Interactive Computer Graphics

Lecture 11: Ray tracing

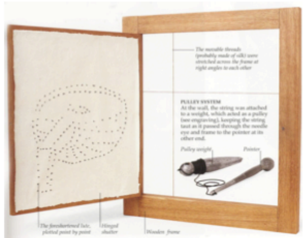
Some slides adopted from
H. Pfister, Harvard

Direct and Global Illumination

- Direct illumination: A surface point receives light directly from all light sources in the scene.
  - Computed by the direct illumination model.
- Global illumination: A surface point receives light after the light rays interact with other objects in the scene.
  - Points may be in shadow.
  - Rays may refract through transparent material.
  - Computed by reflection and transmission rays.

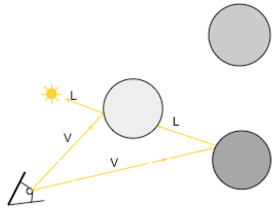
Albrecht Dürer's Ray Casting Machine

- Albrecht Dürer, 16th century



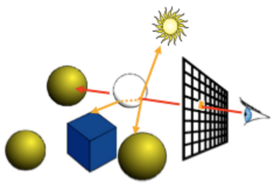
Arthur Appel, 1968

- On calculating the illusion of reality, 1968
- Cast one ray per pixel (ray casting).
  - For each intersection, trace one ray to the light to check for shadows
  - Only a local illumination model
- Developed for pen-plotters

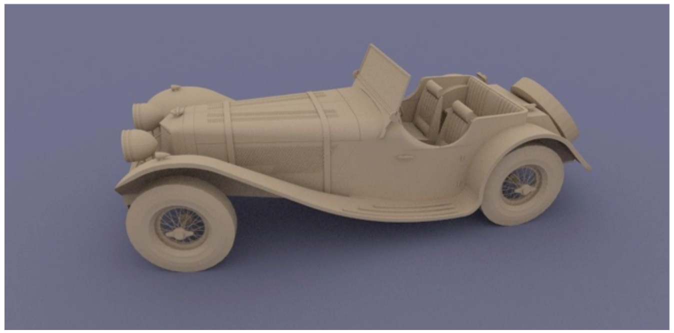


Ray casting

```
cast ray
      Intersect all objects
      color = ambient term
      For every light cast shadow ray
            col += local shading term
```

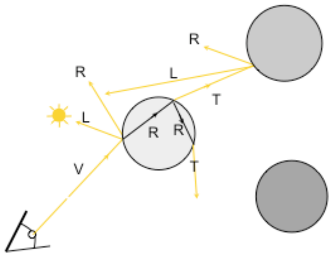


Ray Casting

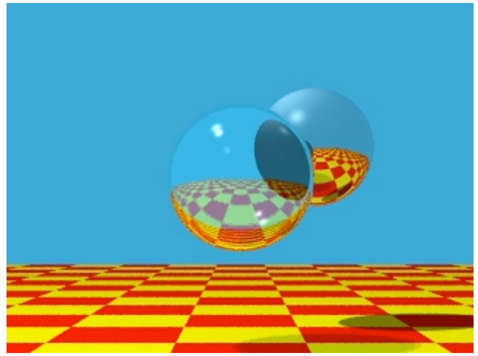


Turner Whitted, 1980

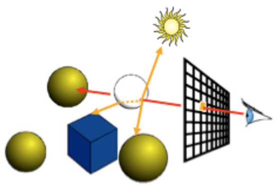
- An Improved Illumination Model for Shaded Display, 1980
- First global illumination model:
  - An object's color is influenced by lights and other objects in the scene
  - Simulates specular reflection and refractive transmission



Turner Whitted, 1980



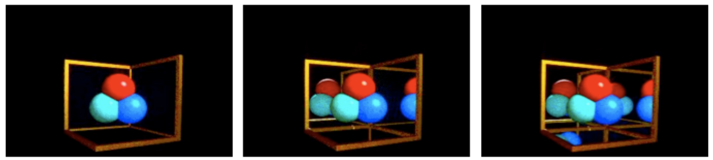
Recursive ray casting



```
trace ray
        Intersect all objects
        color = ambient term
        For every light
                cast shadow ray
                col += local shading term
        If mirror
                col += k_refl * trace reflected ray
        If transparent
                col += k_trans * trace transmitted ray
```

Does it ever end?

