Light and reflection

CS 178, Spring 2009

Begun 5/19/09, finished 5/21/09.

Marc Levoy
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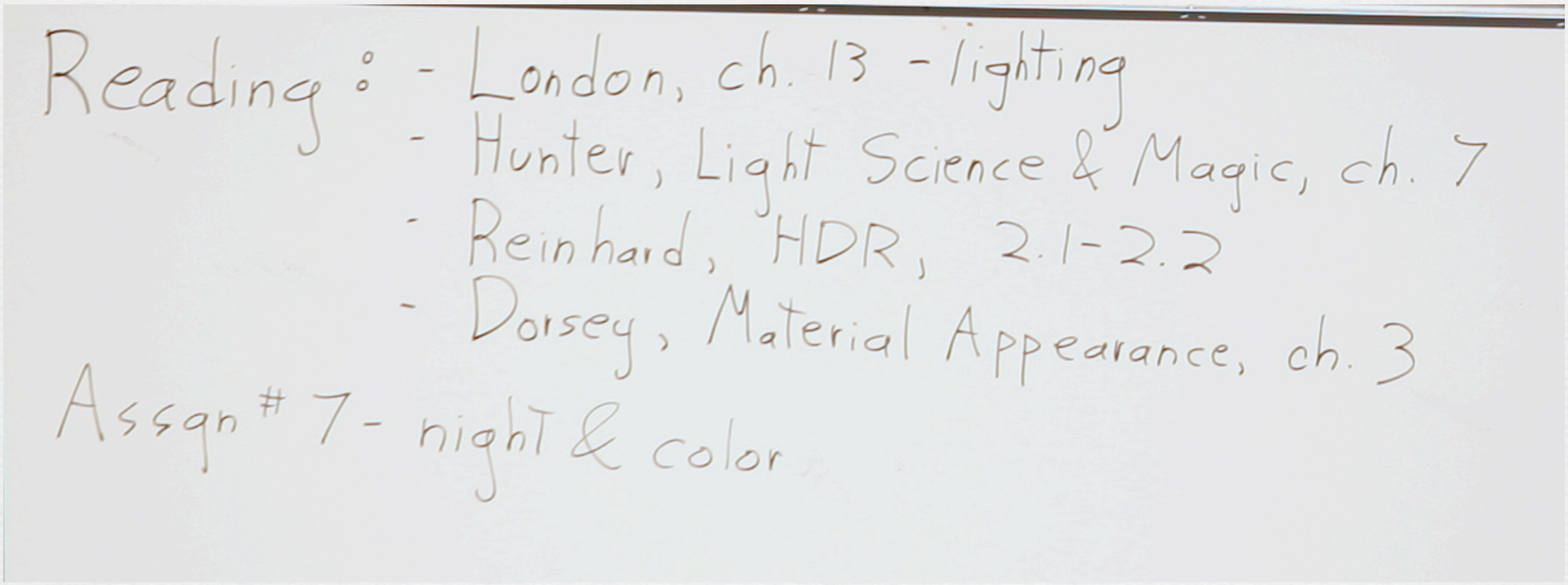
Announcements

- also, don't forget Jesse's (optional) night photography sessions on Wednesday and Saturday evenings (see emails)



Outline

- radiometry versus photometry
- measures of light
  - radiant intensity of a point light
  - radiance leaving an area light
  - radiance arriving on a surface
  - irradiance on a surface
- reflection of light
  - diffuse
  - specular
  - goniometric diagrams
  - BRDFs and BSSRDFs
  - Fresnel equations and other effects

Radiometry versus photometry

- *radiometry* is the study of light w/o considering humans
  - spectroradiometer - power as a function of wavelength
  - radiometer - total power, integrating over all wavelengths
  - measurements include
    - radiant intensity, radiance, irradiance

- *photometry* is the study of light as seen by humans
  - spectrophotometer - power we see as a function of wavelength
  - photometer, a.k.a. photographic light meter
  - measurements include
    - luminous intensity, luminance, illuminance

