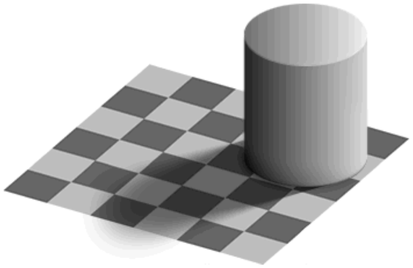
Announcements

Project status reports on Wednesday

- prepare 5 minute ppt presentation
- should contain:
  - problem statement (1 slide)
  - description of approach (1 slide)
  - some images (1 slide)
  - current status + plans (1 slide)

Light

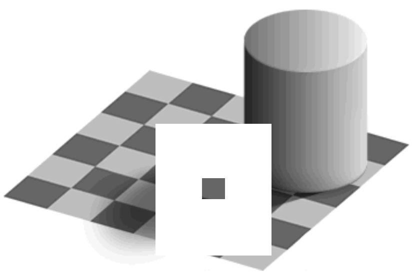


by Ted Adelson

Readings

- Szeliski, 2.2, 2.3.2

Light



by Ted Adelson

Readings

- Szeliski, 2.2, 2.3.2

Properties of light

Today

- What is light?
- How do we measure it?
- How does light propagate?
- How does light interact with matter?

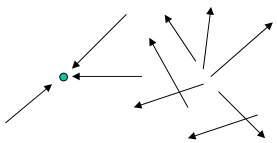
What is light?

Electromagnetic radiation (EMR) moving along rays in space

- R(λ) is EMR, measured in units of power (watts)
  - λ is wavelength

Light field

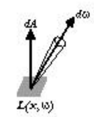
- We can describe all of the light in the scene by specifying the radiation (or **"radiance"** along all light rays) arriving at every point in space and from every direction



$$R(X, Y, Z, \theta, \phi, \lambda, t)$$

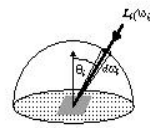
Radiometry

Radiometry is the science of light energy measurement



Radiance

The energy carried by a ray
energy/(area solidangle)



Irradiance

The energy per unit area falling on a surface

Radiosity

The energy per unit area leaving a surface

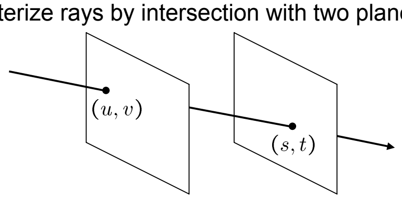
The light field

$R(X, Y, Z, \theta, \phi, \lambda, t)$

- Known as the **plenoptic function**
- If you know *R*, you can predict how the scene would appear from any viewpoint. How?

The **light field** $R(u, v, s, t)$ ← t is *not* time (different from above t !)

- Assume radiance does not change along a ray
  - what does this assume about the world?
- Parameterize rays by intersection with two planes:



- Usually drop λ and time parameters
- How could you capture a light field?

Stanford light field gantry

More info on light fields

If you're interested to read more:

The plenoptic function

- **Original reference:** E. Adelson and J. Bergen, "The Plenoptic Function and the Elements of Early Vision," in M. Landy and J. A. Movshon, (eds) Computational Models of Visual Processing, MIT Press 1991.
- L. McMillan and G. Bishop, "Plenoptic Modeling: An Image-Based Rendering System", Proc. SIGGRAPH, 1995, pp. 39-46.

The light field

- M. Levoy and P. Hanrahan, "Light Field Rendering", Proc SIGGRAPH 96, pp. 31-42.
- S. J. Gortler, R. Grzeszczuk, R. Szeliski, and M. F. Cohen, "The lumigraph," in Proc. SIGGRAPH, 1996, pp. 43-54.

What is light?