- Stopping criteria:
  - Recursion depth: Stop after a number of bounces
  - Ray contribution: Stop if reflected / transmitted contribution becomes too small



0 recursion — 1 recursion — 2 recursions

Ray tracing: Primary rays

- For each ray we need to test which objects are intersecting the ray:
  - If the object has an intersection with the ray we calculate the distance between viewpoint and intersection
  - If the ray has more than one intersection, the smallest distance identifies the visible surface.
- Primary rays are rays from the view point to the nearest intersection point
- Local illumination is computed as before:

$$L = k_a + (k_d(\mathbf{n}\cdot\mathbf{l}) + k_s(\mathbf{v}\cdot\mathbf{r})^q)I_s$$

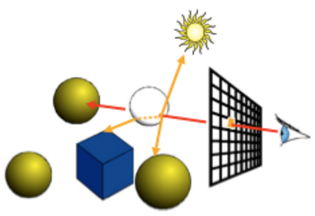
Ray tracing: Secondary rays

- Secondary rays are rays originating at the intersection points
- Secondary rays are caused by
  - rays reflected off the intersection point in the direction of reflection
  - rays transmitted through transparent materials in the direction of refraction
  - shadow rays

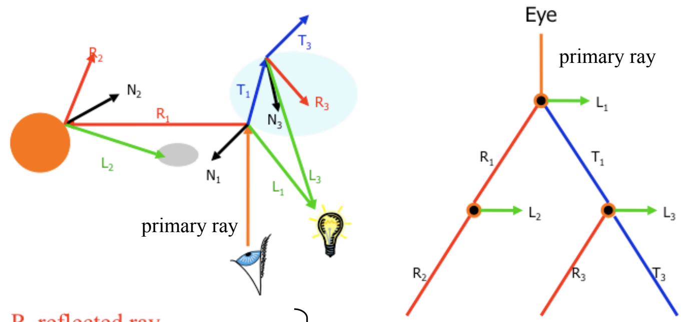
Recursive ray tracing: Putting it all together

- Illumination can be expressed as

$$L = k_a + (k_d(\mathbf{n}\cdot\mathbf{l}) + k_s(\mathbf{v}\cdot\mathbf{r})^q)I_s + k_{reflected}L_{reflected} + k_{refracted}L_{refracted}$$



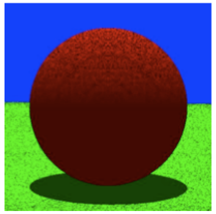
Recursive Ray Tracing: Ray Tree



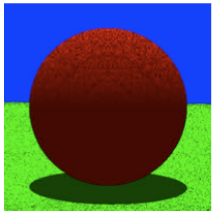
R_i reflected ray
L_i shadow ray
T_i transmitted (refracted) ray

} secondary rays

Precision Problems



Precision Problems



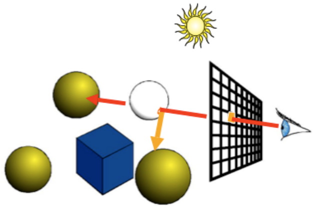
- In ray tracing, the origin of (secondary) rays is often on the surface of objects
  - Theoretically, the intersection point should be on the surface
  - Practically, calculation imprecision creeps in, and the origin of the new ray is slightly beneath the surface
- Result: the surface area is shadowing itself

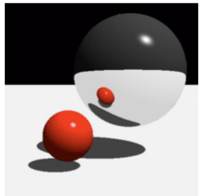
ε to the rescue …

- Check if t is within some epsilon tolerance:
  - if abs(μ) < ε
    - point is on the surface
  - else
    - point is inside/outside
  - Choose the ε tolerance empirically
- Move the intersection point by epsilon along the surface normal so it is outside of the object
- Check if point is inside/outside surface by checking the sign of the implicit (sphere etc.) equation

Mirror reflection

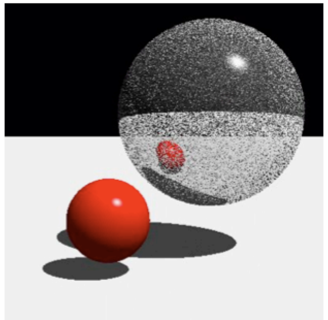
- Compute mirror contribution
- Cast ray in direction symmetric wrt. normal
- Multiply by reflection coefficient (color)