Relationship to tristimulus theory

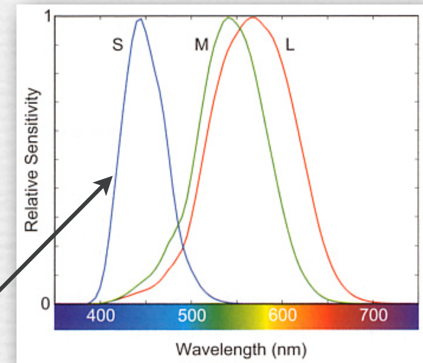
- the response of the human visual system to a spectrum is

$$(\rho,\gamma,\beta) = \left(\int_{400\,nm}^{700\,nm} L_e(\lambda)\,\rho(\lambda)\,d\lambda,\ \int_{400\,nm}^{700\,nm} L_e(\lambda)\,\gamma(\lambda)\,d\lambda,\ \int_{400\,nm}^{700\,nm} L_e(\lambda)\,\beta(\lambda)\,d\lambda \right)$$

luminance

radiance

(Stone)



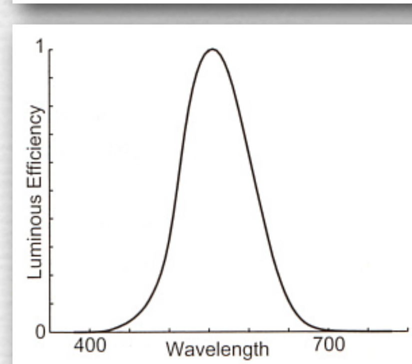
- the total response can be expressed as

$$L = \rho + \gamma + \beta = \int_{400\,nm}^{700\,nm} L_e(\lambda)\,V(\lambda)\,d\lambda$$

- where

$$V(\lambda) = \rho(\lambda) + \gamma(\lambda) + \beta(\lambda)$$

S is actually much lower than M or L



- *V(λ)* is called the luminous efficiency curve

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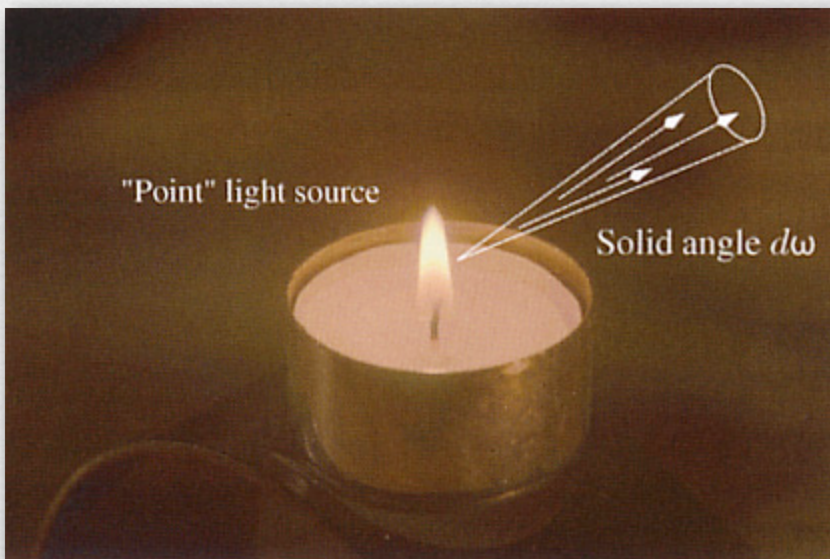
Radiant intensity of a point light

- power given off by the light per unit solid angle

$$I = \frac{P}{\Omega} \qquad \left(\frac{\text{watts}}{\text{steradian}} \right)$$



