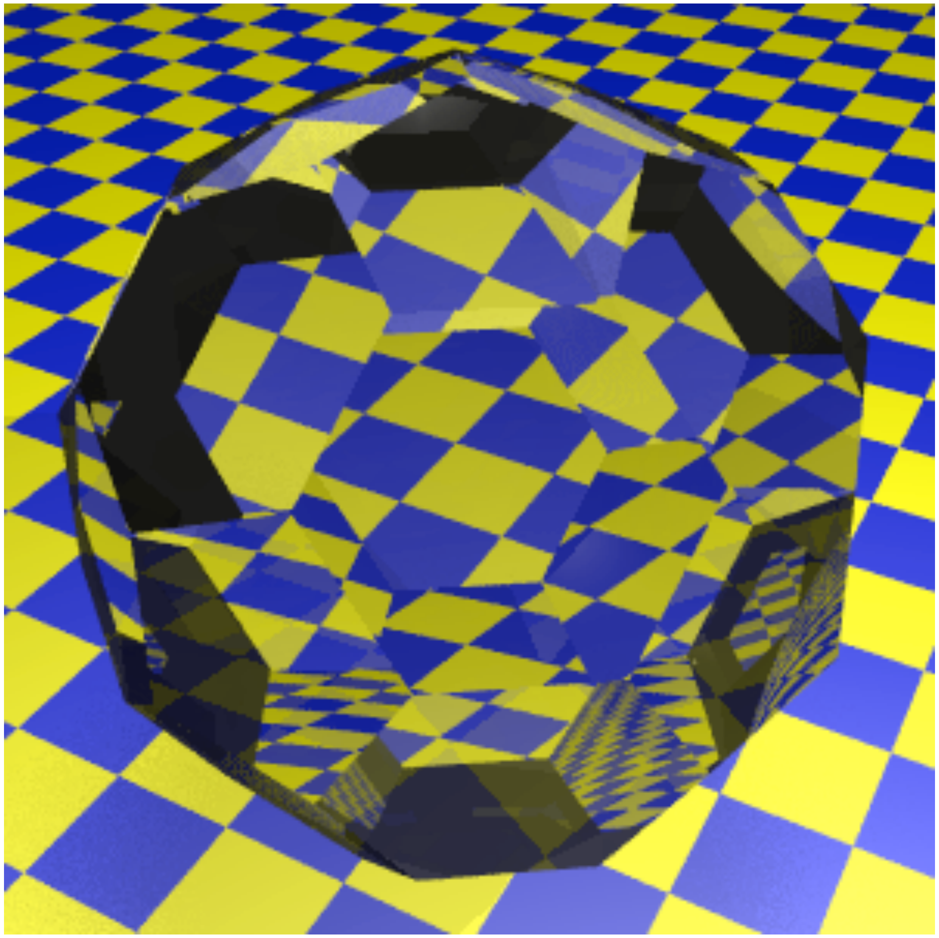
- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don’t have to test intersection with every object

