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DH2323 DGI16

COMPUTER GRAPHICS AND INTERACTION

INTRODUCTION TO

RAYTRACING

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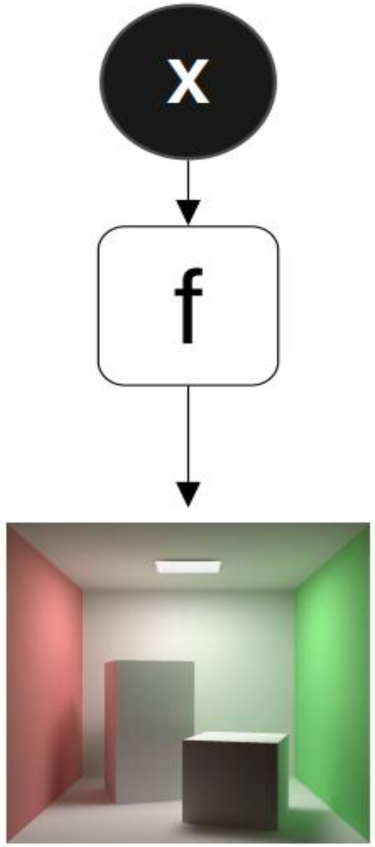
Image Synthesis

In computer graphics, create images based on a *model*

Recall:

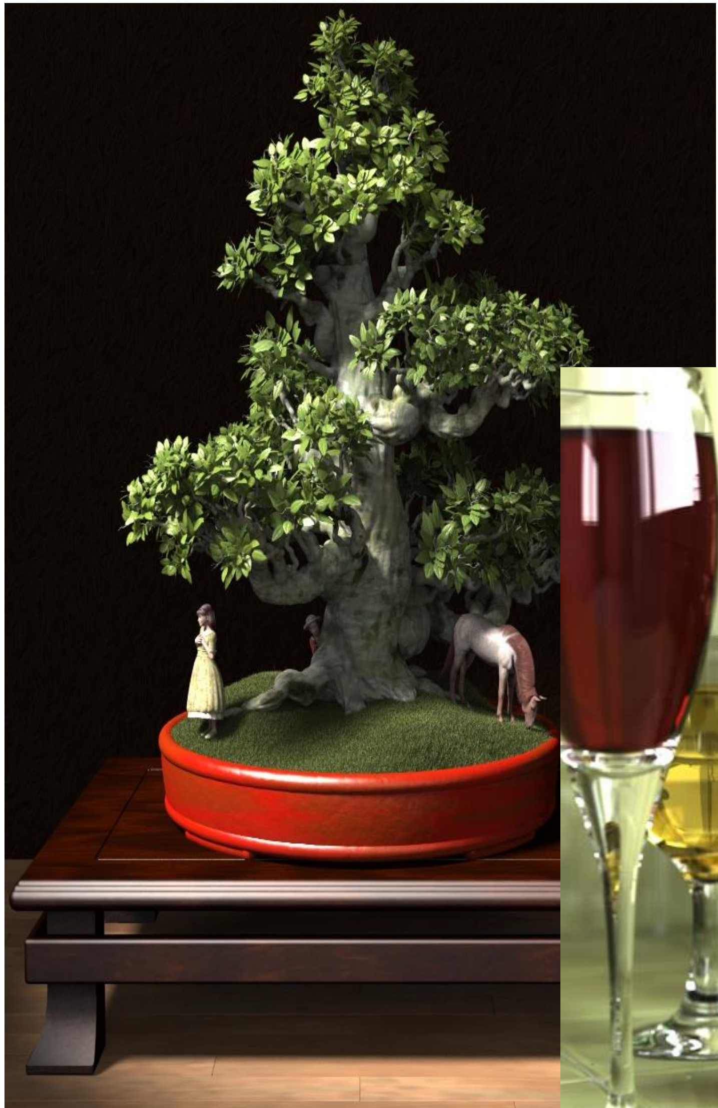
An underlying process generates observations

Can control generation through parameters



Nice Results

"Pebbles" by Jonathan Hunt



"Bonsai Life" by Jeremy M. Praay

"Glasses" by Gilles Tran

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Nice Results

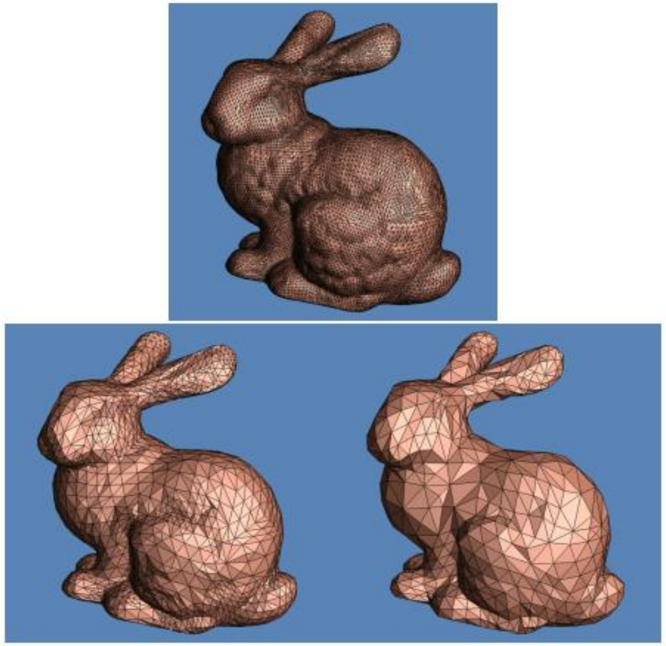
"Distant Shores" by Christoph Gerber

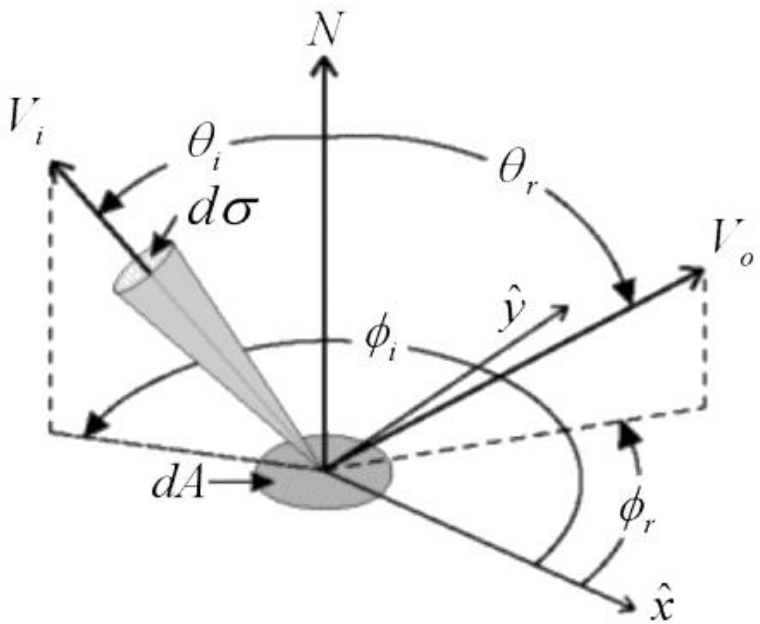
"Christmas Baubles" by Jaime Vives Piqueres

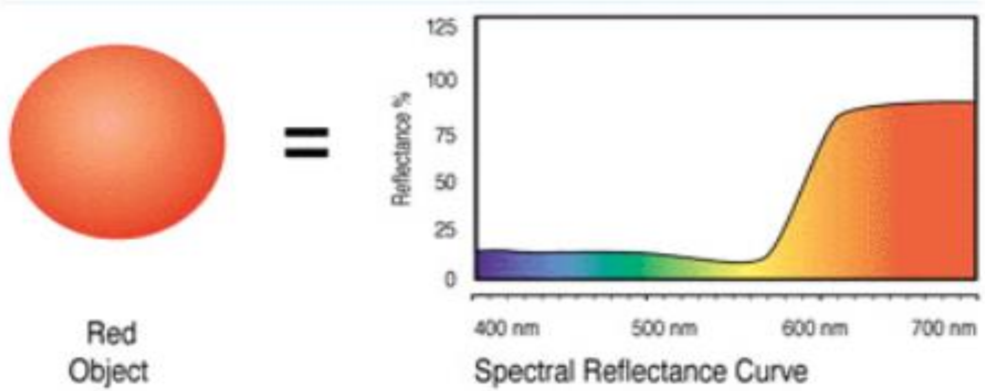
"Still with Bolts" by Jaime Vives Piqueres

Some Constituents I

- Light
- Geometry
- Surface properties
- Anything else?