Electromagnetic radiation (EMR) moving along rays in space

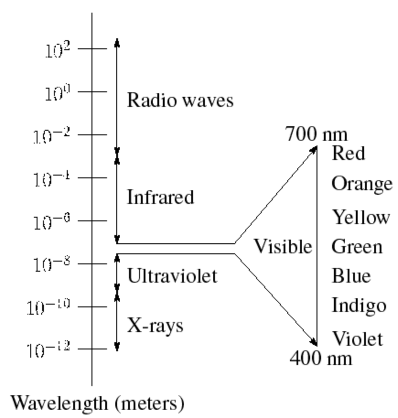
- $R(\lambda)$ is EMR, measured in units of power (watts)
  - λ is wavelength

Perceiving light

- How do we convert radiation into "color"?
- What part of the spectrum do we see?

The visible light spectrum

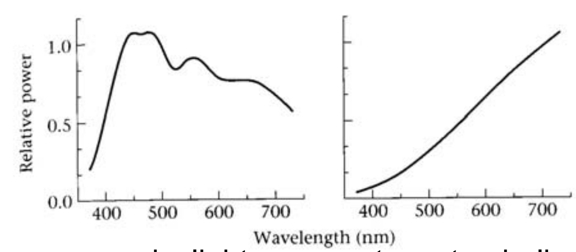
We "see" electromagnetic radiation in a range of wavelengths



Light spectrum

The appearance of light depends on its power **spectrum**

- How much power (or energy) at each wavelength

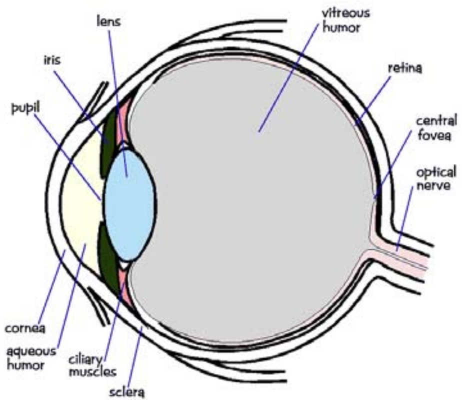


daylight tungsten bulb

Our visual system converts a light spectrum into "color"

- This is a rather complex transformation

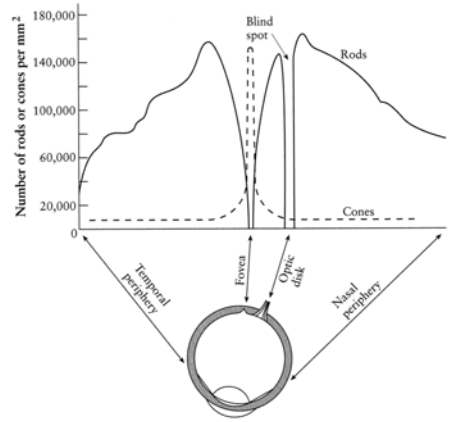
The human visual system



Color perception

- Light hits the retina, which contains photosensitive cells
  - rods and cones
- These cells convert the spectrum into a few discrete values

Density of rods and cones



Rods and cones are *non-uniformly* distributed on the retina

- Rods responsible for intensity, cones responsible for color
- **Fovea** - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
- Less visual acuity in the periphery—many rods wired to the same neuron

Demonstrations of visual acuity

With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).

Demonstrations of visual acuity

With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).

Brightness contrast and constancy

The apparent brightness depends on the surrounding region

- **brightness contrast**: a constant colored region seem lighter or darker depending on the surround:

  – http://www.sandlotscience.com/Contrast/Checker_Board_2.htm

- **brightness constancy**: a surface looks the same under widely varying lighting conditions.

Light response is nonlinear

Our visual system has a large *dynamic range*

- We can resolve both light and dark things at the same time
- One mechanism for achieving this is that we sense light intensity on a *logarithmic scale*
  – an exponential intensity ramp will be seen as a linear ramp
- Another mechanism is *adaptation*
  – rods and cones adapt to be more sensitive in low light, less sensitive in bright light.