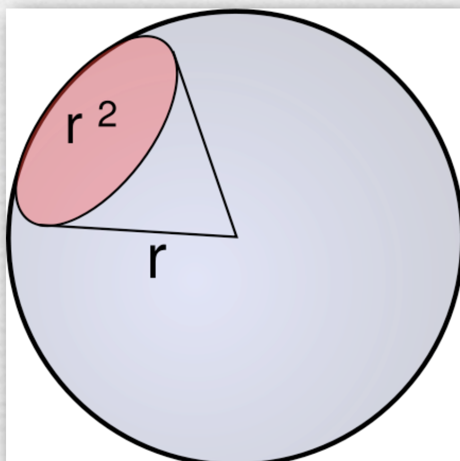
(Reinhard)

Ignore the $d\omega$ in the image. This image is from the readings, which show these equations in differential form, i.e. for infinitesimal solid angles. It's easier to think about large, finite angles, for which solid angle is denoted Ω.

- equivalently, the energy per unit time per unit solid angle
  - 1 watt = 1 joule / second

Steradian as a measure of solid angle

- 1 steradian (sr) is the solid angle such that the area subtended by that solid angle on the surface of a sphere is equal to the sphere's radius^2
  - the area of a sphere is $4\,\pi\,r^2$, so 1 sr ≈ 1/12 of a sphere



(http://www.handprint.com/HP/WCL/color3.html)

- examples
  - circular aperture 65° in diameter
  - square aperture 57° on a side
  - a circle 12.7' in diameter cast by a streetlight 10' high
  - as seen from earth, the moon subtends 0.52°, or 0.000065 sr

Radiant intensity of a point light

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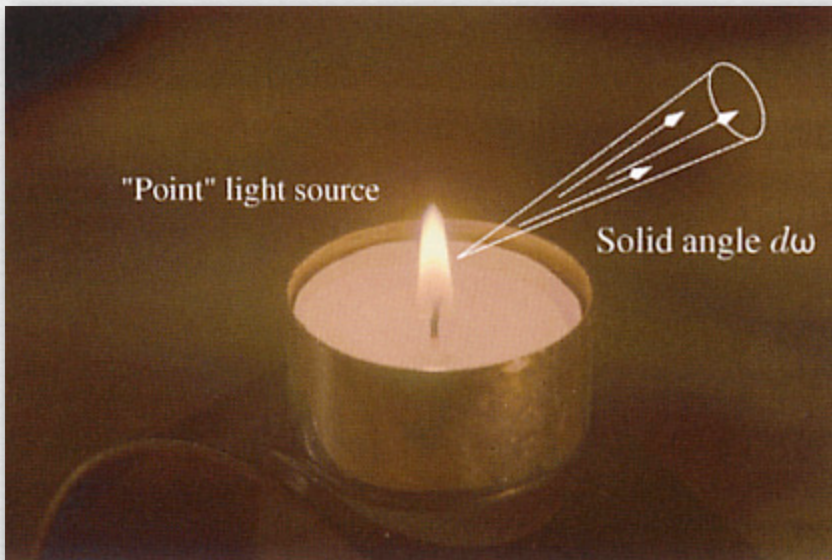


(Reinhard)

(http://www.handprint.com/HP/WCL/color3.html)

- example
  - 100W light bulb gives off 100 watts over the sphere ÷ 4π sr in a sphere = 8 watts within a 12.7’ circle 10’ feet from the bulb

Radiant intensity of a point light

- power given off by the light per unit solid angle

$$I = \frac{P}{\Omega} \qquad \left(\frac{\text{watts}}{\text{steradian}}\right)$$

Pierre Bouguer
(1698-1758)

- related photometric concept is luminous intensity (measured in candelas)
  - 1 candela = 1 lumen / sr
- examples
  - a standard Bouguer candle gives off 1 candela
  - a 100W light bulb with a luminous efficiency of 2.6% (the other 97.4% we don't see) gives off 17.6 lumens per watt × 100W ÷ 4π sr in the sphere = 140 candelas

Photography by candlelight

(digital-photography-school.com)

- need SLR-sized pixels, fast lens, tripod, patient subject
  - moderate shutter speed (1/15 sec) and ISO (400)

