Computer Graphics

- Ray Tracing I -

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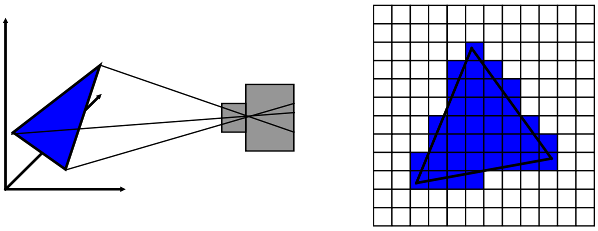
Overview

- **Last Lecture**
  - Introduction
- **Today**
  - Ray tracing I
    - Background
    - Basic ray tracing
    - What is possible?
    - Recursive ray tracing algorithm
- **Next lecture**
  - Ray tracing II: Spatial indices

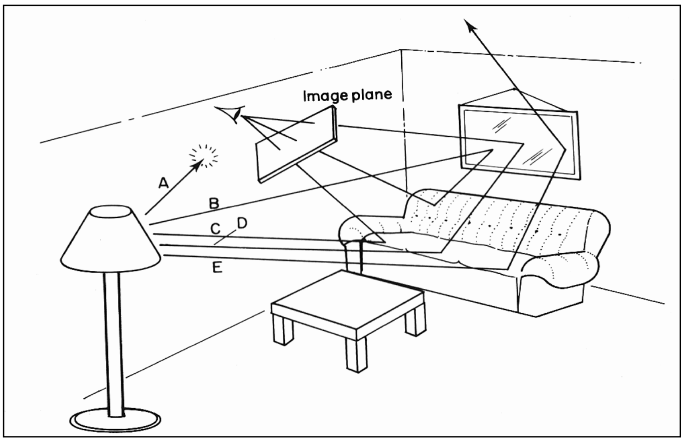
Current Graphics: Rasterization



- **Primitive operation of all interactive graphics !!**
  - Scan convert a single triangle at a time
- **Sequentially processes every triangle individually**
  - Can never access more than one triangle
  - ➔ But most effects need access to the world: shadows, reflection, global illumination

Tracing the Paths of Light

- **Nature:**
  - Follow the path of ***many*** photons
  - Record those hitting the film in a camera



Light Transport

- **Light Distribution in a Scene**
  - Dynamic equilibrium
  - Newly created, scattered, and absorbed photons
- **Forward Light Transport:**
  - Start at the light sources
  - Shoot photons into scene
  - Reflect at surfaces (according to some reflection model)
  - Wait until they are absorbed or hit the camera (very seldom)

  ➔ Nature: massive parallel processing at the speed of light
- **Backward Light Transport:**
  - Start at the camera
  - Trace only paths that transport light towards the camera

  ➔ Ray tracing

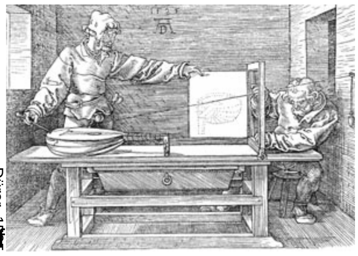
Ingredients

- **Surfaces**
  - 3D geometry of objects in a scene
- **Surface reflectance characteristics**
  - Color, absorption, reflection, refraction, subsurface scattering
  - Local property, may vary over surface
  - Mirror, glass, glossy, diffuse, …
- **Illumination**
  - Position, characteristics of light emitters
  - Repeatedly reflected light → indirect illumination

- **Assumption: air/empty space is totally transparent**
  - Excludes any scattering effects in participating media volumes
  - Would require solving a much more complex problem

  ➔ Volume rendering, participating media

Ray Tracing



Dürer, 1525

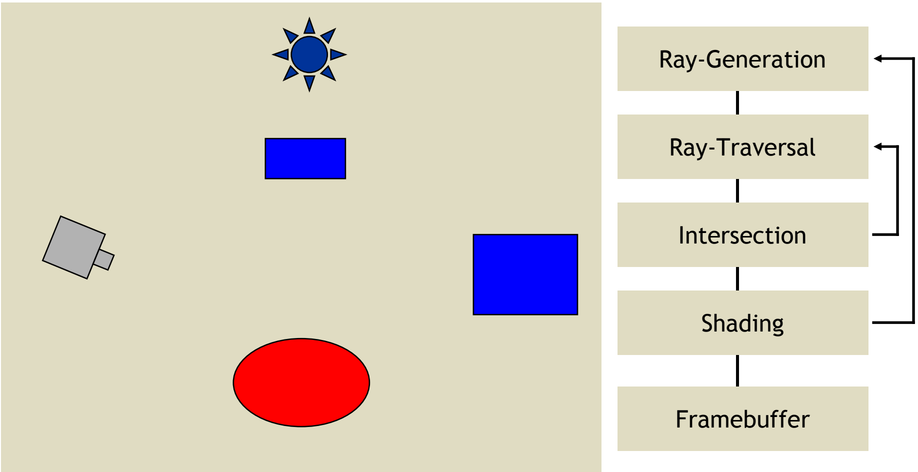
- **The Ray Tracing Algorithm**
  - One of the two fundamental rendering algorithms
- **Simple and intuitive**
  - Easy to understand and implement
- **Powerful and efficient**
  - Many optical global effects: shadows, re
  - Efficient real-time implementation in SW and HW
- **Scalability**
  - Can work in parallel and distributed environments
  - Logarithmic scalability with scene size: O(log n) vs. O(n)
  - Output sensitive and demand driven
- **Not new**
  - Light rays: Empedocles (492-432 BC), Renaissance (Dürer, 1525)
  - Uses in lens design, geometric optics, …

Ray Tracing

- **Highly Realistic Images**
  - Ray tracing enables *correct* simulation of light transport