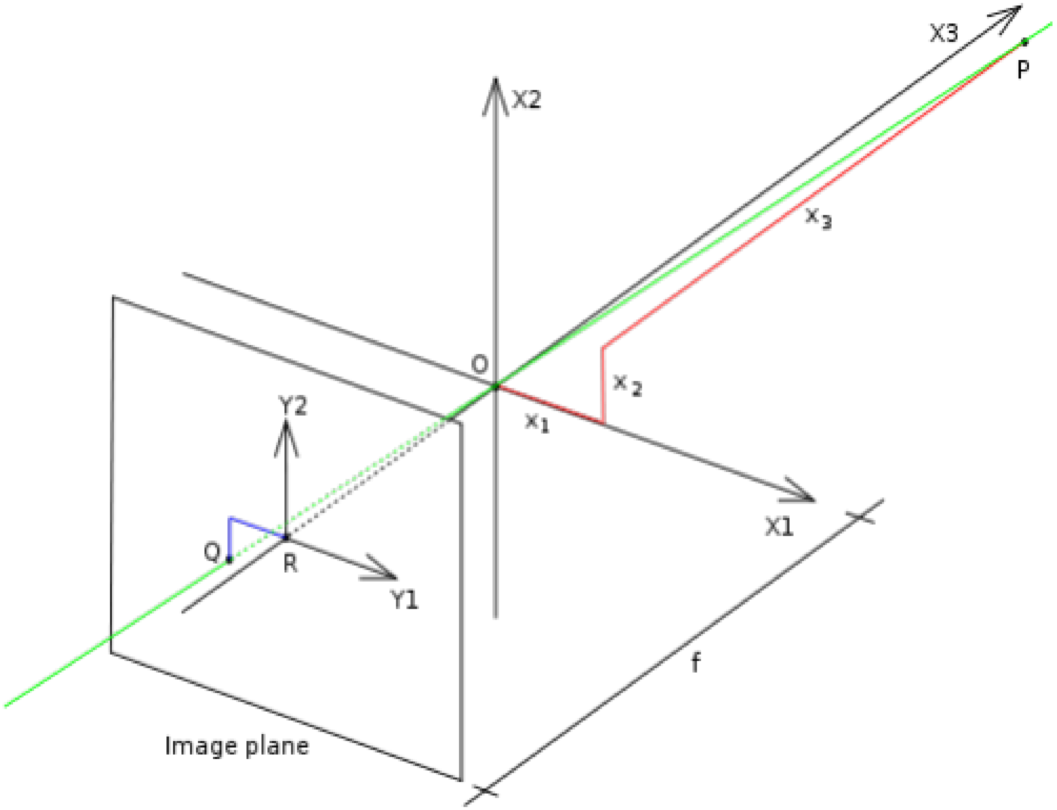


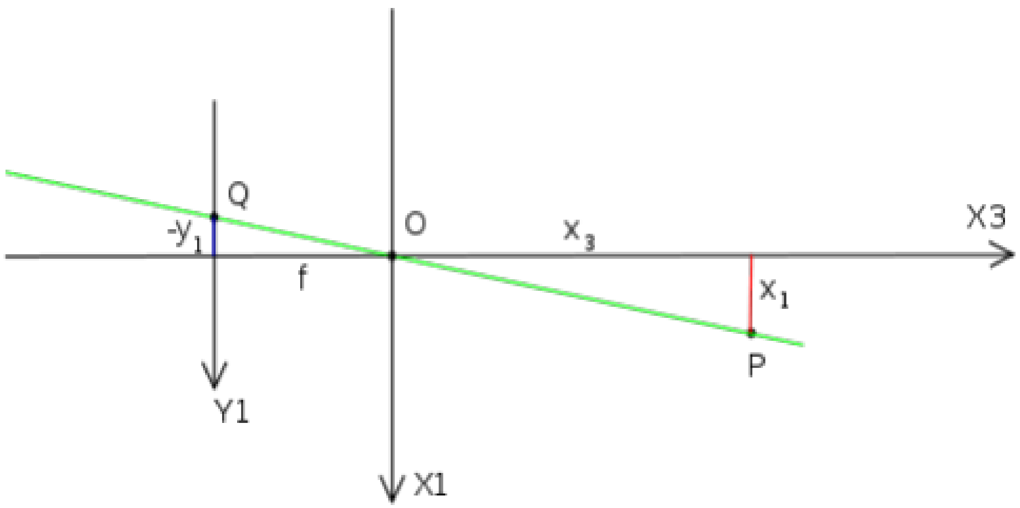




A Camera!

- Camera Model (pinhole)





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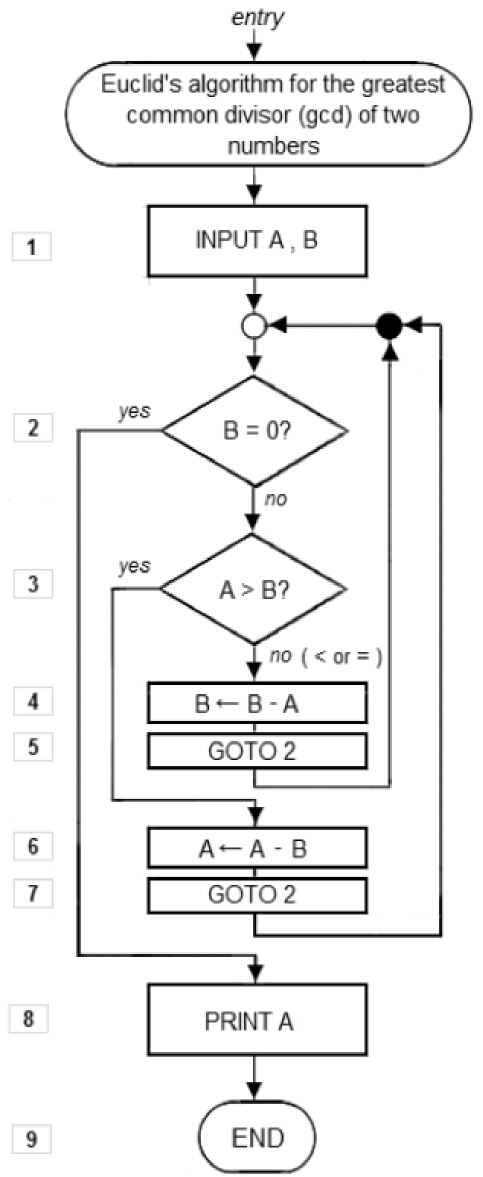
Idea 1

- Use the concept of *light rays* for modelling transport of light
- Define light sources that emit rays
- Test for intersections between rays and geometric shapes in the scene
- When a ray hits the surface of a shape
  - See how much light energy bounces i.e. is *reflected*
- When a ray hits the image plane of the camera
  - Render a colour to the screen

Question

How do we go from this *idea* to a computational model?

i.e. how to define an algorithm or step-by-step procedure



Answer: Remember this?