Cinematography by candlelight

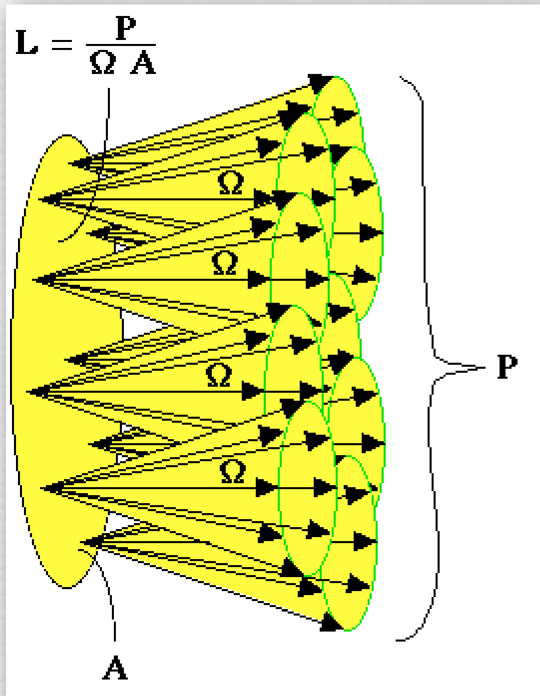
Stanley Kubrick,
Barry Lyndon,
1975

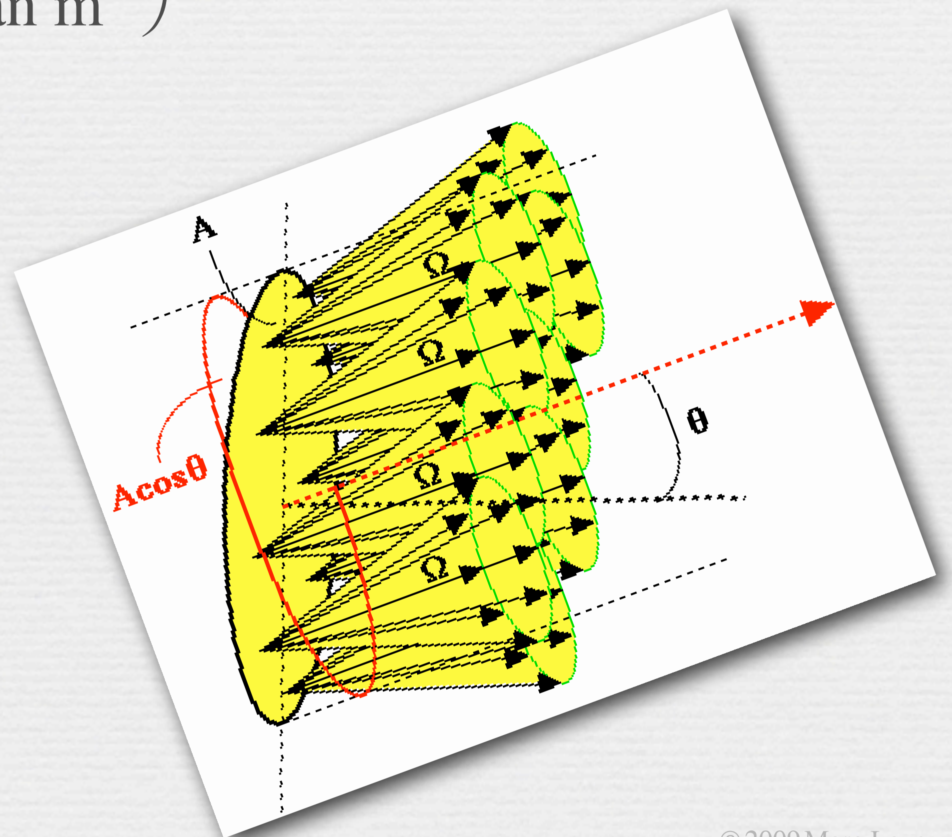
- Zeiss 50mm f/0.7 Planar lens
  - originally developed for NASA's Apollo missions
  - very shallow depth of field in closeups (when U is small)