Internet Ray Tracing Competition, June 2002

Ray Tracing Pipeline



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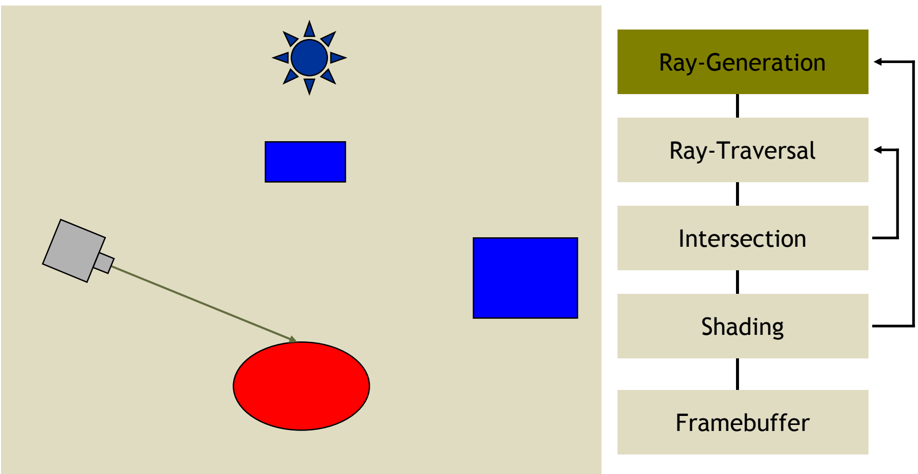

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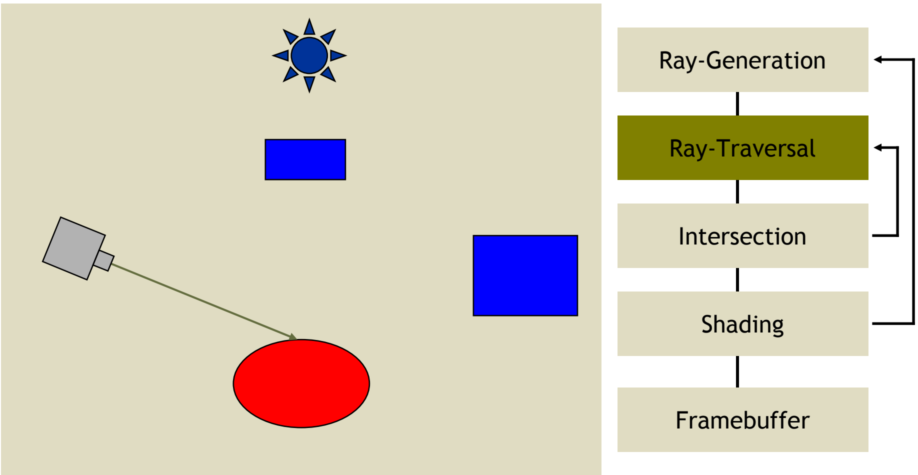

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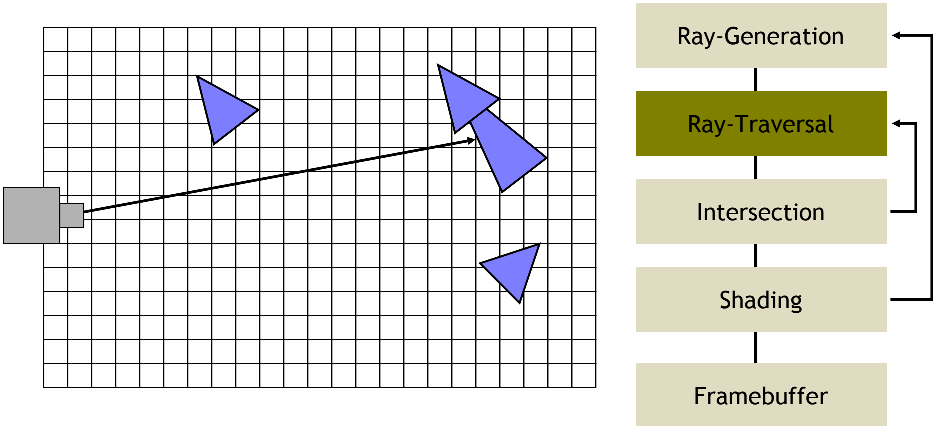

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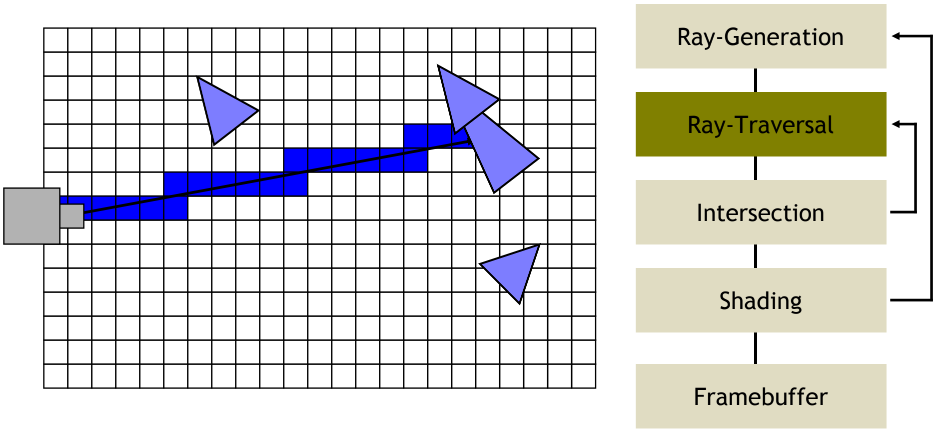

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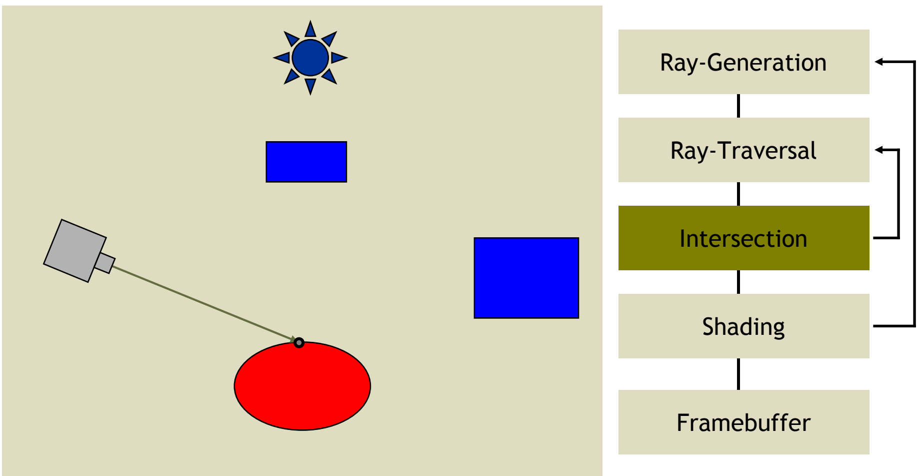