Visual dynamic range

Background	Luminance (candelas per square meter)
Horizon sky	
Moonless overcast night	0.00003
Moonless clear night	0.0003
Moonlit overcast night	0.003
Moonlit clear night	0.03
Deep twilight	0.3
Twilight	3
Very dark day	30
Overcast day	300
Clear day	3,000
Day with sunlit clouds	30,000
Daylight fog	
Dull	300–1,000
Typical	1,000–3,000
Bright	3,000–16,000
Ground	
Overcast day	30–100
Sunny day	300
Snow in full sunlight	16,000

FIGURE 1.13
Luminance of everyday backgrounds. *Source:* Data from Rea, ed., *Lighting Handbook 1984 Reference and Application*, fig. 3-44, p. 3-24.

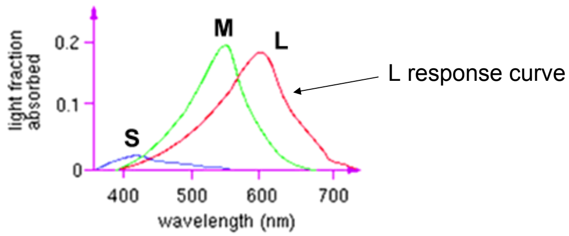
After images

Tired photoreceptors

- Send out negative response after a strong stimulus

http://www.sandlotscience.com/Aftereffects/Andrus_Spiral.htm

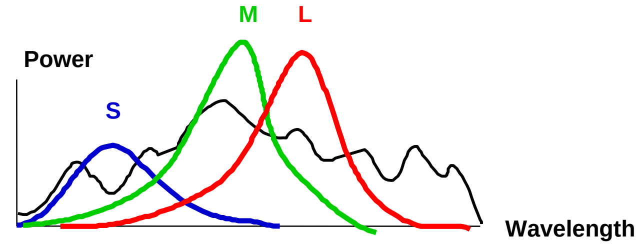
Color perception



Three types of cones

- Each is sensitive in a different region of the spectrum
  - but regions overlap
  - Short (S) corresponds to blue
  - Medium (M) corresponds to green
  - Long (L) corresponds to red
- Different sensitivities: we are more sensitive to green than red
  - varies from person to person (and with age)
- Colorblindness—deficiency in at least one type of cone

Color perception



Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number
- Q: How can we represent an entire spectrum with 3 numbers?
- A: We can't! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable
    - » such spectra are known as **metamers**
    - » http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/spectrum/metamers_guide.html

Perception summary

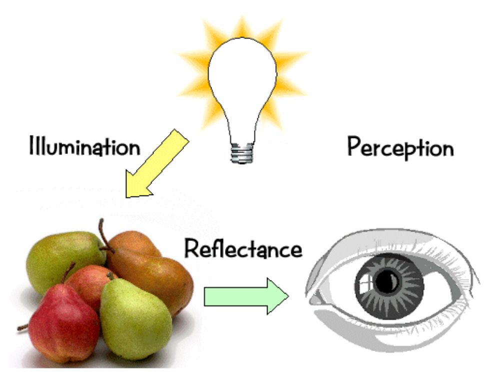
The mapping from radiance to perceived color is quite complex!

- We throw away most of the data
- We apply a logarithm
- Brightness affected by pupil size
- Brightness contrast and constancy effects
- Afterimages

The same is true for cameras

- But we have tools to correct for these effects
  - See Rick's lecture notes on Computational Photography and HDR