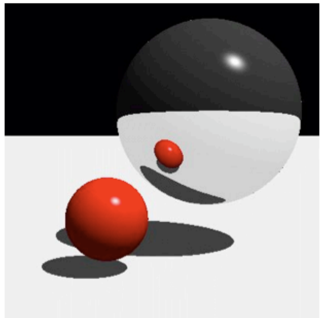


Mirror reflection

- Don't for get to add epsilon to the ray

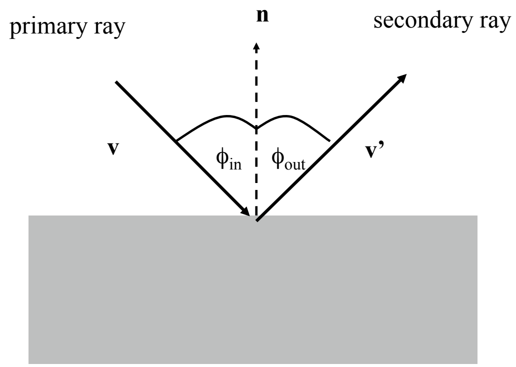


Without epsilon



With epsilon

Mirror reflection



Mirror reflection

- To calculate illumination as a result of reflections
  - calculate the direction of the secondary ray at the intersection of the primary ray with the object.
- given that
  - n is the unit surface normal
  - v is the direction of the primary ray
  - v' is the direction of the secondary ray as a result of reflections

$$\mathbf{v'} = \mathbf{v} - (2\mathbf{v} \cdot \mathbf{n})\mathbf{n}$$

Mirror reflection

The **v**, **v'** and **n** are unit vectors and coplanar so:

$$\mathbf{v'} = \alpha\, \mathbf{v} + \beta\, \mathbf{n}$$

Taking the dot product with **n** yields the eq.:

$$\mathbf{n \cdot v'} = \alpha\, \mathbf{v \cdot n} + \beta = \mathbf{v \cdot n}$$

Requiring v' to be a unit vector yields the second eq.:

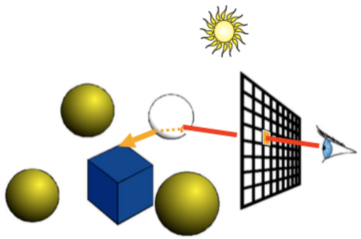
$$1 = \mathbf{v' \cdot v'} = \alpha^2 + 2\,\alpha\,\beta\, \mathbf{v \cdot n} + \beta^2$$

- Solving both equations yields:

$$\mathbf{v'} = \mathbf{v} - (2\mathbf{v} \cdot \mathbf{n})\mathbf{n}$$

Transparency

- Compute transmitted contribution
- Cast ray in refracted direction
- Multiply by transparency coefficient

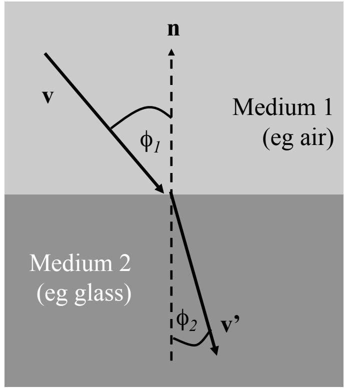


Refraction

- The angle of the refracted ray can be determined by Snell's law:

$$\eta_1 \sin(\phi_1) = \eta_2 \sin(\phi_2)$$

- η_1 is a constant for medium 1
- η_2 is a constant for medium 2
- ϕ_1 is the angle between the incident ray and the surface normal
- ϕ_2 is the angle between the refracted ray and the surface normal



Refraction

- In vector notation Snell's law can be written:

$$k_1(\mathbf{v} \times \mathbf{n}) = k_2(\mathbf{v}' \times \mathbf{n})$$

- The direction of the refracted ray is

$$\mathbf{v}' = \frac{\eta_1}{\eta_2}\left(\left[\sqrt{(\mathbf{n}\cdot\mathbf{v})^2 + \left(\frac{\eta_2}{\eta_1}\right)^2 - 1} - \mathbf{n}\cdot\mathbf{v}\right]\cdot\mathbf{n} + \mathbf{v}\right)$$