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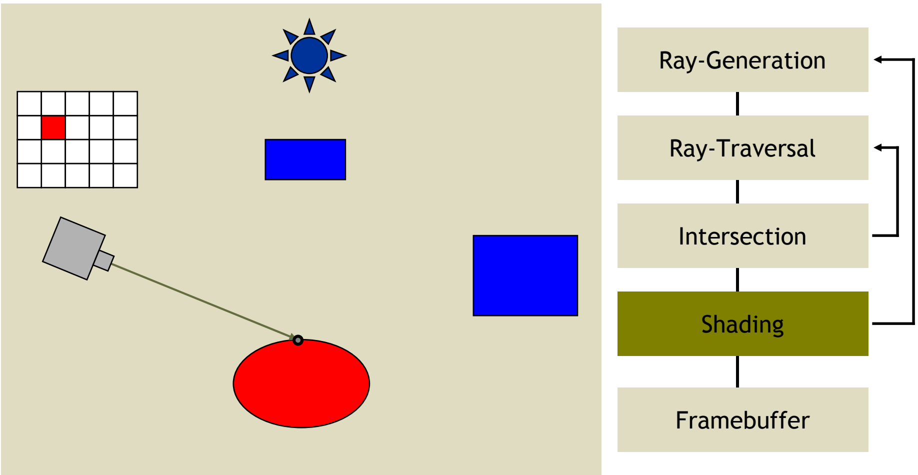
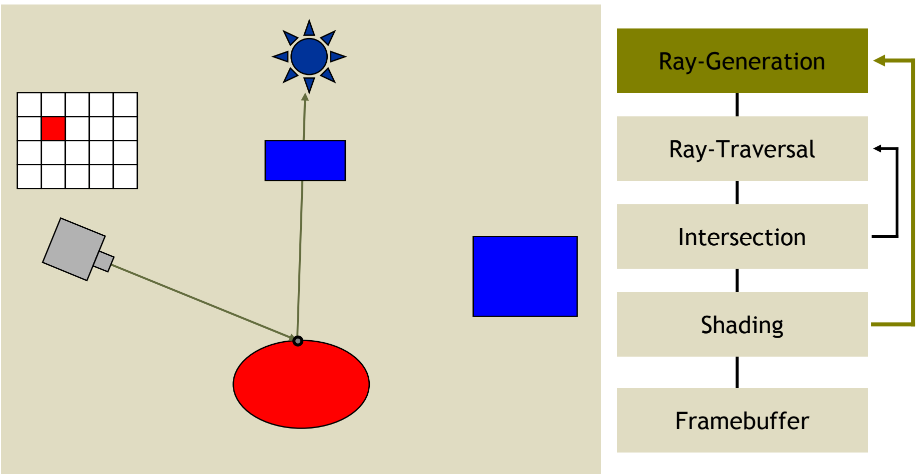
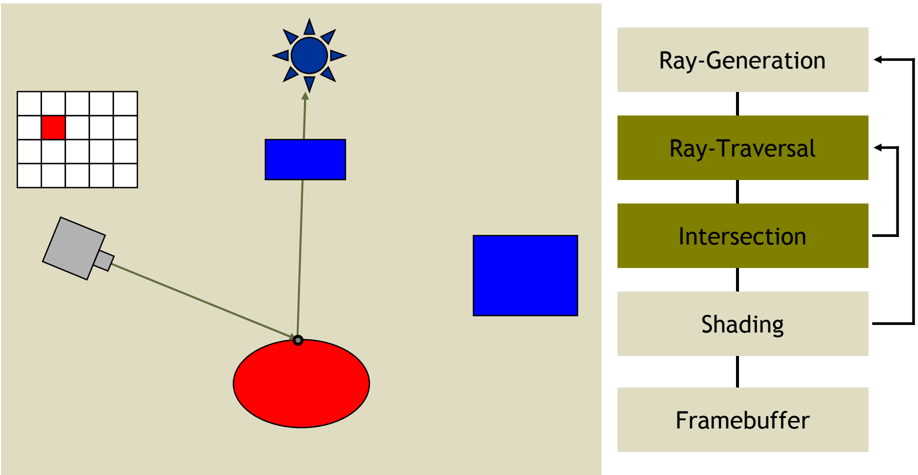


Ray Tracing Pipeline



Ray Tracing Pipeline



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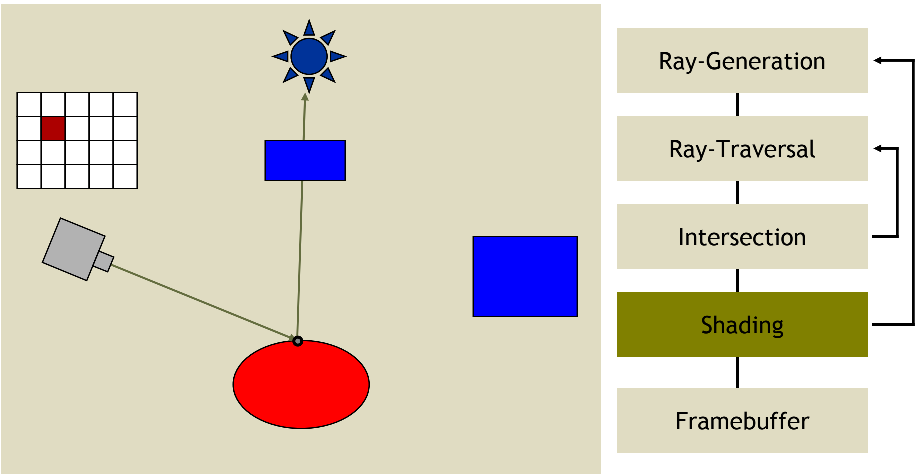

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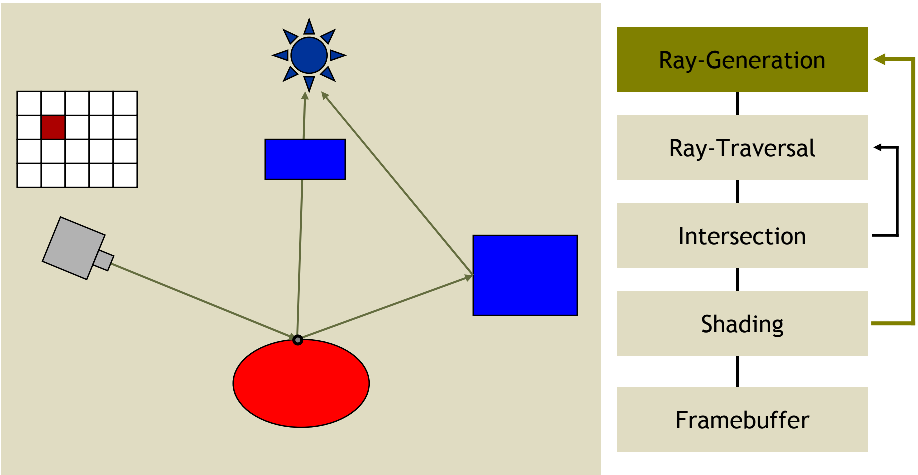

