Rendering

An introduction to global illumination

Rendering Recap

- Ray-tracing
  - For each pixel, for each object
- Graphics pipeline, scan conversion
  - For each object, for each pixel
- Local lighting models
  - Diffuse, Phong
- Shadows
  - Ray casting
- Reflection, refraction

You've learned how to do this

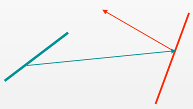
Now we'll see how to do this

Focus

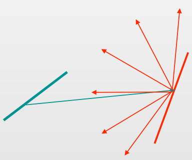
- Graphics hardware
  - Can render scenes with hundreds of thousands of polygons in real-time (>20 fps)
  - Typically surfaces have only simple direct illumination
- Ray tracing
  - Has indirect illumination but for specular surfaces only
- Reality:
  - Most of the light is from diffuse illumination
  - → Simulating proper diffuse illumination adds enormously to realism.

Types of Light Transport

- Specular-specular
  - Ray tracing



- Specular-diffuse



Types of Light Transport

– Diffuse-specular

– Diffuse-diffuse
  • Radiosity

In the next weeks

• Physically based rendering

• Simulation of light transport
  – The radiance equation
  – Radiosity

Let's Start: Physically Based Rendering

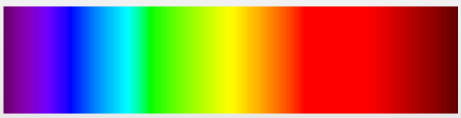
• Simulation of light transport
• Light
  – The nature of light, how it travels in the environment
• Material
  – Anything that interacts with light, how it reflects, refracts or scatters light
  – Bidirectional Reflectance Distribution Function

We will use the Radiance Equation

- Radiance Equation
  - Integral equation
  - Describes the energy (light) in the scene
- A solution of this equation → a solution to the whole rendering problem
- Each approach to computer graphics
  - Is different type of numerical solution or approximation to this equation
- Numerical and Monte Carlo sampling methods are used.

Light

- Visible light is electromagnetic radiation with wavelengths approximately in the range from 400nm to 700nm

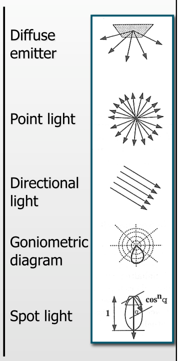


Light: Photons

- Light can be viewed as
  - wave or
  - particle phenomenon
- Particles are photons
  - packets of energy which travel in a straight line in vacuum with velocity c (~300,000 mps)
- The problem of how light interacts with surfaces in a volume of space is an example of a transport problem.

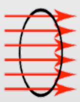
Light Sources

- Types of light sources
  - Point lights
  - Spot-lights
    - Cone of light
    - Radiation characteristic of $\cos^n\theta$
  - Point light sources with non-uniform directional power distribution
  - Area light sources
- Other parameter
  - Attenuation with distance (r) for point light sources
    - $1/(ar^2+br+c)$
    - Physically correct would be $1/r^2$
    - Correction of missing ambient light



Light: Radiant Power

- Φ denotes the radiant energy or **flux** in a volume
- The flux is the **rate of energy flowing** through a surface per unit time ([Watts] = [J/s]).
- The energy is **proportional to the particle flow**, since each photon carries energy.
- The flux may be thought of as the **flow of photons per unit time**.



Light: Flux Equilibrium

- Total flux in a volume in dynamic equilibrium
  - Particles are flowing
  - Distribution is constant
- Conservation of energy
  - Total **energy input** into the volume **=** total energy that is **output** by or absorbed by matter within the volume.

Light: Fundamental Equation

- Input
  - Emission – emitted from within volume
  - Inscattering – flows from outside
- Output
  - Streaming – without interaction with matter in the volume
  - Outscattering – reflected out from matter
  - Absorption – by matter within the volume
- Input = Output

Light: Equation

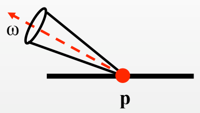
- $\Phi(p,\omega)$ denotes flux at $p \in V$, in direction ω
- It is possible to write down an integral equation for $\Phi(p,\omega)$ based on:
  - Emission+Inscattering = Streaming+Outscattering +Absorption
- Complete knowledge of $\Phi(p,\omega)$ provides a complete solution to the illumination problem.
- Rendering is about solving for $\Phi(p,\omega)$.