Light transport



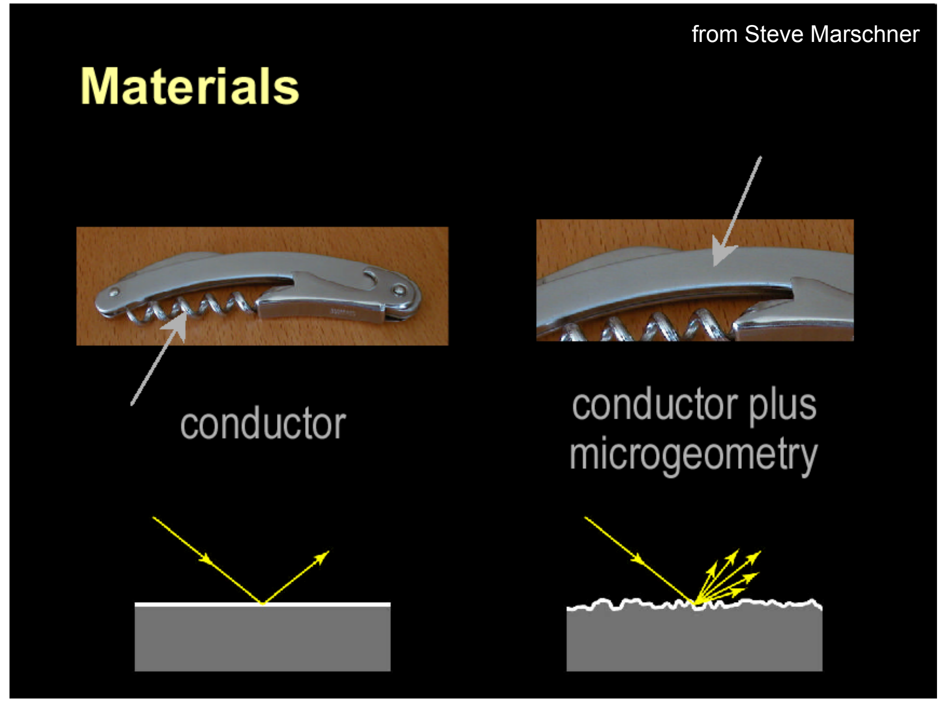
Light sources

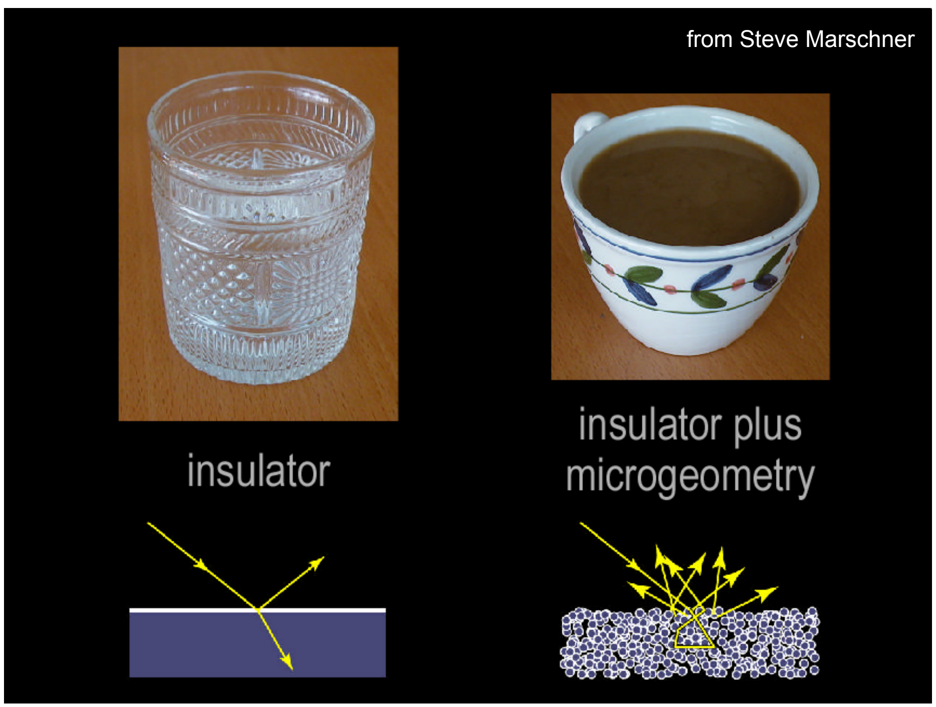
Basic types

- point source
- directional source
  - a point source that is infinitely far away
- area source
  - a union of point sources

More generally

- a light field can describe *any* distribution of light sources





The interaction of light and matter

What happens when a light ray hits a point on an object?