Interactive computer graphics is essentially:

Mathematics programming

Quite possibly the most fun and rewarding maths programming you will ever do*

**disclaimer: you'll get from it what you put in*

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Maths Programming Toolkit

- Define a toolkit of mathematical operations
- Each will be important for our final algorithm
- Important keywords from idea 1:
  - Light rays from light sources
  - Intersections with geometry
  - Bounces/reflects off surfaces
  - Render to screen

What is a 'Light Ray'?

- Concept
  - Idealised narrow beam of light (optics)
  - Discrete, particles
- Geometrically speaking:
  - Similar in some ways to a straight line
  - Has a starting point and direction
  - But extends infinitely in defined direction
- Mathematically:

$$\mathbf{r}_0 = [x_0, y_0, z_0]^{\mathrm{T}}$$

$$\mathbf{r}_d = [x_d, y_d, z_d]^{\mathrm{T}} \ , \ ||\mathbf{r}_d|| = 1$$

$$\mathbf{r}_t = \mathbf{r}_0 + t \cdot \mathbf{r}_d$$

One degree-of-freedom

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Where do they come from?

- Emitted from light sources
- Parameterised
  - Position
  - Colour
  - Intensity

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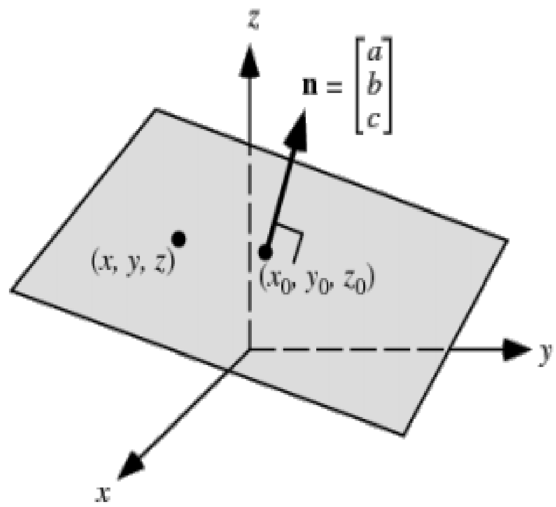
Intersections

- Need to be able to test for intersections between rays and scene geometry (objects)
- Different types of geometry:
  - Planes
  - Spheres
  - Triangles
- Resolving intersections involve solving equations

Ray-plane Intersection

- Plane defined as:
  - Plane normal $\mathbf{n} = [a, b, c]$
  - Unit normal $||n||_2 = 1$
  - d offset to origin
  - Equation $a \cdot x + b \cdot y + c \cdot z + d = 0$
  - *Two degrees-of-freedom*

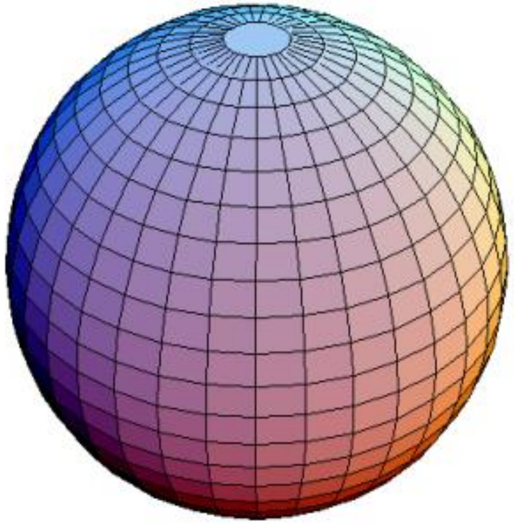


- Intersection point:

$$\mathbf{p}_i = \mathbf{r}_0 - \frac{\mathbf{n}^{\mathrm{T}}\mathbf{r}_0 + d}{\mathbf{n}^{\mathrm{T}}\mathbf{r}_d} \cdot \mathbf{r}_d$$

Ray-sphere Intersection

- Sphere defined as:



- Center of sphere $\mathbf{x}_c = [x_c, y_c, z_c]^{\mathrm{T}}$
- Radius r
- $(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2 = r^2$

- Intersections:

$$\mathbf{p}_i = -\mathbf{r}_d^{\mathrm{T}}(\mathbf{r}_0 - \mathbf{r}_c) \pm \sqrt{\mathbf{r}_d^{\mathrm{T}}(\mathbf{r}_0 - \mathbf{r})_c - (\mathbf{r}_0 - \mathbf{x}_c)^{\mathrm{T}}(\mathbf{r}_0 - \mathbf{x}_c) + \mathbf{r}^2}$$

Worked Example

(recommend to work this out later using a pen and paper)

Find the intersections, if any, between the Ray with $r_0 = (0,2,0)^T$, $r_d = (0,-1,0)^T$ and the Sphere with $x_c = (0,0,0)^T$, $r = 1$

Apply the quadratic formula $t = -b \pm \mathrm{sqrt}(b^2-4ac)/(2a)$ to find two solutions, where:

$a = r_d.r_d$

$b = 2r_d.(r_0-x_c)$

$c = (r_0-x_c).(r_0-x_c)-r^2$

The value of b^2-4ac indicates how many roots the equation has, where negative number indicates no intersections between the ray and sphere, a zero indicates a single intersection on the edge of the sphere and a positive number indicates two intersections where the ray enters and exits the sphere. In this example, b^2-4ac is positive indicating **two intersections**.

Apply formula; $r_d.r_d t^2+2r_d.(r_0-x_c)t+(r_0-x_c).(r_0-x_c)-r^2=0$

Entering the above value gives **$t^2-4t+3=0$**

=> t = 3 and t = 1

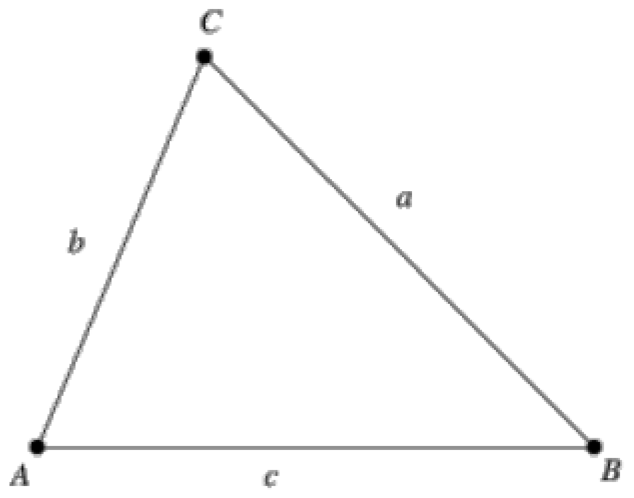
Recalling ray equation: $r_0+t.r_d$

t=1: (0,2,0)+(0,-1,0) = **(0,1,0) … first intersection point**

t=3: (0,2,0)+(0,-3,0) = **(0,-1,0) … second intersection point**

Ray-triangle Intersection

- Triangle defined as:
  - Three vertices
    - $\mathbf{t}_i = [x, y, z]^{\mathrm{T}}, i = 1 \ldots 3$