Refraction

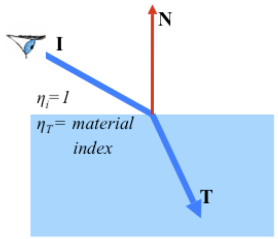
- This equation only has a solution if

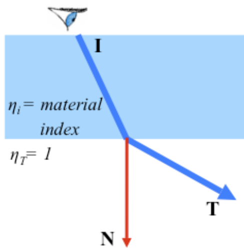
$$(\mathbf{n}\cdot\mathbf{v})^2 > 1 - \left(\frac{\eta_2}{\eta_1}\right)^2$$

- This illustrates the physical phenomenon of the limiting angle:
  - if light passes from one medium to another medium whose index of refraction is low, the angle of the refracted ray is greater than the angle of the incident ray
  - if the angle of the incident ray is large, the angle of the refracted ray is larger than 90º
  - ➨ the ray is reflected rather than refracted

Refraction

- Make sure you know whether you are entering or leaving the transmissive material

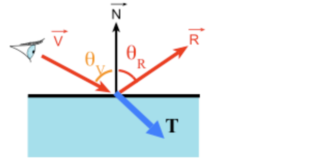




Amount of reflection and refraction

- Traditional (hacky) ray tracing
  - Constant coefficient reflectionColor
  - Component per component multiplication
- Better: Mix reflected and refracted light according to the Fresnel factor.

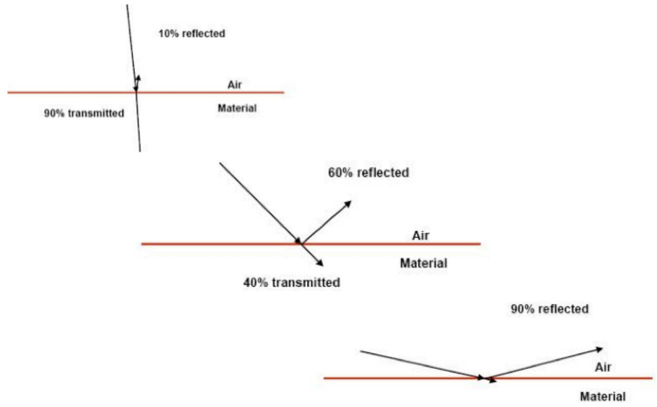
$$L = k_{fresnel} L_{reflected} + (1 - k_{fresnel}) L_{refracted}$$



Fresnel factor

- More reflection at grazing angle

Fresnel factor



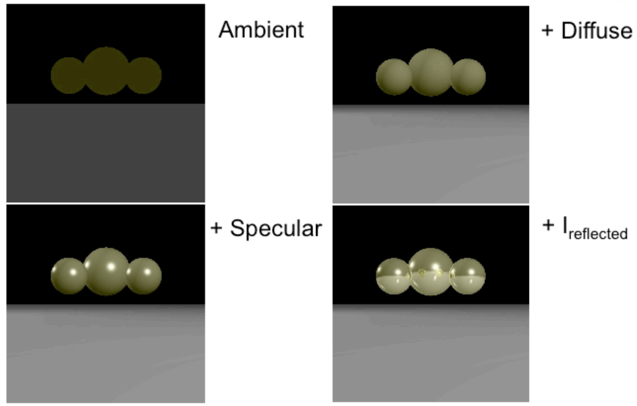
Schlick's Approximation

- Schlick's approximation

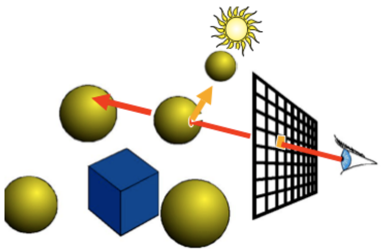
$$k_{fresnel}(\theta) = k_{fresnel}(0) + (1 - k_{fresnel}(0))(1 - (\mathbf{n} \cdot \mathbf{l}))^5$$

- $k_{fresnel}(0)$ = Fresnel factor at zero degrees
- Choose $k_{fresnel}(0) = 0.8$, this will look like stainless steel

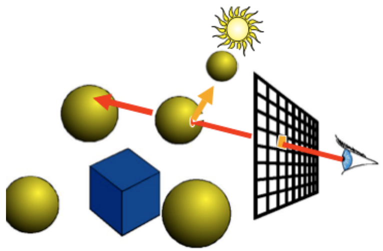
Example



How do we add shadows?