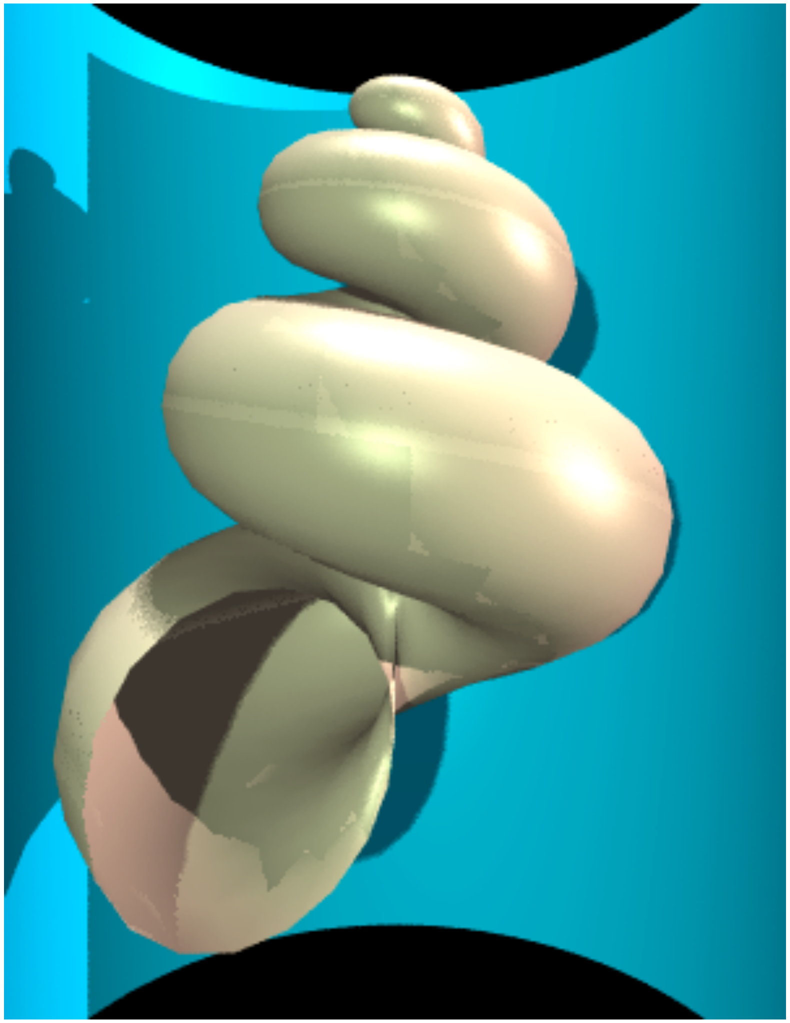
Optimized Ray-Tracing

- 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)