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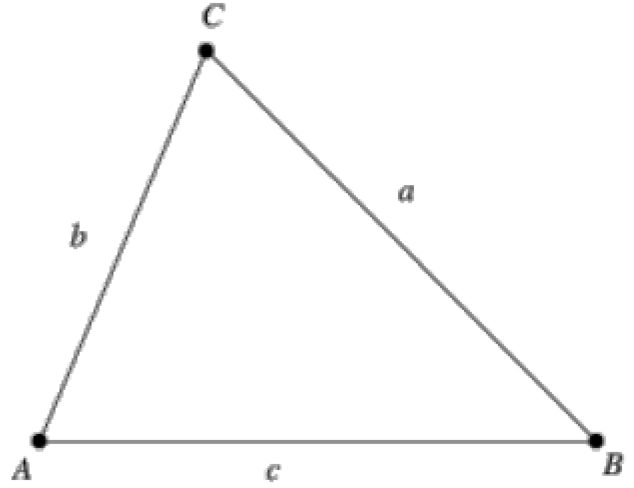
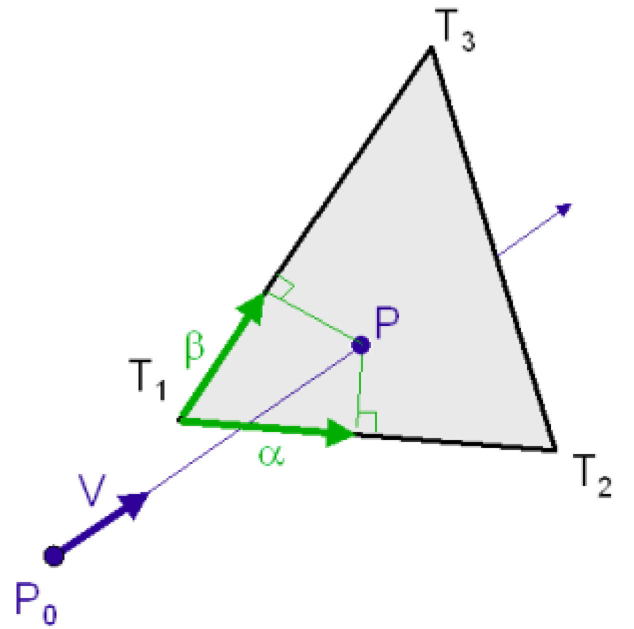


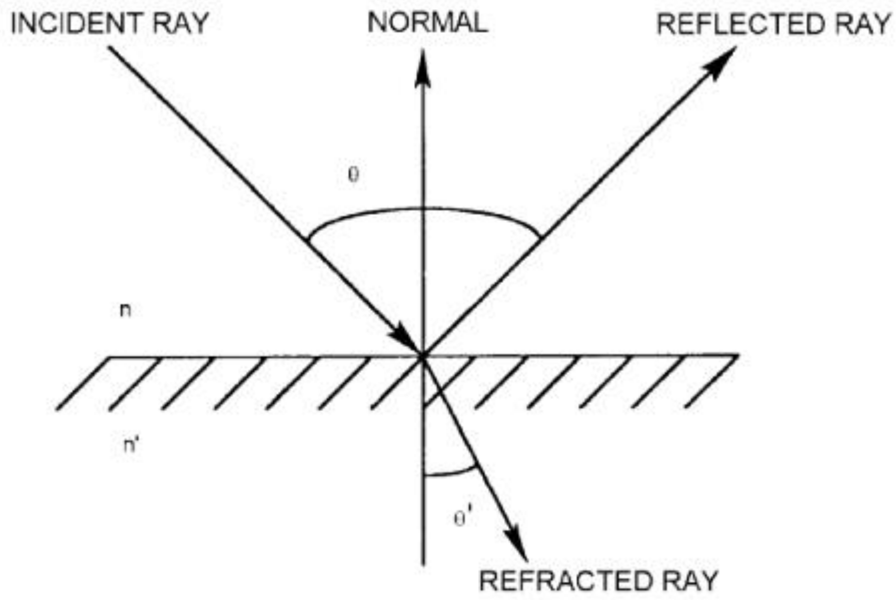
- Intersection:
  1. Check collision with plane
  2. Check if inside triangle
     - $0 \leq \alpha, \beta \leq 1$
     - $\alpha + \beta \leq 1$



Surfaces

Must also consider rays hitting and bouncing off surfaces

1. Incoming ray hits surface
2. Divided into,
   - reflected component
   - refracted component



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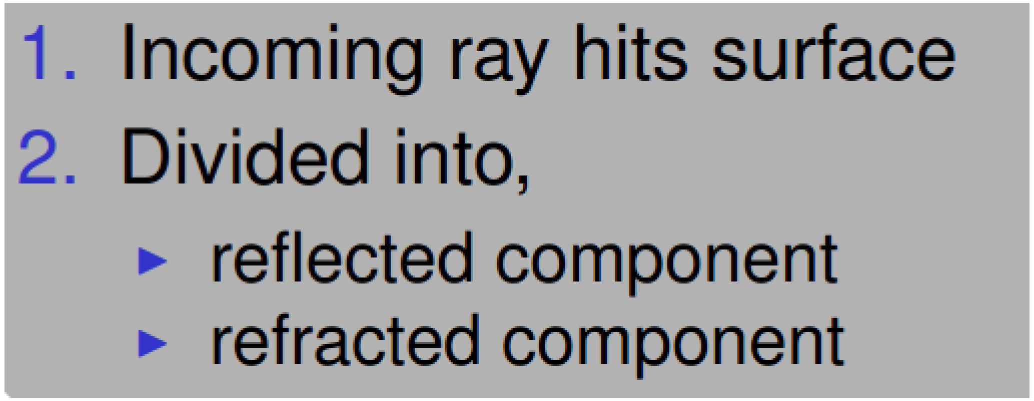

