University of British Columbia
CPSC 314 Computer Graphics
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Advanced Rendering

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2013

Advanced Rendering

Reading for This Module

- FCG Sec 8.2.7 Shading Frequency
- FCG Chap 4 Ray Tracing
- FCG Sec 13.1 Transparency and Refraction

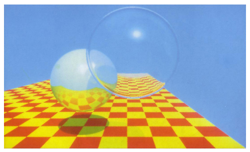
- Optional: FCG Chap 24 Global Illumination

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

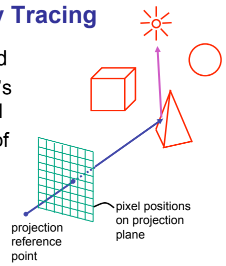
Ray Tracing

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



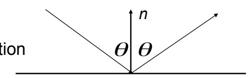
Simple Ray Tracing

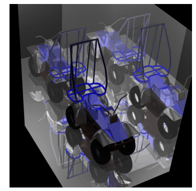
- view dependent method
  - cast a ray from viewer's eye through each pixel
  - compute intersection of ray with first object in scene
  - cast ray from intersection point on object to light sources

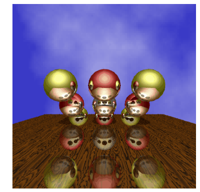


Reflection

- mirror effects
  - perfect specular reflection

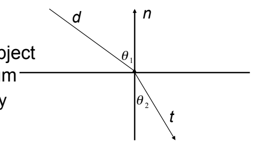


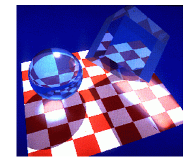




Refraction

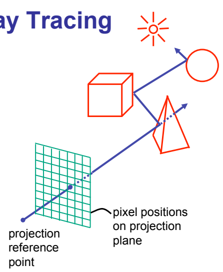
- happens at interface between transparent object and surrounding medium
  - e.g. glass/air boundary
- Snell's Law
  - $c_1 \sin\theta_1 = c_2 \sin\theta_2$
  - light ray bends based on refractive indices c_1, c_2





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
    }
}
```

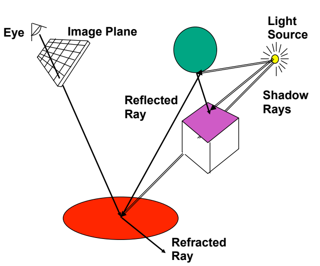

Basic Ray Tracing Algorithm

```
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

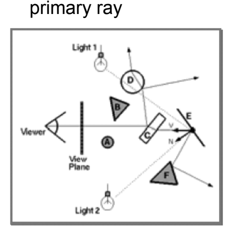


Ray-Tracing Terminology

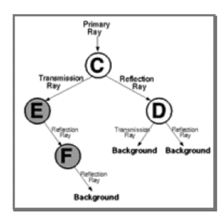
- terminology:
  - primary ray: ray starting at camera
  - shadow ray
  - reflected/refracted ray
  - ray tree: all rays directly or indirectly spawned off by a single primary ray
- note:
  - need to limit maximum depth of ray tree to ensure termination of ray-tracing process!

Ray Trees

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



Ray traced through scene



Ray tree

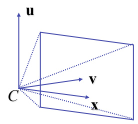
w.cs.virginia.edu/~gfx/Courses/2003/Intro.fall.03/slides/lighting_web/lighting.pdf

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

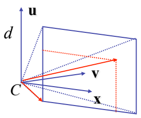
- camera coordinate system
  - origin: C (camera position)
  - viewing direction: **v**
  - up vector: **u**
  - x direction: **x**= **v** × **u**
- note:
  - corresponds to viewing transformation in rendering pipeline
  - like gluLookAt



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):*

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

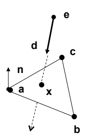
  - solve for *t* (find roots)
    - simple quadratic equation

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



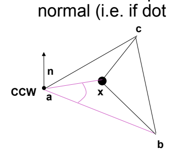
$$\text{normal}: \mathbf{n} = (\mathbf{b} - \mathbf{a}) \times (\mathbf{c} - \mathbf{a})$$
$$\text{ray}: \mathbf{x} = \mathbf{e} + t\mathbf{d}$$
$$\text{plane}: (\mathbf{p} - \mathbf{x}) \cdot \mathbf{n} = 0 \Rightarrow \mathbf{x} = \frac{\mathbf{p} \cdot \mathbf{n}}{\mathbf{n}}$$
$$\frac{\mathbf{p} \cdot \mathbf{n}}{\mathbf{n}} = \mathbf{e} + t\mathbf{d} \Rightarrow t = -\frac{(\mathbf{e} - \mathbf{p}) \cdot \mathbf{n}}{\mathbf{d} \cdot \mathbf{n}}$$

p is **a** or **b** or **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 inverse 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: $F(x,y,z) = x^2 + y^2 + z^2 - r^2$

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

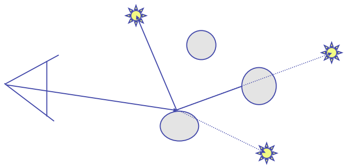
needs to be normalized!