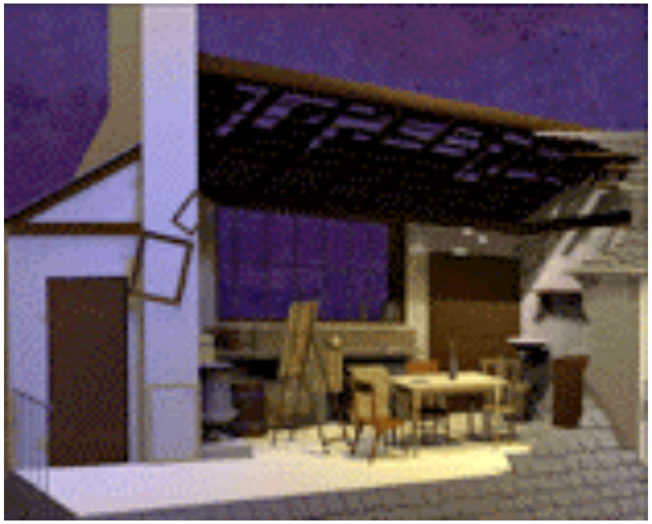
Example Images





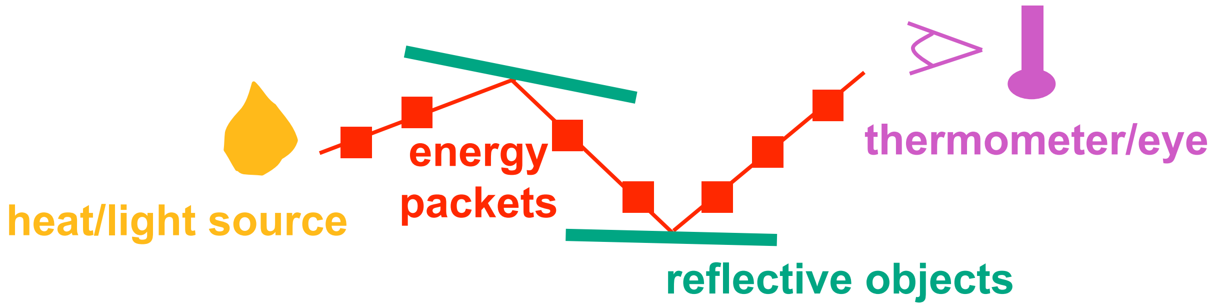
Radiosity

- 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

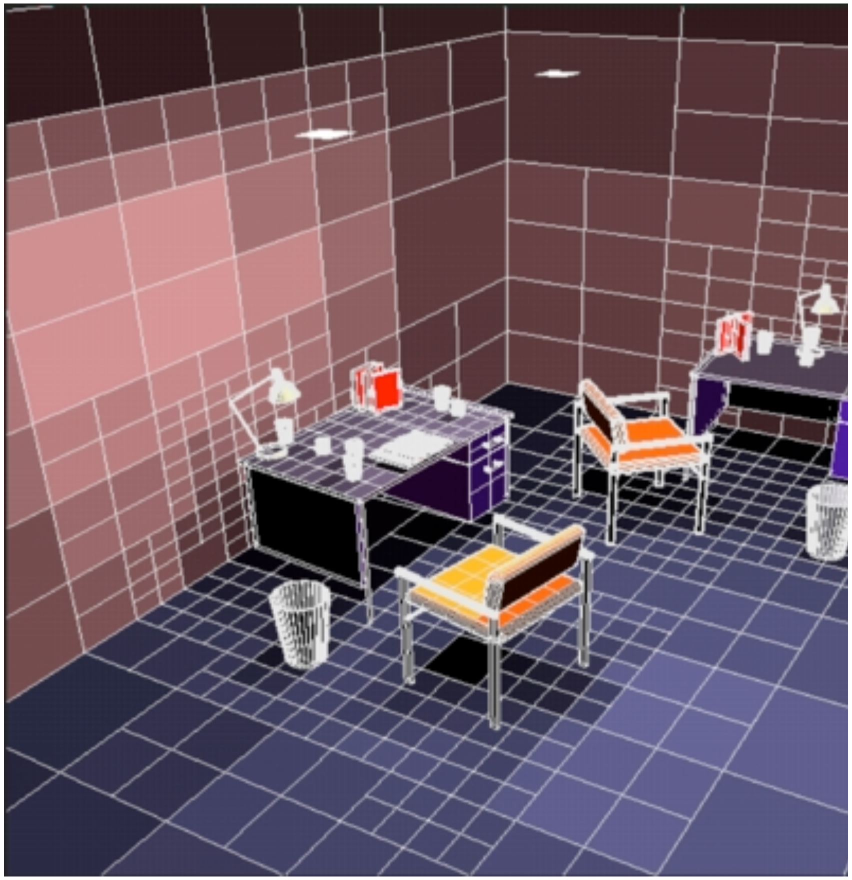


  - conserve light energy in a volume
  - model light transport as packet flow until convergence
  - solution captures diffuse-diffuse bouncing of light

- 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)



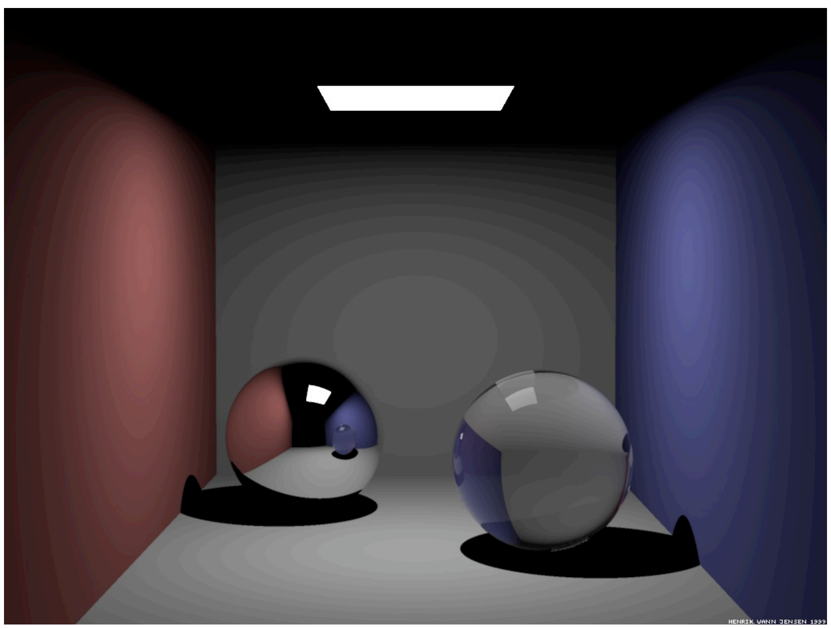
escience.anu.edu.au/lecture/cg/GlobalIllumination/Image/discrete.jpg