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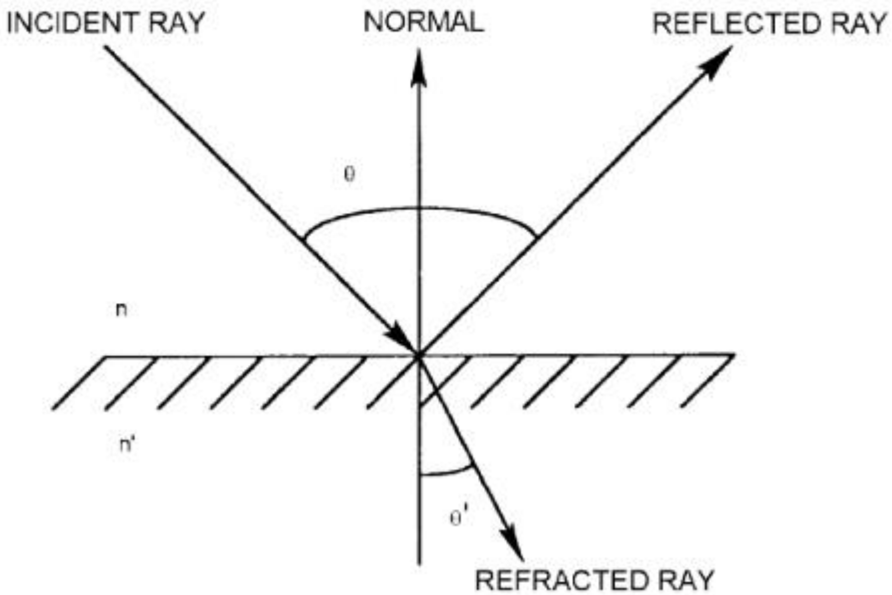
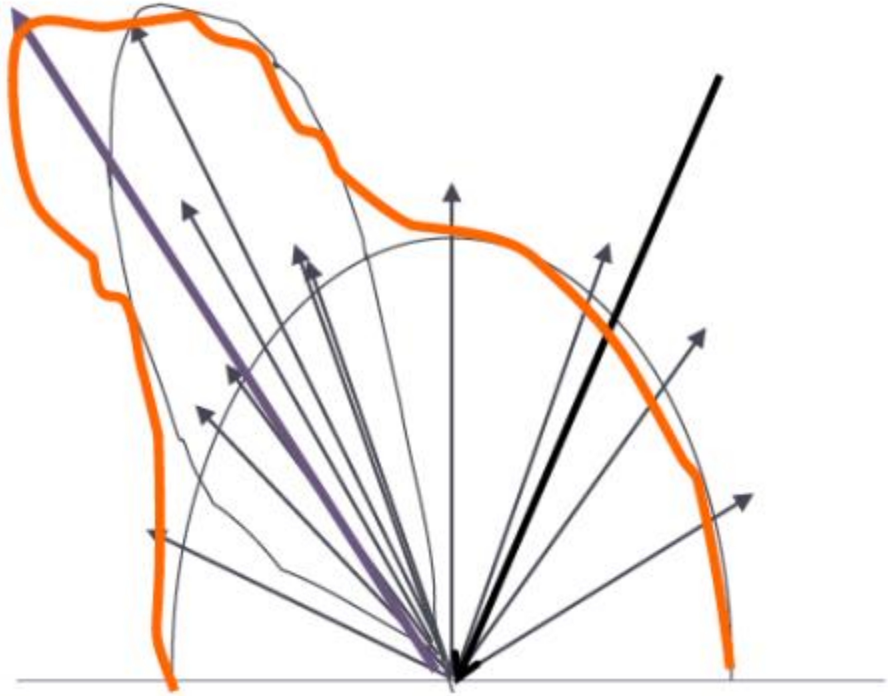


Surface types can reflect/refract rays in different ways

Accurate Reflection

Complex opaque surfaces scatter incoming light in many different directions

- BRDF - **B**idirectional **R**eflectance **D**istribution **F**unction



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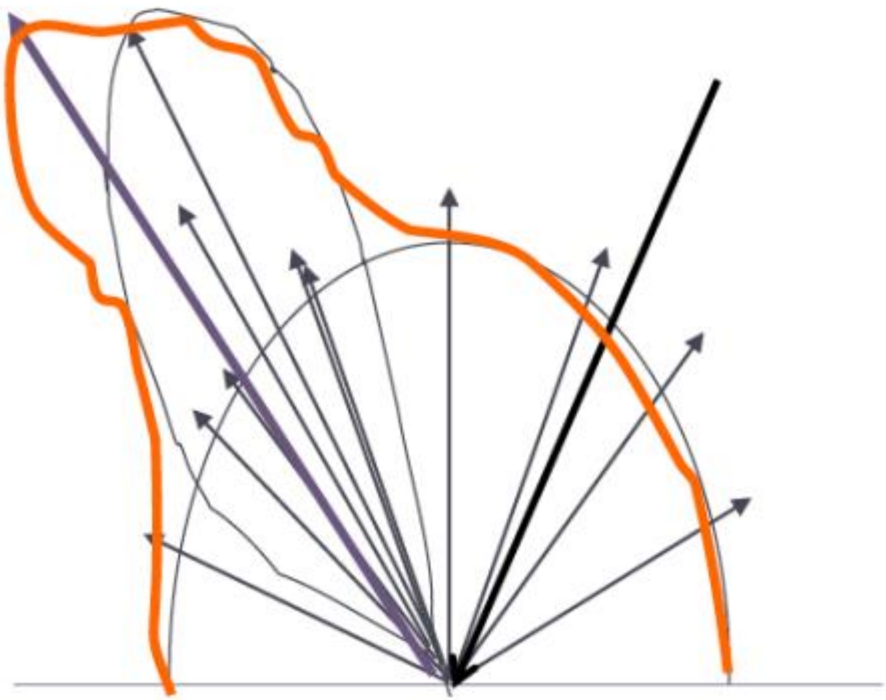

Where does this information come from?

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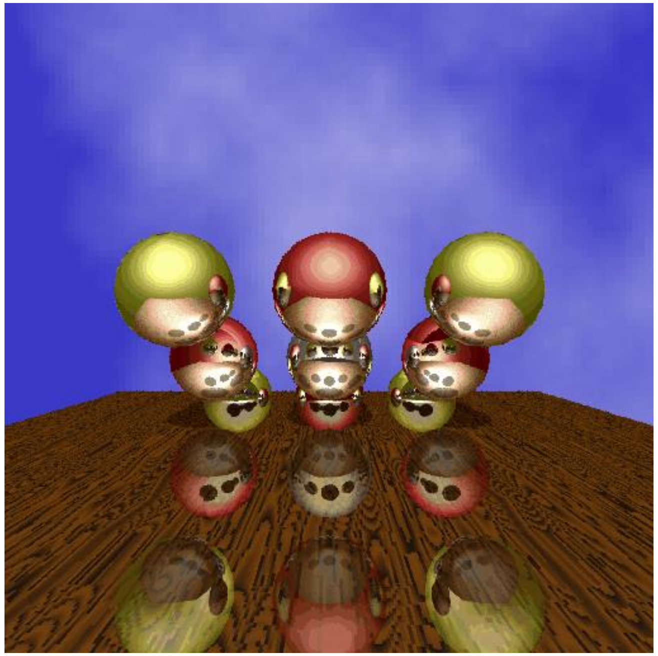
Surfaces

Specular surfaces are like mirrors

Light from a single incoming direction reflected into a single outgoing direction

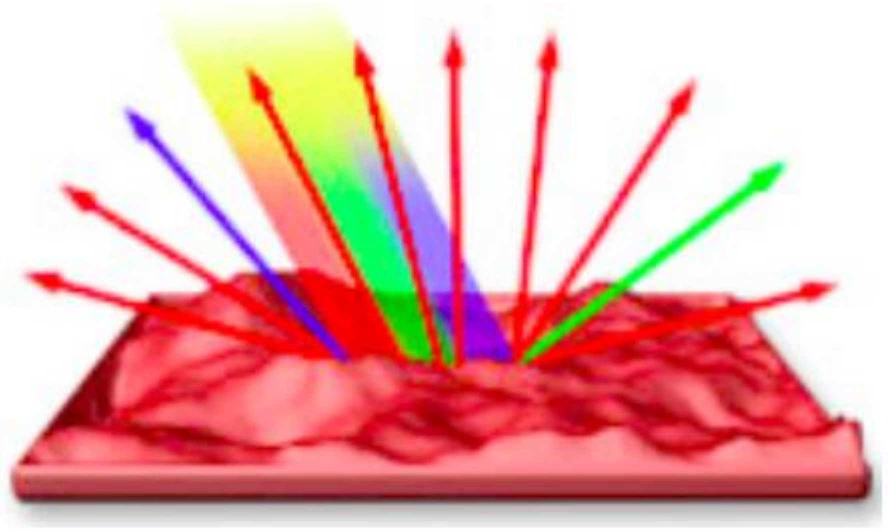


Surfaces

Diffuse (matte) surfaces are more rough

Light from a single incoming direction reflected in multitude of outgoing directions