Simplifying Assumptions

- Wavelength independence
  - No interaction between wavelengths (no fluorescence)
- Time invariance
  - Solution remains valid over time unless scene changes (no phosphorescence)
- Light transports in a vacuum (non-participating medium)
  - ‘free space’ – interaction only occurs at the surfaces of objects

Rendering Equation – Overview

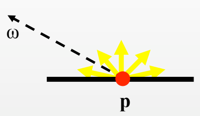
The Rendering Equation



$$L(p, \omega) = L_e(p, \omega) + \int f(p, \omega_i, \omega) L(p^*, -\omega_i) \cos\theta_i \, d\omega_i$$

$L(p,\omega)$ is the radiance from a point on a surface in a given direction ω

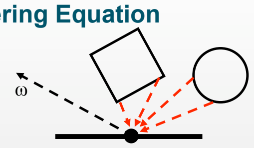
The Rendering Equation



$$L(p, \omega) = L_e(p, \omega) + \int f(p, \omega_i, \omega) L(p^*, -\omega_i) \cos\theta_i \, d\omega_i$$

$L_e(p,\omega)$ is the emitted radiance from a point: L_e is non-zero only if p is emissive (= a light source)

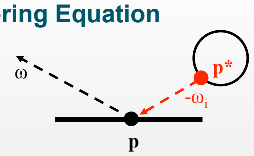
The Rendering Equation



$$L(p, \omega) = L_e(p, \omega) + \underbrace{\int f(p, \omega_i, \omega)\, L(p^*, -\omega_i) \cos\theta_i \, d\omega_i}$$

Sum the contribution from all of the other surfaces in the scene

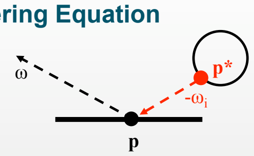
The Rendering Equation



$$L(p, \omega) = L_e(p, \omega) + \int f(p, \omega_i, \omega)\, L(p^*, -\omega_i) \cos\theta_i \, d\omega_i$$

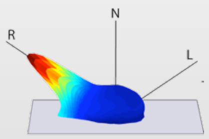
For each ω_i, compute $L(p^*, -\omega_i)$: the radiance at point p* in the direction $-\omega_i$ (i.e., radiance arriving at p)

The Rendering Equation

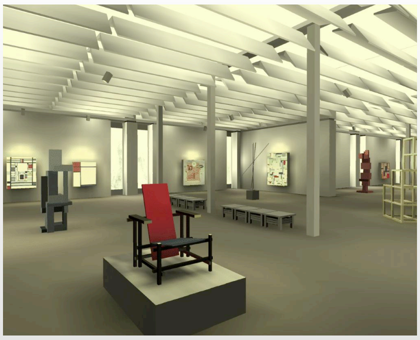


$$L(p, \omega) = L_e(p, \omega) + \int f(p, \omega_i, \omega)\, L(p^*, -\omega_i) \cos\theta_i \, d\omega_i$$

Scale the contribution by $f(x,\omega_i,\omega)$, the reflectivity (BRDF) of the surface at p



Questions?



Museum simulation. Program of Computer Graphics, Cornell University.
50,000 patches. Note indirect lighting from ceiling.

Details

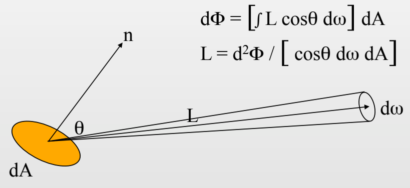
Radiometric terms

- Radiant energy Q, measured in joules (J)
  - This is the basic unit of energy, each particle can be thought of carrying some number of joules of energy
- Radiant power or flux Φ, measured in watts (W)
  - The flux is the rate of energy flowing through a surface per unit time
  - $\Phi = dQ/dt$

Radiance

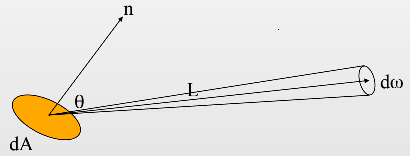
- Radiance (L) is the **flux** that leaves a surface, **per unit projected area** of the surface, **per unit solid angle** of direction. Its unit is: [W/(m² sr)].

$$d\Phi = \left[\int L \cos\theta \, d\omega\right] dA$$
$$L = d^2\Phi \,/\, \left[\cos\theta \, d\omega \, dA\right]$$



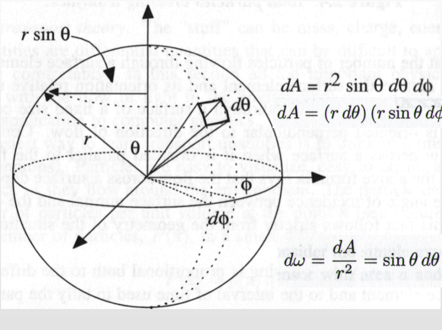
Radiance

- For computer graphics the basic particle is not the photon and the energy it carries but the ray and its associated radiance.