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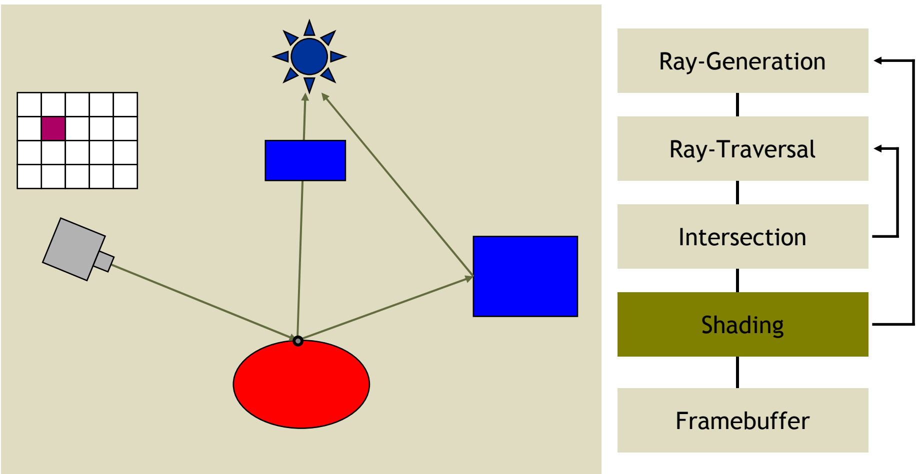

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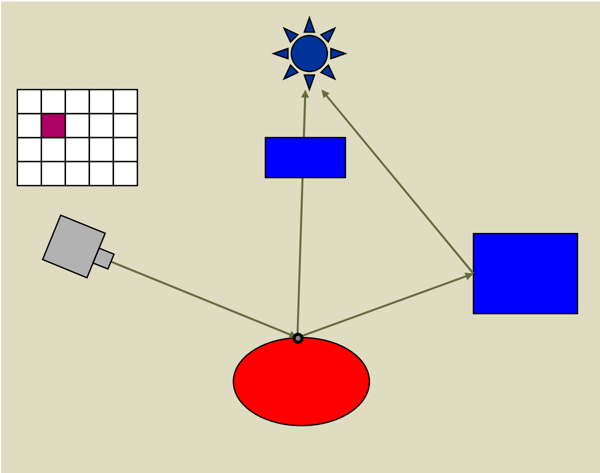
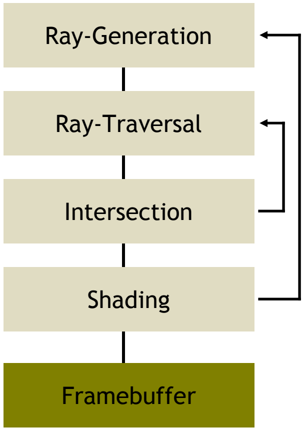
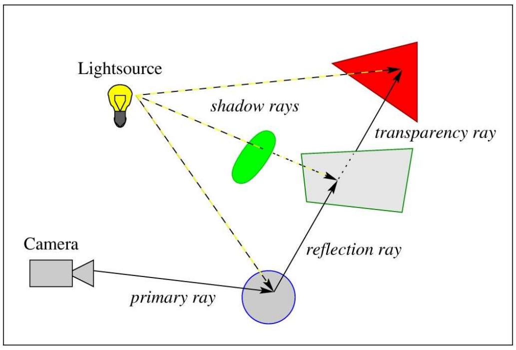




Ray Tracing



- Global effects
- Parallel (as nature)
- Fully automatic
- Demand driven
- Per pixel operations
- Highly efficient

➔ Fundamental Technology for Next Generation Graphics

Ray Tracing

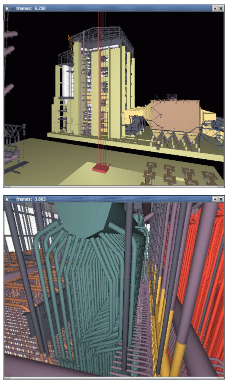
- **In the Past**
  - Only used as an off-line technique
  - Was computationally far too demanding
  - Rendering times of minutes and hours
- **Recently**
  - Interactive ray tracing on supercomputers [Parker, U. Utah‘98]
  - Interactive ray tracing on PCs [Wald‘01]
  - Distributed ray tracing on PC clusters [Wald’01]
- **OpenRT-System (www.openrt.de)**
  - Demo later today

What is Possible?

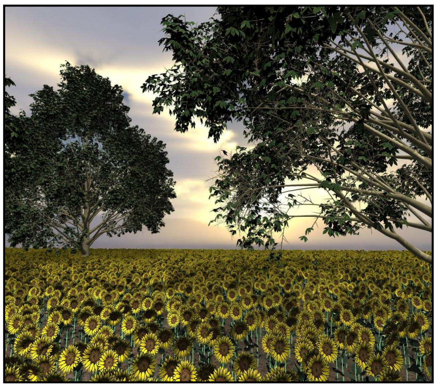
- **Models Physics of Global Light Transport**
  - Dependable, physically-correct visualization


What is Possible?