How do we add shadows?

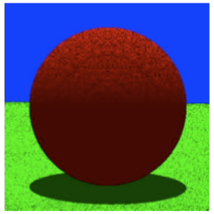


$$L = k_a + s(k_d(\mathbf{n} \cdot \mathbf{l}) + k_s(\mathbf{v} \cdot \mathbf{r})^q)I_s + k_{reflected}L_{reflected} + k_{refracted}L_{refracted}$$

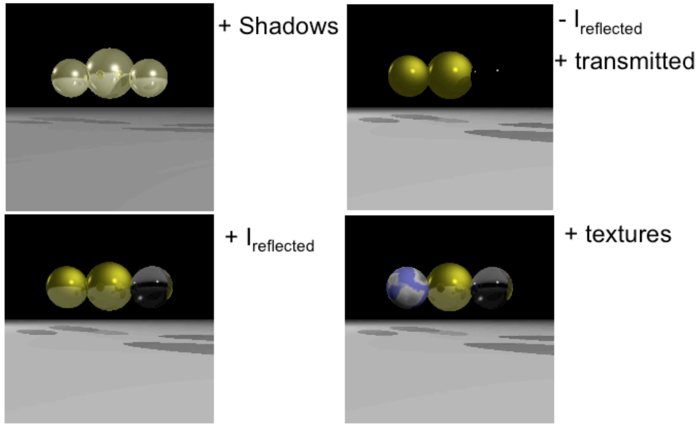
$$s = \begin{cases} 0 & \text{if light source is obscured} \\ 1 & \text{if light source is not obscured} \end{cases}$$

Shadows: Problems?

- Make sure to avoid self-shadowing

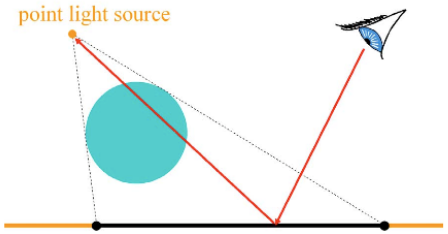


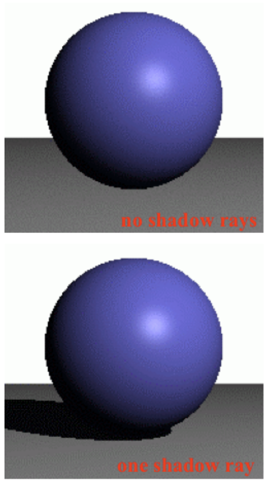
Example



Shadows

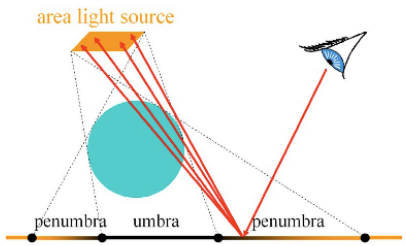
- One shadow ray per intersection per point light source

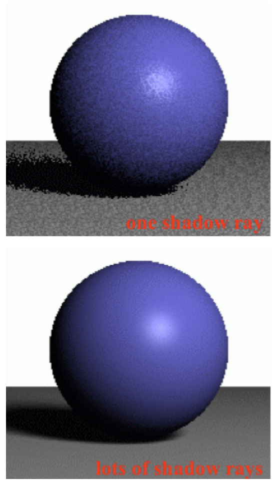




Soft shadows

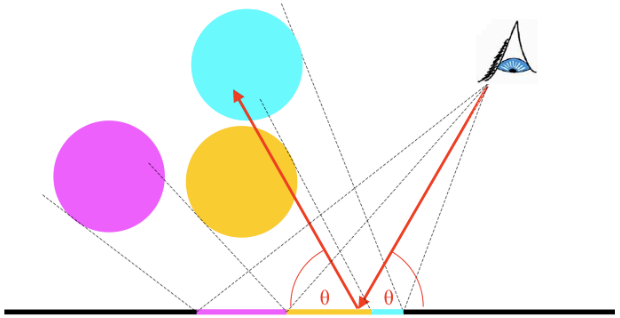
- Multiple shadow rays to sample area light source