Lambertian surface

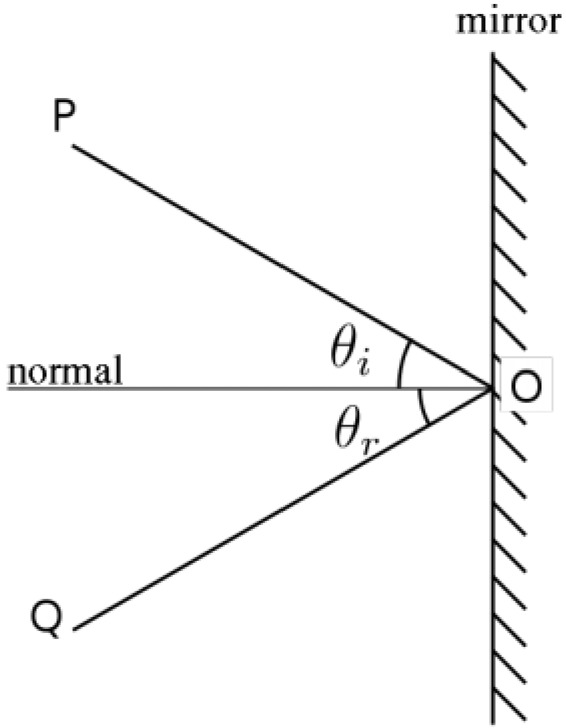


Modelling Specular Surfaces

Incoming ray *P*, outgoing ray *Q* and face normal are in the same plane

Angle from normal the same between incoming and outgoing ray

Rays *P* and *Q* are on opposite sides of the face normal



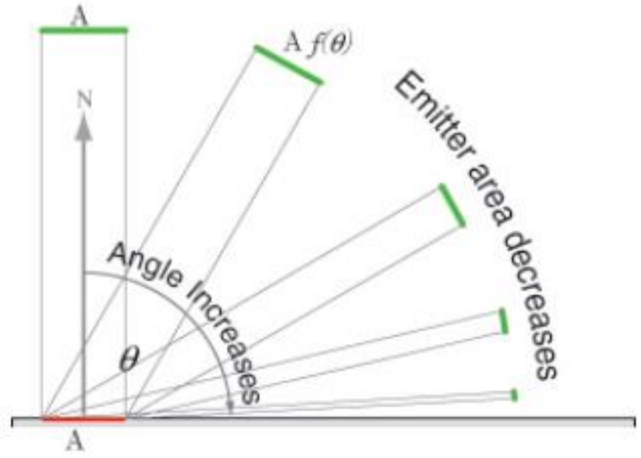
$$\mathbf{d}_o = \mathbf{d}_i - 2(\mathbf{d}_i^{\mathrm{T}} \cdot \mathbf{n})\mathbf{n}$$

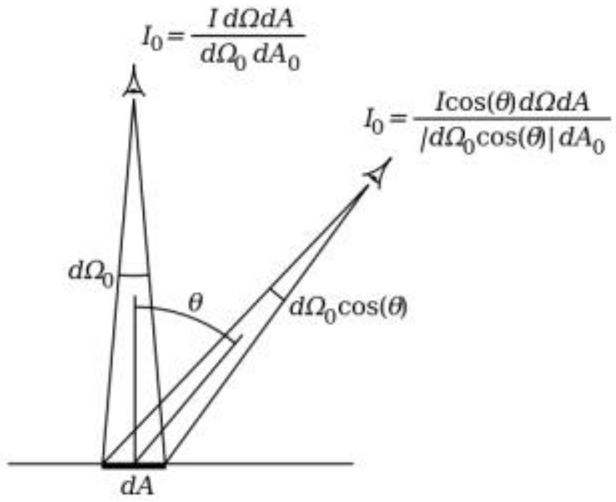
Modelling Diffuse Surfaces

Lambertian reflection

Surface is equally bright independent of viewing angle

Isotropic – uniform in all directions





Lambert's Cosine Law

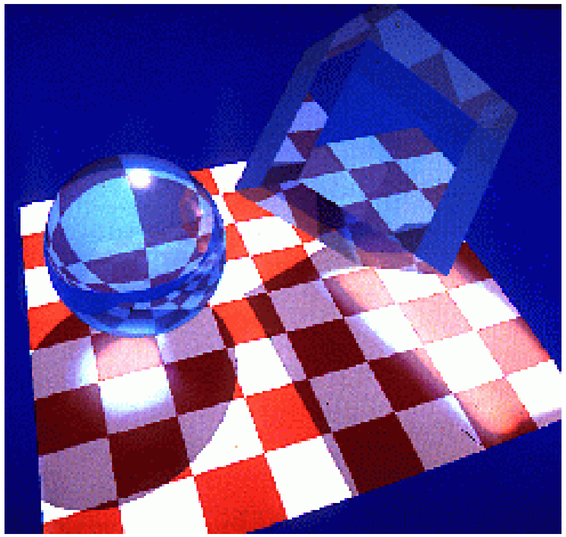
$$I_0 = I\frac{\cos(\theta)d\Omega dA}{\cos(\theta)d\Omega_0 dA_0}$$