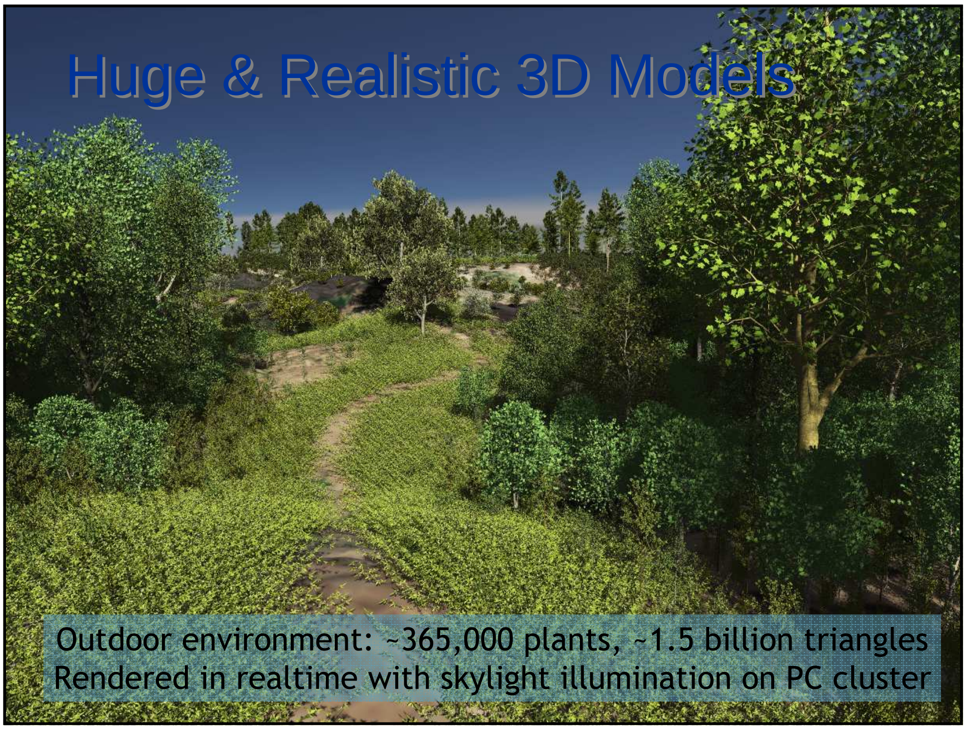
- **Huge Models**
  - Logarithmic scaling in scene size



12.5 Million Triangles



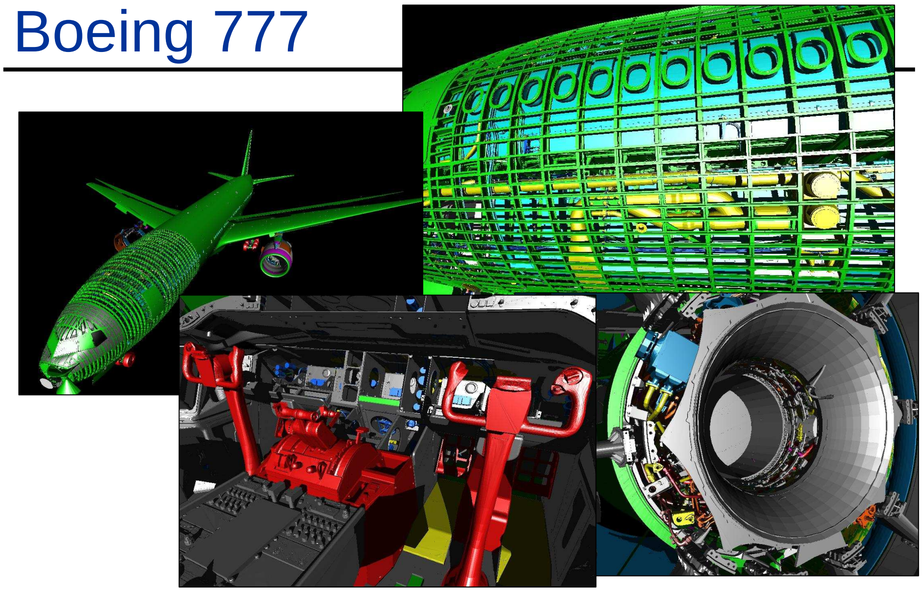
~1 Billion Triangles



Huge & Realistic 3D Models

Outdoor environment: ~365,000 plants, ~1.5 billion triangles
Rendered in realtime with skylight illumination on PC cluster

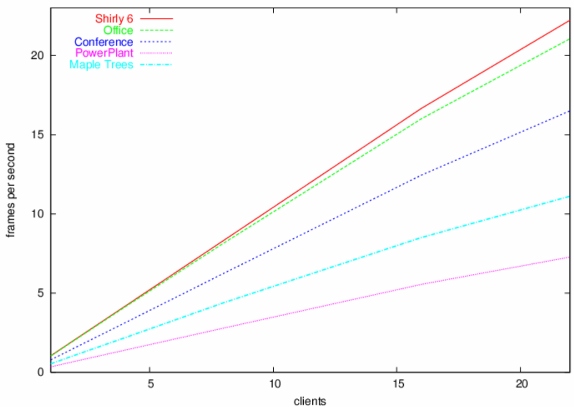
Boeing 777



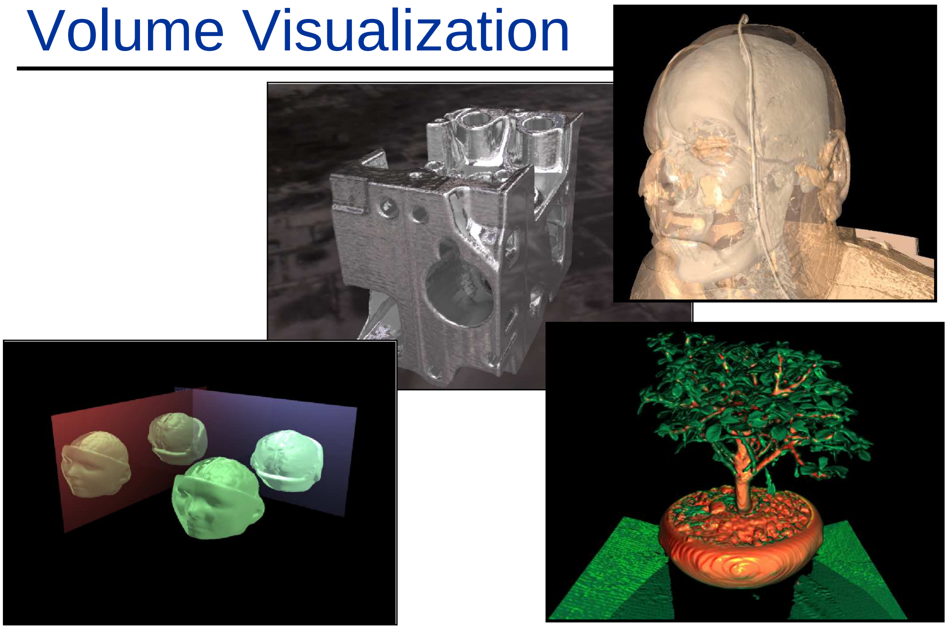
Boeing 777: ~350 million individual polygons, ~30 GB on disk

What is Possible?