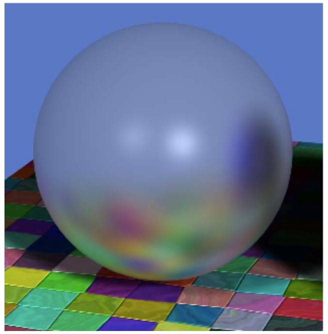
Reflection: Conventional ray tracing

- One reflection per intersection



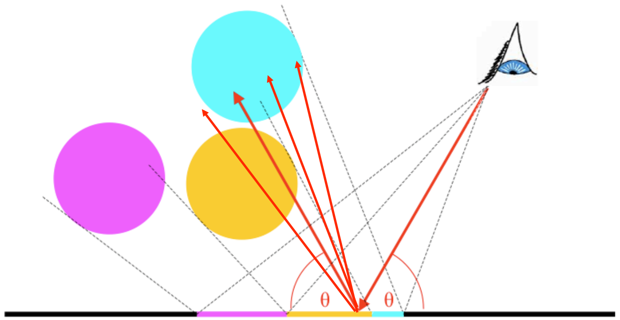
Reflection: Conventional ray tracing

- How can we create effects like this?

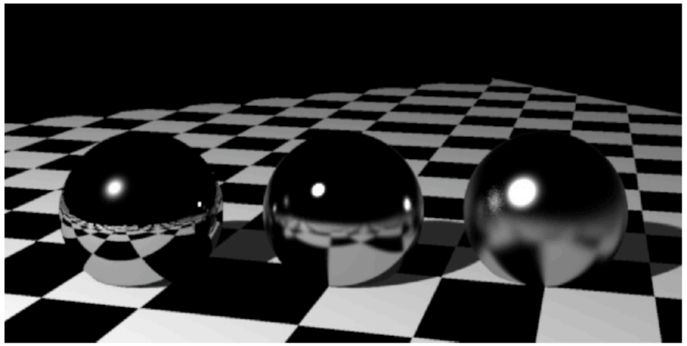


Reflection: Monte Carlo ray tracing

- Random reflection rays around mirror direction

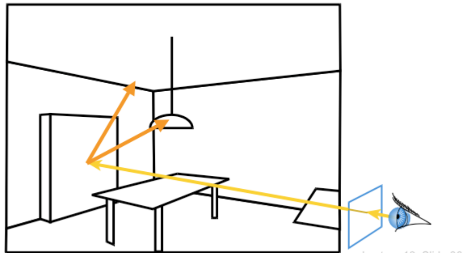


Glossy surfaces



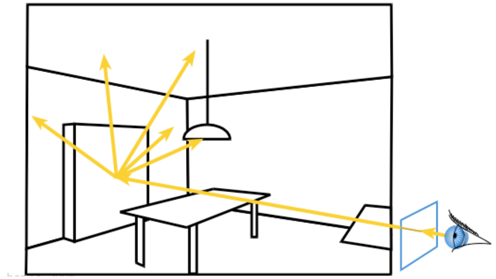
Ray tracing

- Cast a ray from the eye through each pixel
- Trace secondary rays (light, reflection, refraction)



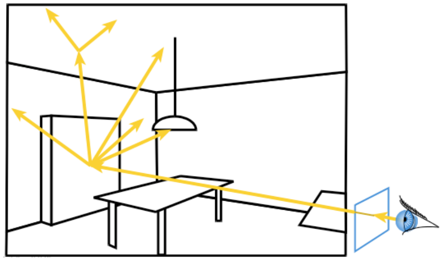
Monte-Carlo Ray Tracing

- Cast a ray from the eye through each pixel
- Cast random rays from the visible point
  - Accumulate radiance contribution



Monte-Carlo Ray Tracing

- Cast a ray from the eye through each pixel
- Cast random rays from the visible point
- Recurse