Radiance is constant along a ray.

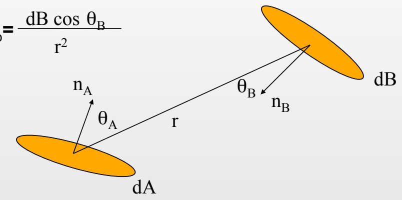
Solid Angle



$$dA = r^2 \sin\theta \, d\theta \, d\phi$$
$$dA = (r\,d\theta)\,(r\sin\theta\,d\phi) = r^2 \sin\theta \, d\theta \, d\phi$$
$$d\omega = \frac{dA}{r^2} = \sin\theta \, d\theta \, d\phi$$

Solid Angle

$$d\omega_b = \frac{dB \cos \theta_B}{r^2}$$



Radiosity and Irradiance

- **Radiosity** is the **flux per unit area** that **radiates** from a surface, denoted by *B*, measured in [W/m²]
  - dΦ = B dA
- **Irradiance** is the **flux per unit area** that **arrives** at a surface, denoted by *E,* measured in [W/m²]
  - dΦ = E dA

Radiosity and Irradiance

- L(p,ω) is radiance at p in direction ω
- E(p) is irradiance at p
- E(p) = (dΦ/dA) = ∫ L(p,ω) cosθ dω

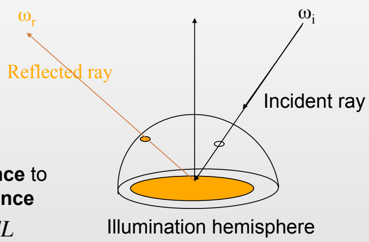
~~(or: L = dE/dA)~~

UCL

Reflectance

$f_r(p, \omega_i, \omega_r)$ Unit: 1/sr

- BRDF
  - **B**i-directional
  - **R**eflectance
  - **D**istribution
  - **F**unction
- Relates
  - Reflected **radiance** to incoming **irradiance**



$$f_r(p,\omega_i,\omega_r) = \frac{dL}{dE}$$

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BRDF

- Boils down to: How much light is reflected for a given light/ view direction at a point?
- Defines the "look" of the surface
- Important part for realistic surfaces:
  - Variation (in texture, gloss, …)

UCL

Describing the reflectance

- As for the light, we simplify the physical reality
- We consider in computer graphics the following properties
  - Diffuse, Specular
  - Isotropic, Anisotropic
- But
  - This is a sample of the real complexity
    - No fluorescence, phosphorescence, diffraction, etc…
  - Often approximated for an area or a full object, although in reality different in every point!

BRDF

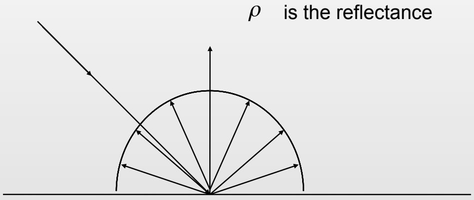
- In practice BRDF's hard to specify
- Rely on ideal types
  - Perfectly diffuse reflection
  - Perfectly specular reflection
  - Glossy reflection
- BRDFs taken as additive mixture of these

Perfectly diffuse

- Radiance reflected equally in every direction independently of the incoming direction

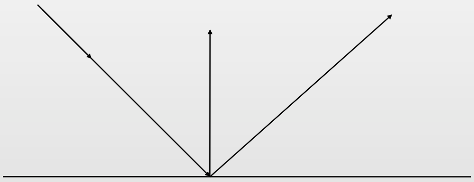
$$f_r(\omega_i, \omega_r) = \rho / \pi$$