- Some of the light gets absorbed
  - converted to other forms of energy (e.g., heat)
- Some gets transmitted through the object
  - possibly bent, through "refraction"
- Some gets reflected
  - as we saw before, it could be reflected in multiple directions at once

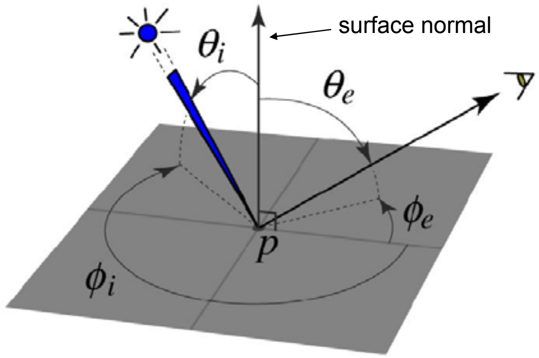
Let's consider the case of reflection in detail

- In the most general case, a single incoming ray could be reflected in all directions. How can we describe the amount of light reflected in each direction?

The BRDF

The Bidirectional Reflection Distribution Function

- Given an incoming ray (θ_i, ϕ_i) and outgoing ray (θ_e, ϕ_e) what proportion of the incoming light is reflected along outgoing ray?



Answer given by the BRDF: $\rho(\theta_i, \phi_i, \theta_e, \phi_e)$

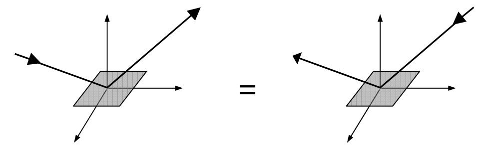
Constraints on the BRDF

Energy conservation

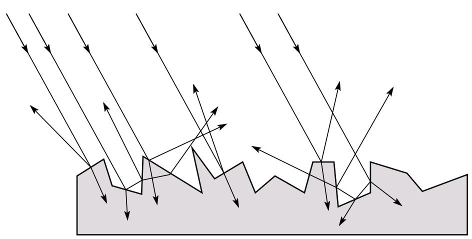
- Quantity of outgoing light ≤ quantity of incident light
  - integral of BRDF ≤ 1

Helmholtz reciprocity

- reversing the path of light produces the same reflectance



Diffuse reflection



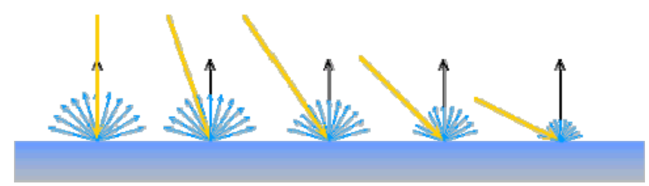
Diffuse reflection

- Dull, matte surfaces like chalk or latex paint
- Microfacets scatter incoming light randomly
- Effect is that light is reflected equally in all directions

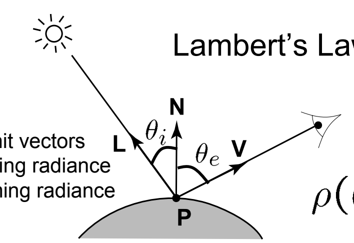
Diffuse reflection

Diffuse reflection governed by **Lambert's law**

- Viewed brightness does not depend on viewing direction
- Brightness *does* depend on direction of illumination
- This is the model most often used in computer vision



L, **N**, **V** unit vectors
I_e = outgoing radiance
I_i = incoming radiance



Lambert's Law: $I_e = k_d \mathbf{N} \cdot \mathbf{L} I_i$

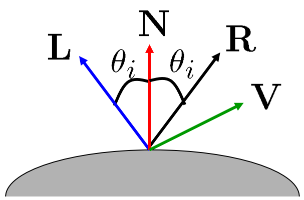
k_d is called **albedo**

BRDF for **Lambertian surface**

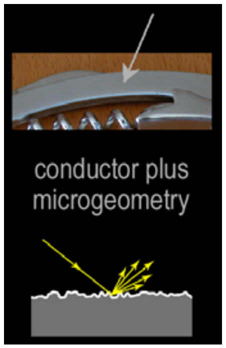
$$\rho(\theta_i, \phi_i, \theta_e, \phi_e) = k_d cos\theta_i$$