- **Highly Scalable**
  - Output sensitivity with build-in occlusion culling
  - Linear in number of pixels, rays, and processors

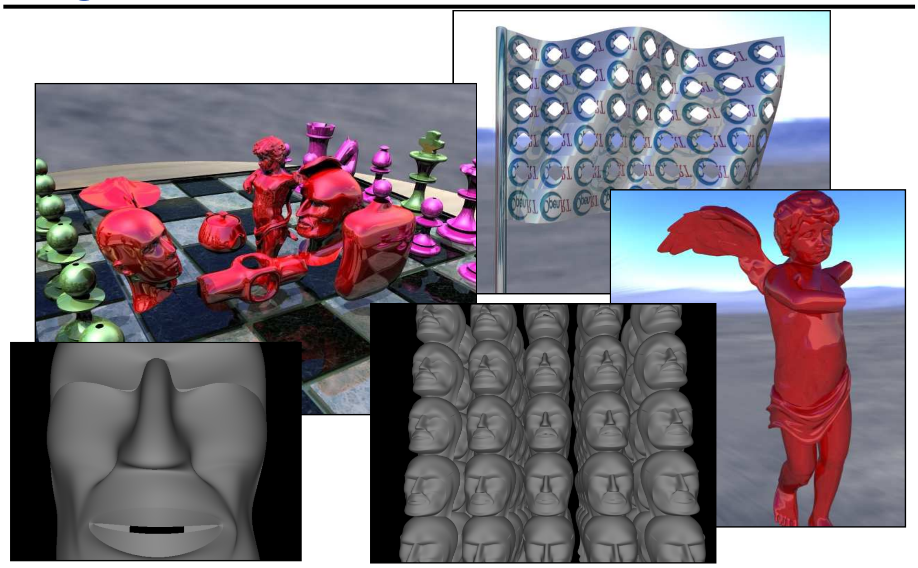


Volume Visualization



Iso-Surface Volume Rendering

Higher Order Surfaces

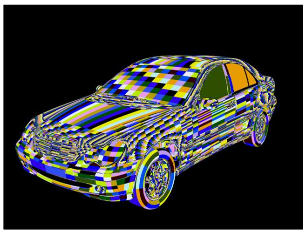


Splines & Subdivision Surfaces: little memory, constant fps

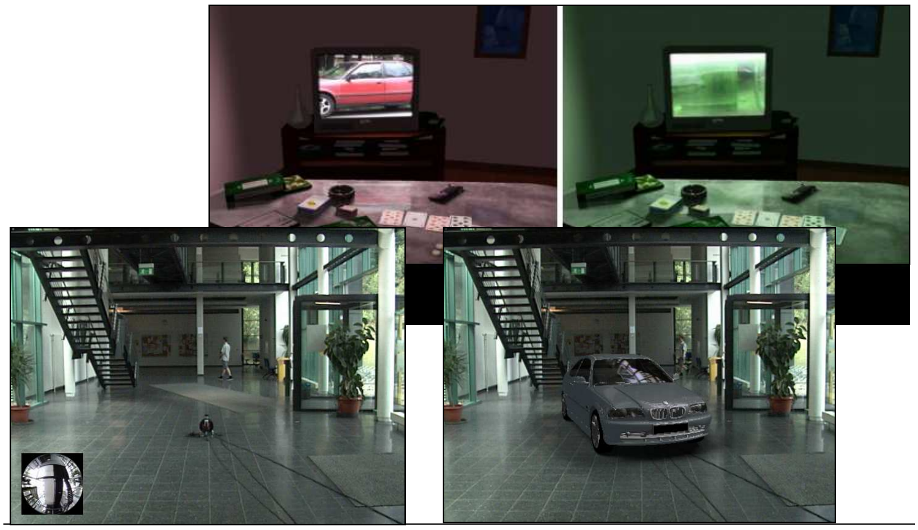
Measured Materials

Data Courtesy R. Klein, Uni Bonn

Realistic Visualization: CAD



Realistic Visualization: VR/AR



Games?

Games?

Realtime Lighting Simulation

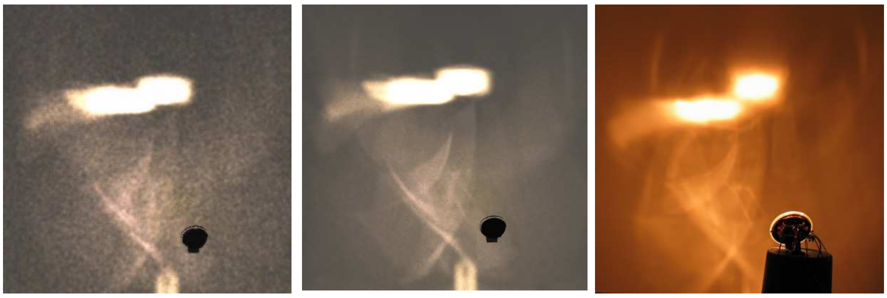
Lighting Simulation

- **Complex Scattering**
- **Highly accurate Results**

250k / 3 fps

25M / 11 fps

Photograph



Fundamental Ray Tracing Steps

- **Generation of primary rays**
  - Rays from viewpoint along viewing directions into 3D scene
  - (At least) one ray per picture element (pixel)
- **Ray tracing**
  - Traversal of spatial index structures
  - Intersection of ray with scene geometry
- **Shading**
  - From intersection, determine “light color” sent along primary ray
  - Determines “pixel color”
  - Needed
    - Local material color and reflection properties
      - Object texture
    - Local illumination of intersection point
      - Can be hard to determine correctly