ρ is the reflectance



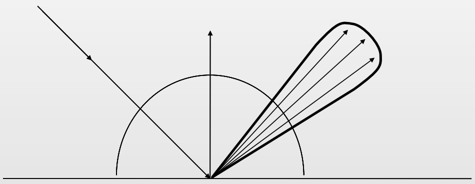
Perfectly specular

- Reflected dependently of the incident light



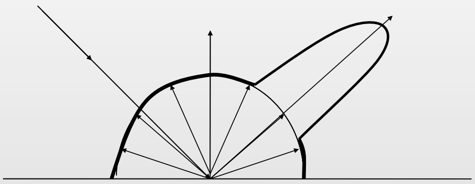
BRDF

- Glossy



BRDF

- Diffuse + Glossy



How to define a BRDF

- Define
  - By hand (difficult)
  - Data basis (measured)
  - Estimate from photographs (inverse illumination)
- How to visually compensate for rough approximation?
  - Define the same BRDF for a whole surface
  - Apply a texture

Properties of BRDFs

- Non-negativity

$$f_r(\omega_i, \omega_r) \geq 0$$

- Energy Conservation

$$\int_\Omega f_r(\omega_i, \omega_r) d\mu(\omega_r) \leq 1 \quad \text{for all } \omega_i$$

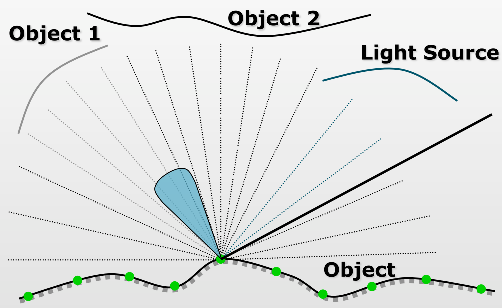
- Reciprocity

$$f_r(\omega_i, \omega_r) = f_r(\omega_r, \omega_i)$$

  - Aside: actually does often **not** hold for real materials [see Eric Veach's PhD Thesis!]

How to compute amount of reflected light?

- Integrate all incident light * BRDF



The Radiance Equation

- Radiance L(p, ω) at a point p in direction ω is the sum of
  - Emitted radiance L_e(p, ω)
  - Total reflected radiance

Radiance =
Emitted Radiance + Total Reflected Radiance

The Radiance Equation: Reflection

- Total **reflected radiance** in direction ω:

  $\int f(p, \omega_i, \omega)\, L(p^*, -\omega_i) \cos\theta_i \, d\omega_i$

- Full Radiance Equation:

(p* is closest point in direction ω_i)

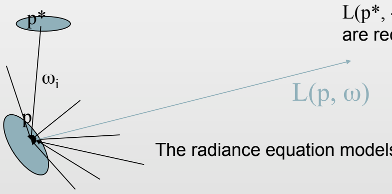
$$L(p, \omega) = L_e(p, \omega) + \int f(p, \omega_i, \omega)\, L(p^*, -\omega_i) \cos\theta_i \, d\omega_i$$

  – (Integration over the illumination hemisphere)

The Radiance Equation

- Light incident at p from direction ω_i, is in fact light that is reflected from p* in direction $-\omega_i$:
  – $L_{incident}(p, \omega_i) = L(p^*, -\omega_i)$

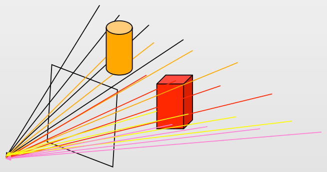
$L(p, \omega)$ depends on all $L(p^*, -\omega_i)$ which in turn are recursively defined.



The radiance equation models global illumination.

Traditional Solutions to the Radiance Equation

- The radiance equation embodies totality of all views (2D projections).
- Extraction a 2D projection to form an image is called rendering.



Traditional Solutions

	Local Illumination	Global Illumination
View Dependent	'Real time' graphics: OpenGL	Ray tracing Path tracing
View Independent	Flat shaded graphics (IBR)	Radiosity (Photon Tracing)

OpenGL

- In OpenGL, we can define the reflectance with different material properties
  - glMaterialf(GL_FRONT,GL_DIFFUSE, r,g,b);
  - glMaterialf(GL_FRONT, GL_DIFFUSE, 0.3, 0.3, 0.4);
  - glMaterialf(GL_FRONT, GL_SPECULAR, 0.3, 0.4, 0.4);
- You can add a transparency coefficient α
  - glMaterialf(GL_FRONT, GL_DIFFUSE, R,G,B,A);
  - glMaterialf(GL_FRONT, GL_DIFFUSE, 0.3, 0.3, 0.4, 1);
  - $\alpha \in [0..1]$, 1 for completely opaque, 0 for completely transparent
- But OpenGL does not provide a global illumination solution!

Other Solutions

- Will be the topic over the next few lectures