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

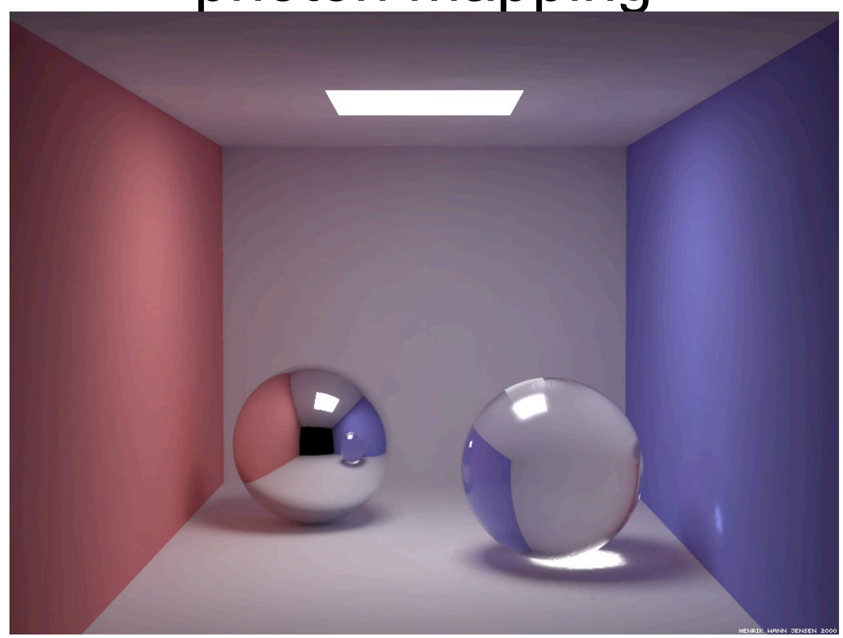
Better Global Illumination

- 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



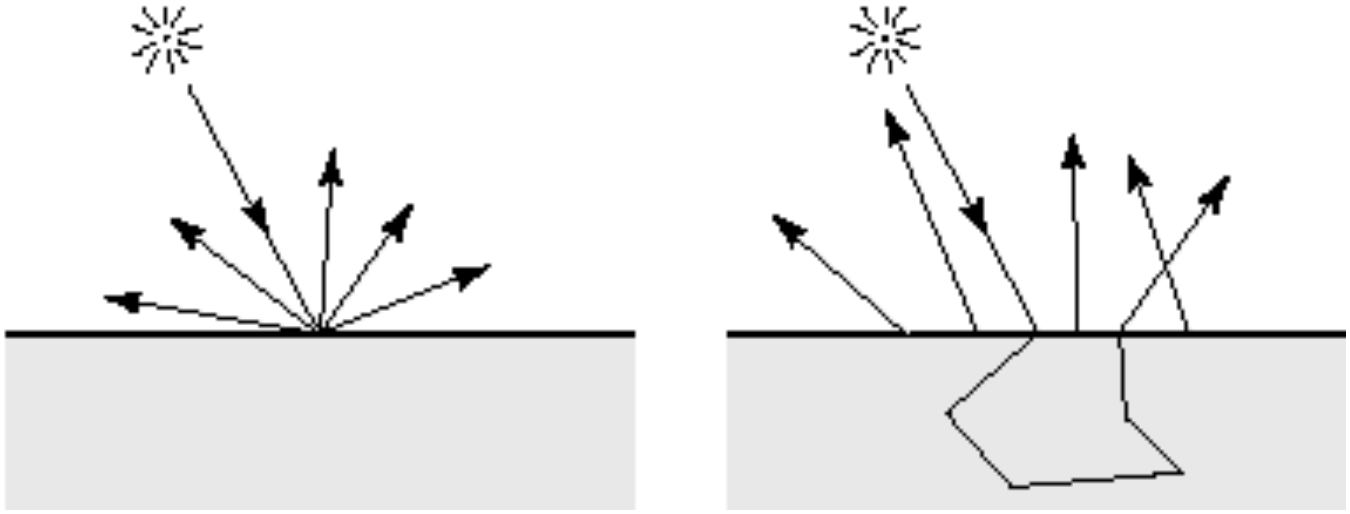
photon mapping



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

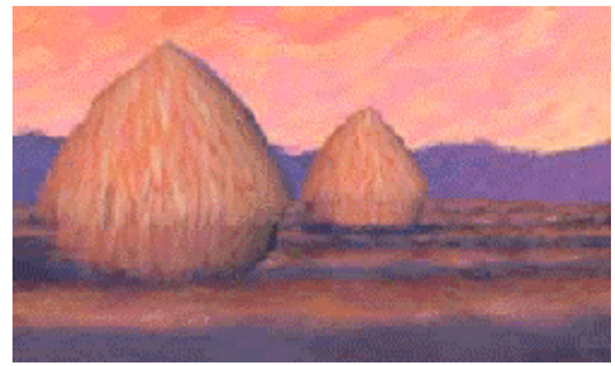
Subsurface Scattering: Skin

Subsurface Scattering: Skin

Non-Photorealistic Rendering

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





www.red3d.com/cwr/npr/