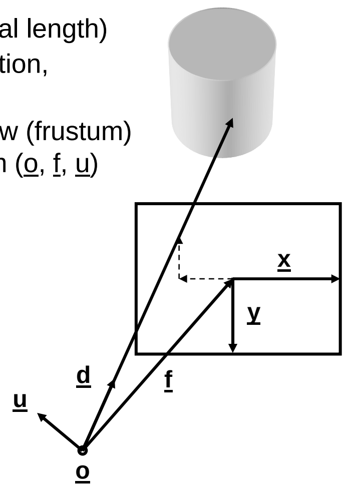
Ray and Object Representations

- **Ray in space: $\underline{\mathbf{r}}(t)=\underline{\mathbf{o}}+t\,\underline{\mathbf{d}}$**
  - $\underline{\mathbf{o}}=(o_x, o_y, o_z)$
  - $\underline{\mathbf{d}}=(d_x, d_y, d_z)$
- **Scene geometry**
  - Sphere: $(\underline{p}-\underline{c})\cdot(\underline{p}-\underline{c})-r^2=0$
    - $\underline{\mathbf{c}}$: sphere center
    - r : sphere radius
    - $\underline{\mathbf{p}}$: any surface point
  - Plane: $(\underline{p}-\underline{a})\cdot\underline{n}=0$
    - Implicit definition
    - $\underline{\mathbf{n}}$: surface normal
    - $\underline{\mathbf{a}}$: one given surface point
    - $\underline{\mathbf{p}}$: any surface point
  - Triangles: Plane intersection plus barycentric coordinates

Perspective Camera Model

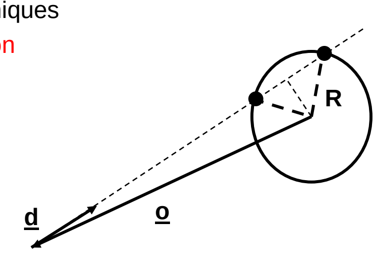
- **Definition of the pinhole camera**
  - $\underline{o}$: Origin (point of view)
  - $\underline{f}$: Vector to center of view (focal length)
  - $\underline{u}$: Up-vector of camera orientation, in one plane with $\underline{y}$ vector
  - $\underline{x}$, $\underline{y}$: Span half the viewing window (frustum) relative to coordinate system ($\underline{o}$, $\underline{f}$, $\underline{u}$)
  - xres, yres: Image resolution

```
for (x= 0; x < xres; x++)
  for (y= 0; y < yres; y++)
  {
    d= f + 2(x/xres - 0.5)·x
         + 2(y/yres - 0.5)·y;
    d= d/|d|; // Normalize
    col= trace(o, d);
    write_pixel(x,y,col);
  }
```



Intersection Ray – Sphere

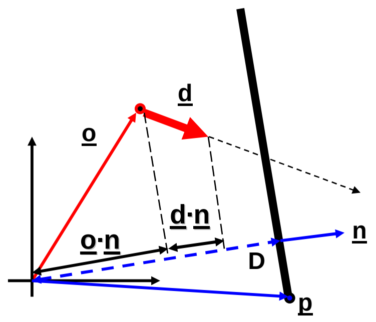
- **Sphere**
  - Given a sphere at the origin
    $x^2 + y^2 + z^2 - 1 = 0$
  - Given a ray
    $\underline{r} = \underline{o} + t\underline{d}$ ($r_x = o_x + td_x$ and so on)
    $\underline{o}$: origin, $\underline{d}$: direction
  - Substituting the ray into the equation for the sphere gives
    $t^2(d_x^2 + d_y^2 + d_z^2) + 2t\,(d_x o_x + d_y o_y + d_z o_z) + (o_x^2 + o_y^2 + o_z^2) - 1 = 0$
    - Easily solvable with standard techniques
    - But beware of numerical imprecision
  - Alternative: Geometric construction
    - Ray and center span a plane
    - Simple 2D construction



Intersection Ray – Plane

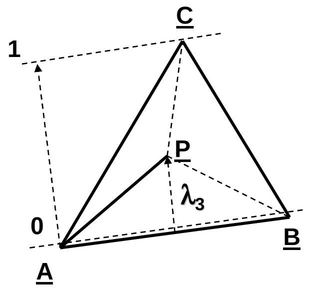
- **Plane: Implicit representation (Hesse form)**
  - Plane equation: $\underline{p}\cdot\underline{n} - D = 0$, $|\underline{n}| = 1$
    - $\underline{n}$: Normal vector:
    - D: Normal distance of plane from (0, 0, 0):
- **Two possible approaches**
  - Geometric
  - Mathematic
    - Substitute $\underline{o} + t\underline{d}$ for p
    - $(\underline{o} + t\underline{d})\cdot\underline{n} - D = 0$
    - Solving for t gives

$$t = \frac{D - \underline{o}\cdot\underline{n}}{\underline{d}\cdot\underline{n}}$$



Intersection Ray – Triangle

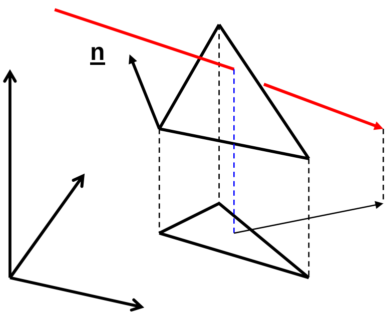
- **Barycentric coordinates**
  - Non-degenerate triangle ABC
  - Every point P in the plane can be described using
    $\underline{P} = \lambda_1 \underline{A} + \lambda_2 \underline{B} + \lambda_3 \underline{C}$
  - $\lambda_1 + \lambda_2 + \lambda_3 = 1$
    - Interpretation of barycentric coordinates
      $\lambda_3 = \angle(APB) / \angle(ACB)$ etc
  - For fixed λ_3, $\underline{P}$ may move parallel to AB
  - For $\lambda_1 + \lambda_2 = 1$
    $\underline{P} = (1-\lambda_3)(\lambda_1 \underline{A} + \lambda_2 \underline{B}) + \lambda_3 \underline{C}$ $(0 < \lambda_3 < 1)$
    - $\underline{P}$ moves between $\underline{C}$ and AB



- **Point is in triangle, iff all λ_i greater or equal than zero**

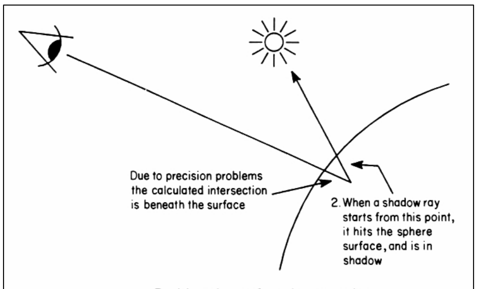
Intersection Ray – Triangle (2)

- **Compute intersection with triangle plane**
- **Given the 3D intersection point**
  - Project point into xy, xz, yz coordinate plane
  - Use coordinate plane that is most aligned
    - xy: if n_z is maximal, etc.
  - Coordinate plane and 2D vertices can be pre-computed
- **Compute barycentric coordinates**
- **Test for positive BCs**