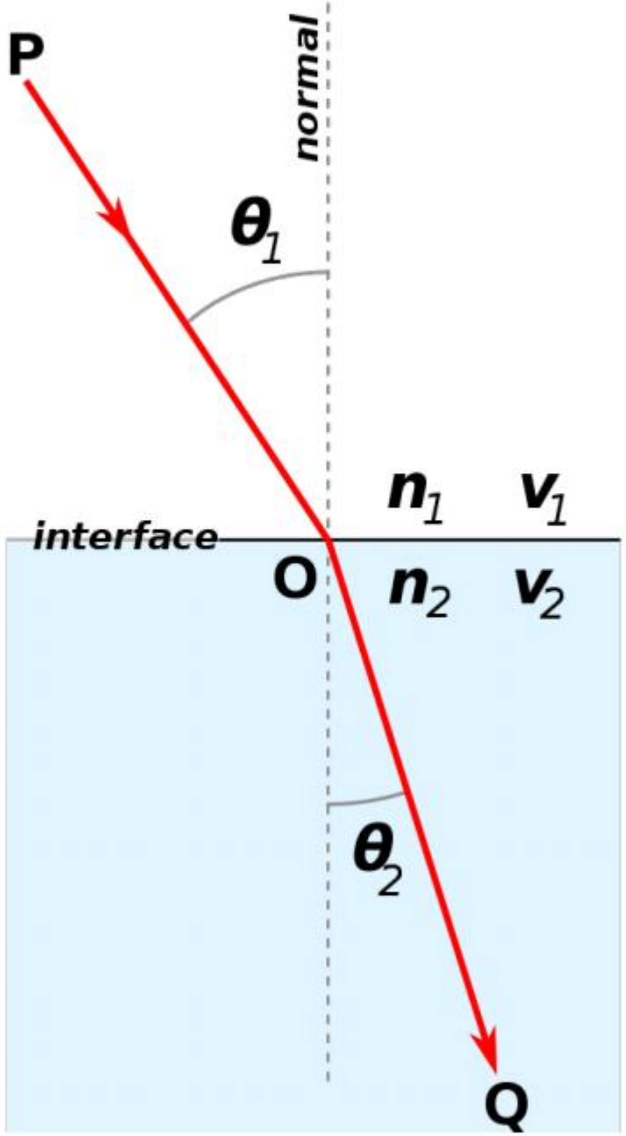
Modelling Refraction

- Snell's Law

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

  - Refractive Index of Material





Some Light Types

Ambient Lighting

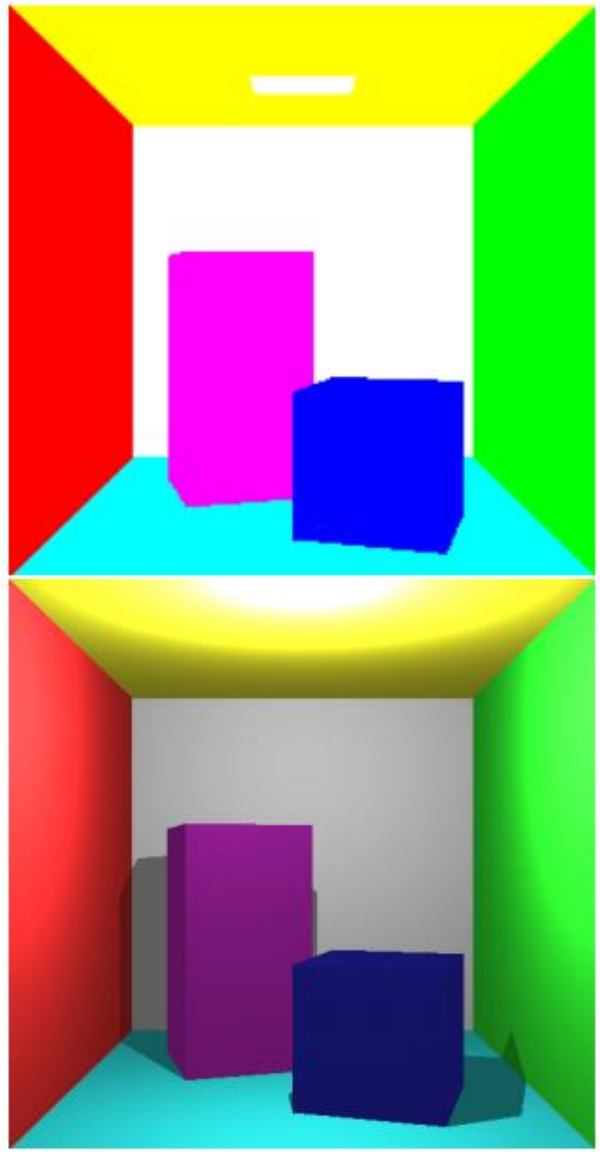
Constant light affecting each part of the scene equally

Point Light Sources

Rays travelling from a point in all directions

Spotlight Sources

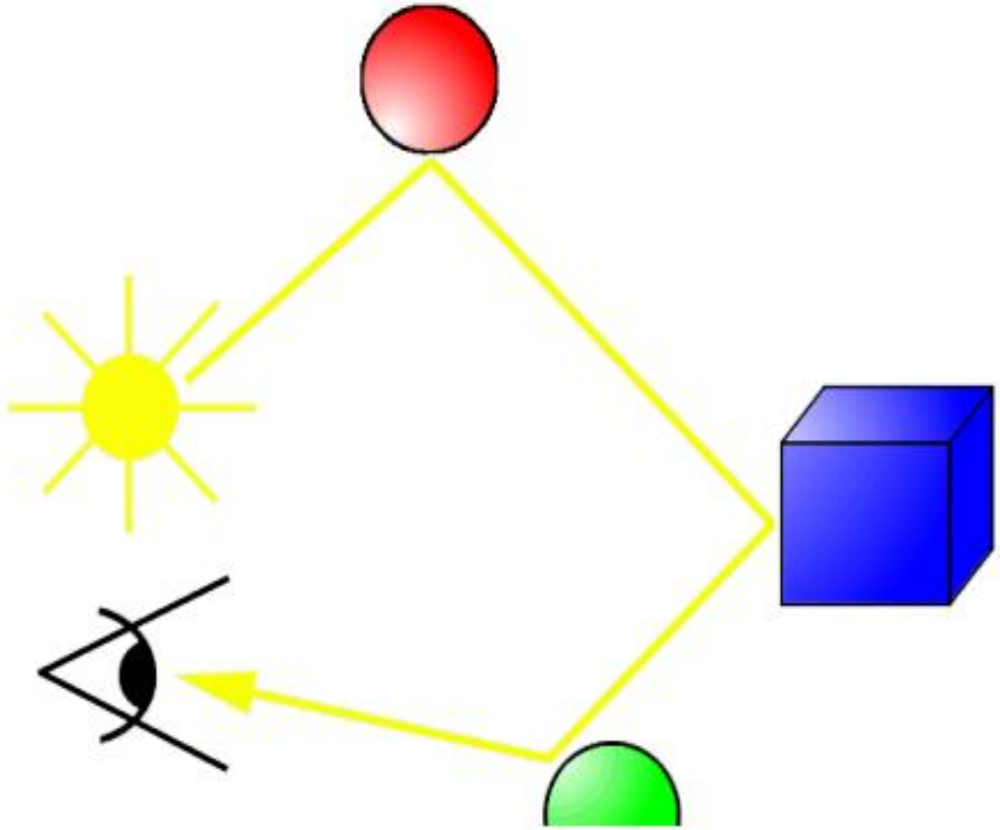
Rays travelling from a point in limited directions



Our Initial Idea

We have now defined some modelling elements

Remember our initial idea:



Question

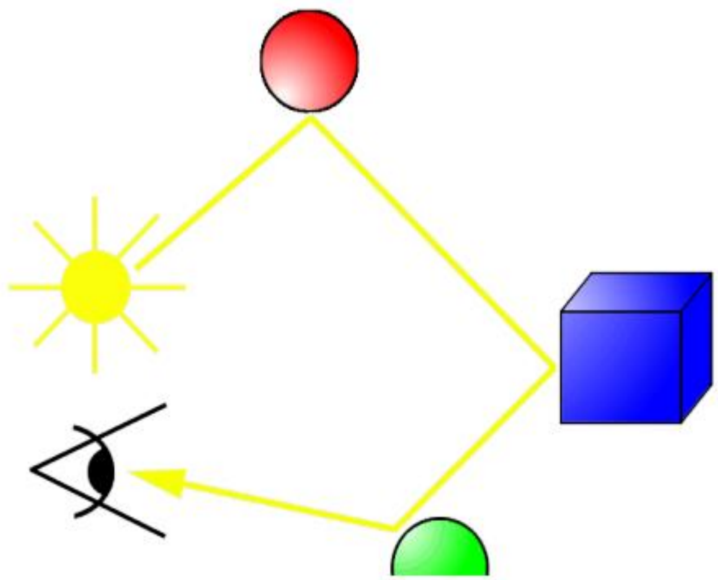
Is this feasible??

Question

Is this feasible??

Think of what the procedure may look like:

```
for(i=0;i<nr_rays,i++)
{
  while(!hit image&&!infinity)
  {
    /*
    compute new direction
    compute new colour
    */
  }
}
```



Idea 2

Cast rays of light backwards through the viewing plane, into the scene

Test for intersections between each ray and virtual objects in the scene

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Idea 2

- Cast rays of light backwards through the viewing plane, into the scene
- Test for intersections between each ray and virtual objects in the scene
- Ray fails to hit anything
  - Background or default colour returned