Specular reflection

For a perfect mirror, light is reflected about **N**

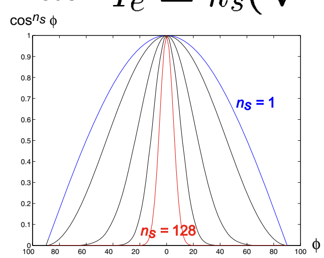


$$I_e = \begin{cases} I_i & \text{if } \mathbf{V} = \mathbf{R} \\ 0 & \text{otherwise} \end{cases}$$

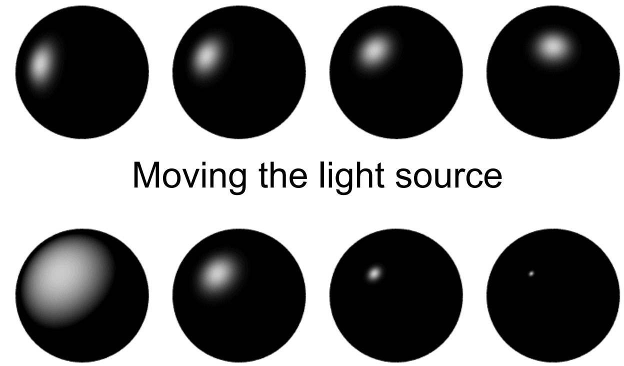


Near-perfect mirrors have a **highlight** around **R**

- common model: $I_e = k_s (\mathbf{V} \cdot \mathbf{R})^{n_s} I_i$



Specular reflection



Moving the light source

Changing n_s

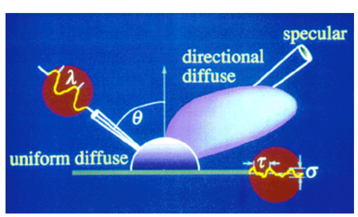
Phong illumination model

Phong approximation of surface reflectance

- Assume reflectance is modeled by three components
  - Diffuse term
  - Specular term
  - Ambient term (to compensate for inter-reflected light)

$$I_e = k_a I_a + I_i \left[k_d (\mathbf{N} \cdot \mathbf{L})_+ + k_s (\mathbf{V} \cdot \mathbf{R})_+^{n_s} \right]$$

L, **N**, **V** unit vectors
I_e = outgoing radiance
I_i = incoming radiance
I_a = ambient light
k_a = ambient light reflectance factor
$(x)_+$ = max(x, 0)



BRDF models

Phenomenological

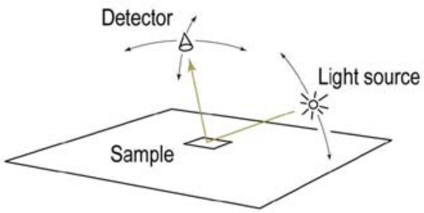
- Phong [75]
- Ward [92]
- Lafortune et al. [97]
- Ashikhmin et al. [00]

Physical

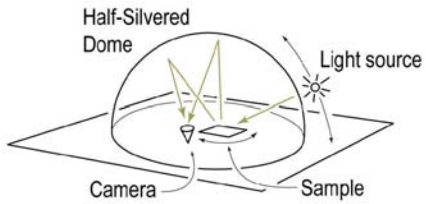
- Cook-Torrance [81]
- Dichromatic [Shafer 85]
- He et al. [91]

Here we're listing only some well-known examples

Measuring the BRDF



traditional



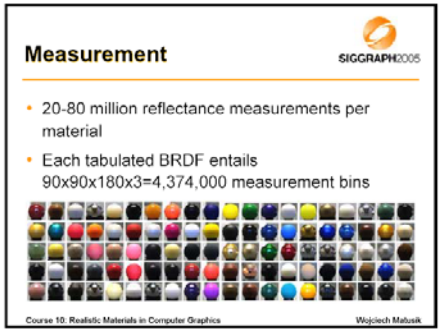
design by Greg Ward

Gonioreflectometer

- Device for capturing the BRDF by moving a camera + light source
- Need careful control of illumination, environment

BRDF databases

- MERL (Matusik et al.): 100 isotropic, 4 nonisotropic, dense



- CURET (Columbia-Utrect): 60 samples, more sparsely sampled, but also bidirectional texure functions (BTF)