Precision Problems

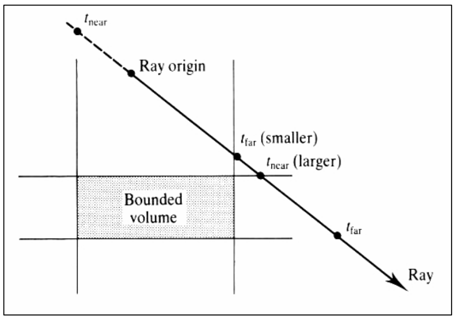
Inaccuracies of the intersection points computations due to floating-point arithmetic can result in incorrect shadow rays (self-shadowing) or infinite loops for secondary rays which have origins at a previously found intersection point. A simple solution is to check if the value of parameter *t* (used for intersection point calculations) is within some tolerance. For example, if *abs(t) < 0.00001*, then that *t* describes the origin of some ray as being on the object. The tolerance should be scaled to the size of the environment.

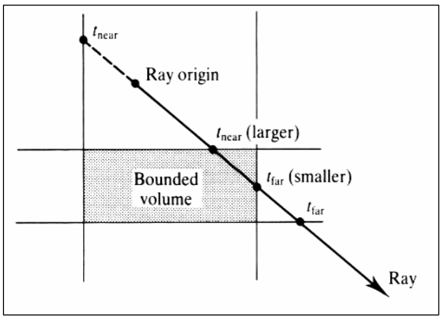


Problem in surface intersection.

Intersection Ray- Box

Ray/box intersections are important because boxes are used as bounding volumes, especially in hierarchical schemes. To check if a ray intersects a box, we treat each pair of parallel planes in turn, calculating the distance along the ray to the first plane t_{near} and the second plane t_{far}. If the value of t_{near} for one pair of planes is greater than t_{far} for another pair of planes, the ray cannot intersect the box.





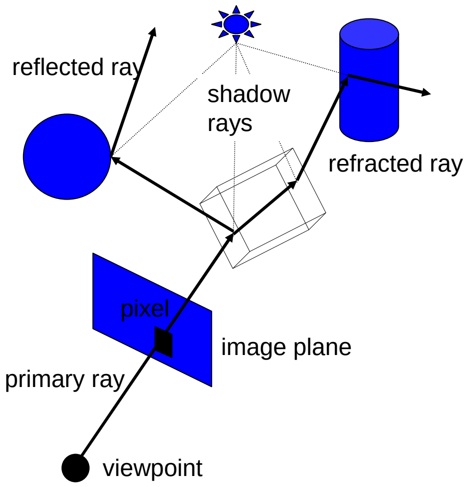
History of Intersection Algorithms

- **Ray-geometry intersection algorithms**
  - Polygons: [Appel ’68]
  - Quadrics, CSG: [Goldstein & Nagel ’71]
  - Recursive Ray Tracing: [Whitted ’79]
  - Tori: [Roth ’82]
  - Bicubic patches: [Whitted ’80, Kajiya ’82]
  - Algebraic surfaces: [Hanrahan ’82]
  - Swept surfaces: [Kajiya ’83, van Wijk ’84]
  - Fractals: [Kajiya ’83]
  - Deformations: [Barr ’86]
  - NURBS: [Stürzlinger ’98]
  - Subdivision surfaces: [Kobbelt et al ’98]

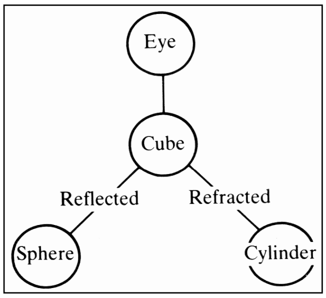
Shading

- **Intersection point determines primary ray’s “color”**
- **Diffuse object: color at intersection point**
  - No variation with viewing angle: diffuse (Lambertian)
  - Must still be illuminated
    - Point light source: shadow ray
    - Scales linearly with received light (Irradiance)
    - No illumination: in shadow = black
- **Non-Lambertian Reflectance**
  - Appearance depends on illumination *and* viewing direction
    - Local Bi-directional Reflectance Distribution Function (BRDF)
  - Simple cases
    - Mirror, glass: secondary rays
- **Area light sources, indirect illumination can be difficult**

Recursive Ray Tracing



- **Searching recursively for paths to light sources**
  - Interaction of light & material at intersection points
  - Recursively trace new rays in reflection, refraction, and light direction



Ray Tracing Algorithm

- **Trace(ray)**
  - Search the next intersection point ➔ (hit, material)
  - Return Shade(ray, hit, material)
- **Shade(ray, hit, material)**
  - For each light source
    - if ShadowTrace(ray to light source, distance to light)
      - Calculate reflected radiance (i.e. Phong)
      - Adding to the reflected radiance
  - If mirroring material
    - Calculate radiance in reflected direction: Trace(R(ray, hit))
    - Adding mirroring part to the reflected radiance
  - Same for transmission
  - Return reflected radiance
- **ShadowTrace(ray, dist)**
  - Return false, if intersection point with distance < dist has been found

Ray Tracing

- **Incorporates into a single framework**
  - Hidden surface removal
    - Front to back traversal
    - Early termination once first hit point is found
  - Shadow computation
    - Shadow rays/ shadow feelers are traced between a point on a surface and a light sources
  - Exact simulation of some light paths
    - Reflection (reflected rays at a mirror surface)
    - Refraction (refracted rays at a transparent surface, Snell's law)
- **Limitations**
  - Easily gets inefficient for full global illumination computations
    - Many reflections (exponential increase in number of rays)
    - Indirect illumination requires many rays to sample all incoming directions

Ray Tracing: Approximations

- **Usually RGB color model instead of full spectrum**
- **Finite number of point lights instead of full indirect light**
- **Approximate material reflectance properties**
  - Ambient: constant, non-directional background light
  - Diffuse: light reflected uniformly in all directions,
  - Specular: perfect reflection, refraction
- **All are based on purely empirical foundation**

Computer Graphics WS05/06 – Ray Tracing I

Wrap-Up

- **Background**
  - Forward light transport vs. backward search in RT
- **Ray tracer**
  - Ray generation, ray-object intersection, shading
- **Ray-geometry intersection calculation**
  - Sphere, plane, triangle, box
- **Recursive ray tracing algorithm**
  - Primary, secondary, shadow rays

- **Next lecture**
  - Advanced acceleration techniques