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



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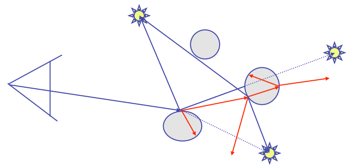
Global Reflections/Refractions

- 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



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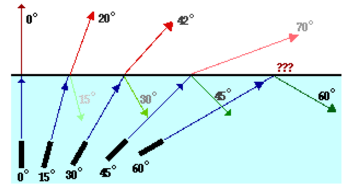
Total Internal Reflection

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

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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

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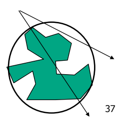
Optimized Ray-Tracing

- 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)



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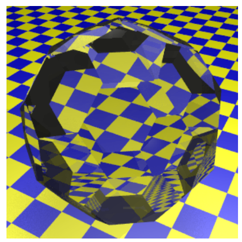
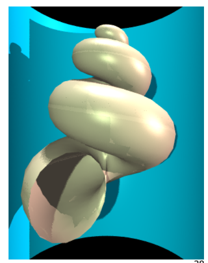
Example Images





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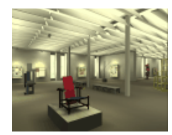
Radiosity

- 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



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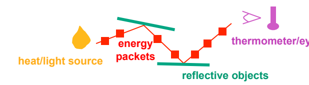
Radiosity

- 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

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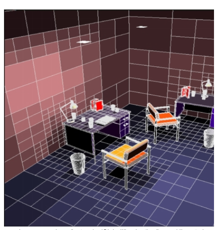
Radiosity

- 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

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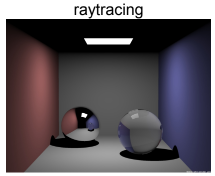
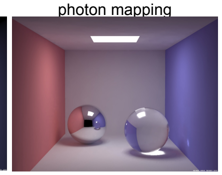
Better Global Illumination

- 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

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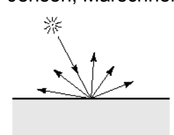
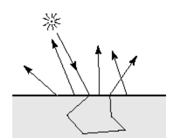
Subsurface Scattering: Translucency

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





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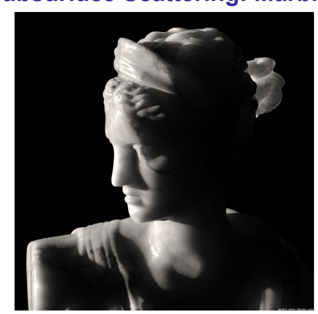
Subsurface Scattering: Marble



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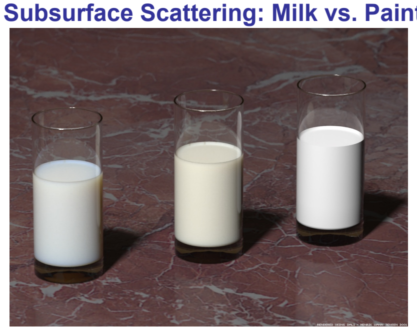
Subsurface Scattering: Milk vs. Paint



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Subsurface Scattering: Skin

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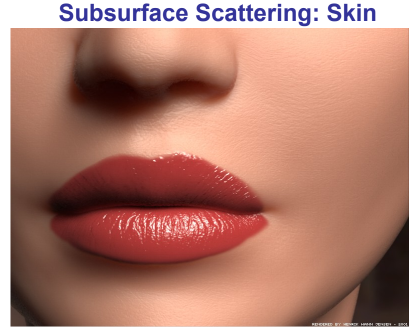
Subsurface Scattering: Skin



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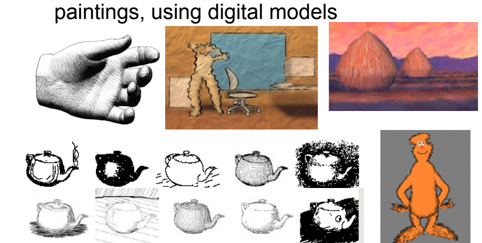
Non-Photorealistic Rendering

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



www.red3d.com/cwr/npr/

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