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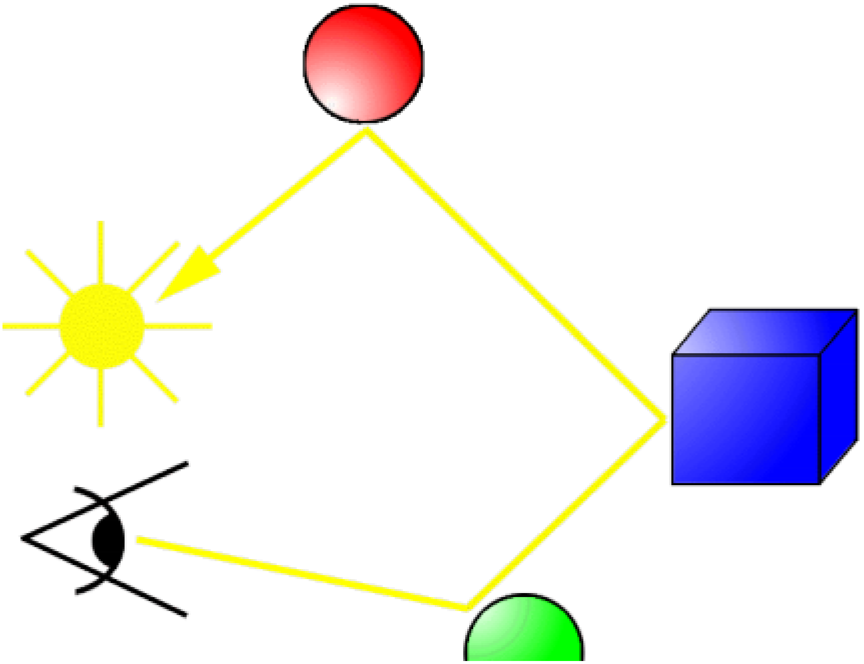
Idea 2

- Cast rays of light backwards through the viewing plane, into the scene
- Test for intersections between each ray and virtual objects in the scene
- Ray fails to hit anything
  - Background or default colour returned
- When ray hits (i.e. 'intersects') first object
  - Cast ray from intersection point on object to light sources
  - Test material properties of object

Backwards Raytracing

```
for(v=0;v<height,v++)
{
  for(u=0;u<width;u++)
  {
    for(i=0;i<max_nr_bounce;i↩
        ++)
    {
      /*
      compute new direction
      compute new colour
      */
    }
  }
}
```



Termination Criteria

1. No intersection

Termination Criteria

1. No intersection

2. Reach maximal depth

   Number of bounces

Termination Criteria

1. No intersection

2. Reach maximal depth

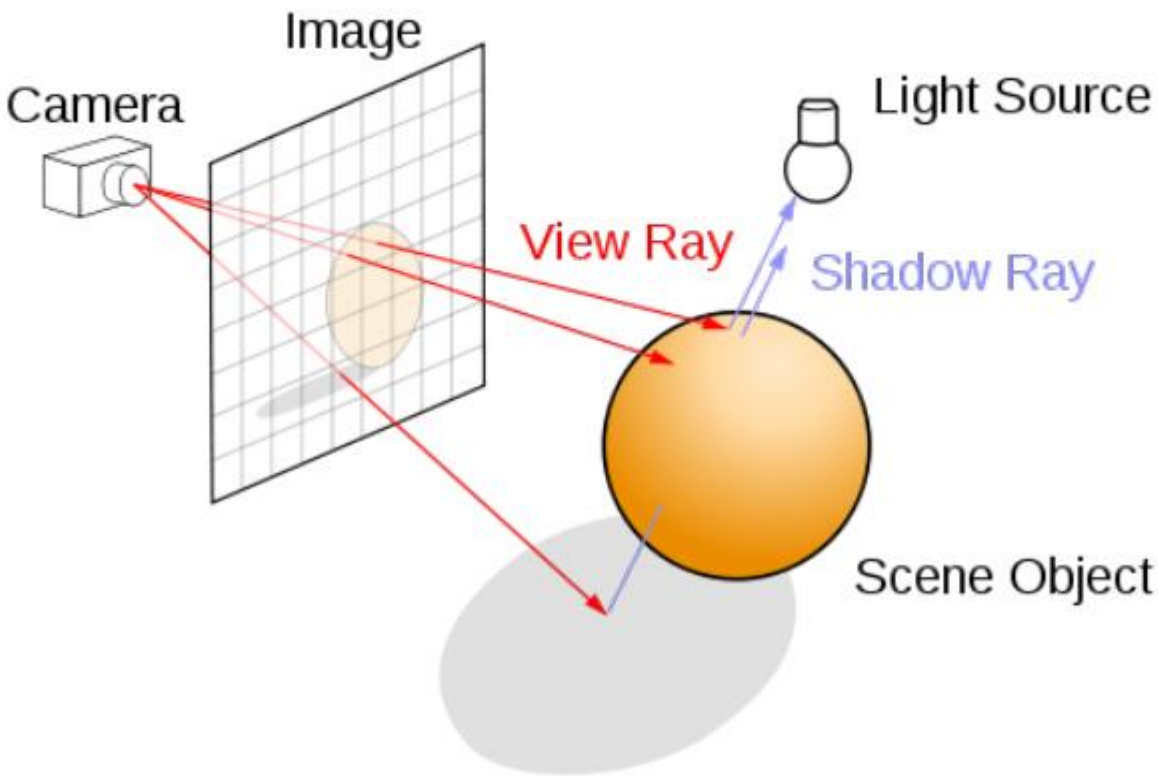
    Number of bounces

3. Contribution of secondary ray attenuated below threshold

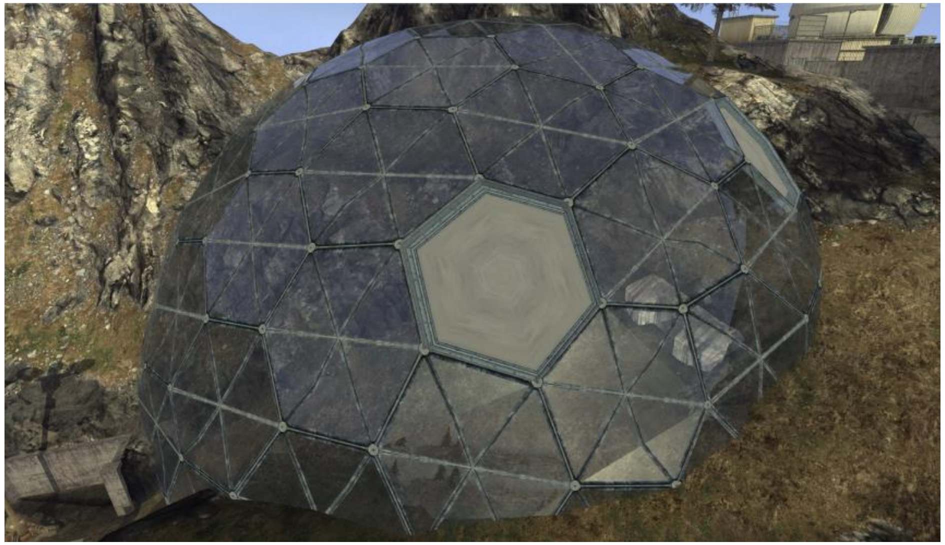
    Each reflection/refraction bounce attenuates ray

Shadows

1. Shoot ray
2. Intersection
   - Shoot ray to light
   - Free/Blocked



Raytracing in General



Quake Wars: Ray-traced

- Simple algorithm
  - Capable of simulating complex light interactions
- Well-suited for software rendering
  - Very flexible
  - Easy to incorporate new effects
- Not always viewed as so interactive
  - But things are changing

Overall

One of a number of *global illumination* models

Global illumination
- More realism
- More computation

Others include:
1. *Radiosity*
2. *Photon mapping*
3. *Path tracing*
4. *Ambient occlusion*

Museum scene with radiosity

Battlefield 3 radiosity

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Next lecture

- More details about projects
  Monday 18th April
  08:00 – 10:00, B2
- Next lab session:
  Monday 11th April
  10:00-12:00, Visualization Studio
- Labs:
  - You are doing well at this stage if you have a basic version of the lab building
  - The C++ tutorial and introduction lab session will run again