Monte-Carlo Ray Tracing

- Cast a ray from the eye through each pixel
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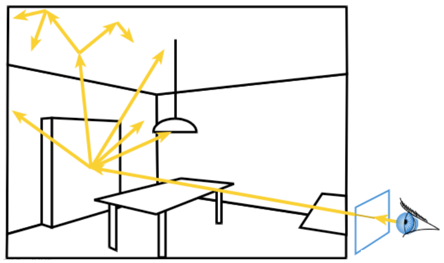
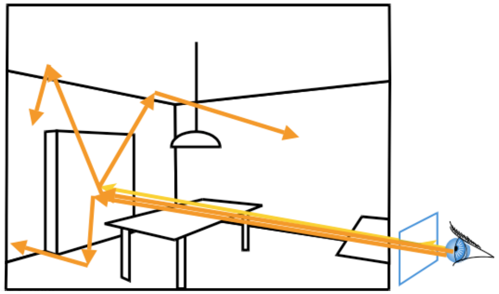


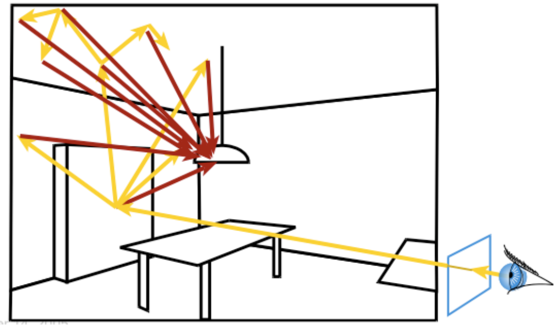
Monte Carlo Path Tracing

- Trace only one secondary ray per recursion
- But send many primary rays per pixel

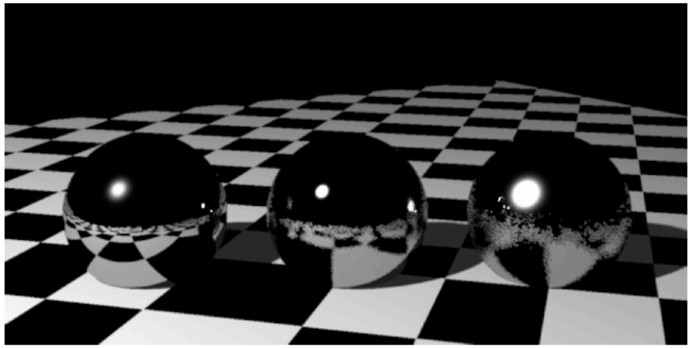


Monte Carlo Ray Tracing

- Send rays to light

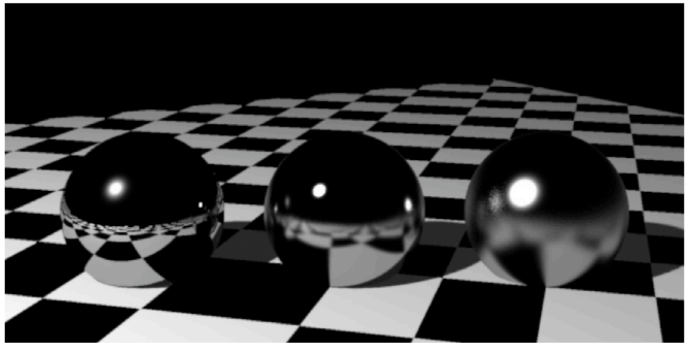


Example



- 1 sample per pixel

Example



- 256 samples per pixel

Some cool pictures

Some cool pictures

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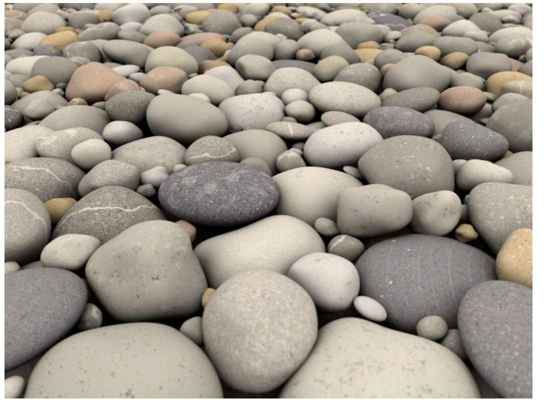
Some cool pictures

Some cool pictures



took 4.5 days to render!