Radiance leaving an area light

- power given off by the light per unit solid angle per unit area, viewed at an angle of θ away from straight-on

$$L = \frac{P}{\Omega A \cos\theta} \qquad \left(\frac{\text{watts}}{\text{steradian m}^2}\right)$$





(http://omlc.ogi.edu/classroom/ece532/class1/radiance.html)

Radiance leaving an area light

- power given off by the light per unit solid angle per unit area, viewed at an angle of θ away from straight-on

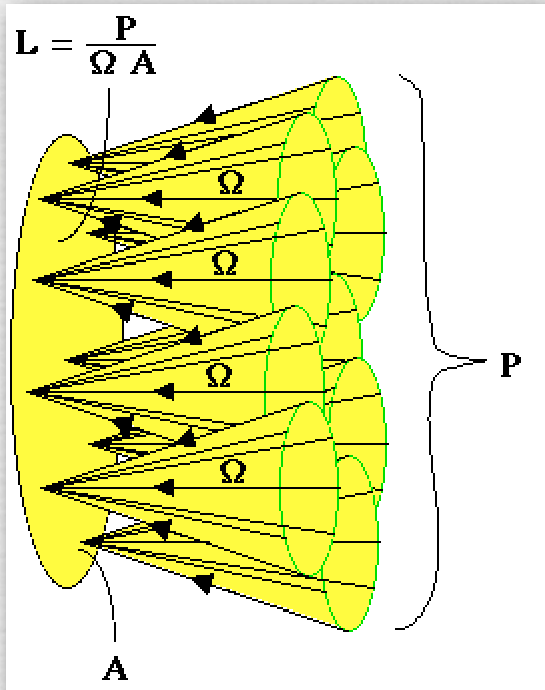
$$L = \frac{P}{\Omega A \cos\theta} \qquad \left(\frac{\text{watts}}{\text{steradian m}^2}\right)$$

- related photometric concept is luminance (measured in nits) (yup, nits!)
  - 1 nit = 1 candela / m^2 = 1 lumen / sr m^2
- example
  - viewed perpendicularly, a computer display gives off 50-300 candelas per meter^2 of the display surface, about the same as a 100W light bulb but spread out

Radiance arriving on a surface

- power arriving on a surface per unit solid angle per unit area, illuminated from an declination of θ

$$L = \frac{P}{\Omega A \cos\theta} \qquad \left(\frac{\text{watts}}{\text{steradian m}^2}\right)$$



Radiance arriving on a surface

- power arriving on a surface per unit solid angle per unit area, illuminated from an declination of θ

$$L = \frac{P}{\Omega A \cos\theta} \qquad \left(\frac{\text{watts}}{\text{steradian m}^2}\right)$$

As I mentioned in class, there is a proof missing here that the luminance leaving teach point on the surface of the moon (per unit solid angle per unit area on the moon, at least for points that perpendicularly face the earth) is the same as the luminance arriving on each point of the earth (per united solid angle per unit area on the earth, at least for points that perpendicularly face the moon). If you're interested in this proof that luminance (or radiance) is preserved during the transport of light, take CS 348B!

- examples (most from Minnaert)
  - luminance arriving on a surface from a full (overhead) sun is 100,000 candelas/cm^2 (100,000 lumens/sr cm^2)
  - luminance reflected by a diffuse white surface illuminated by the sun is 2 cd/cm^2
  - reflected by a black surface is 0.04 cd/cm^2
  - arriving from a full overhead moon is 0.3 cd/cm^2
  - luminance arriving from a white cloud (fully lit by the sun) is 10 × luminance of the blue sky, a difference of 3.3 f/stops

Irradiance on a surface

- power accumulating on a surface per unit area, considering light arriving from all directions

$$E = \frac{P}{A} \qquad \left(\frac{\text{watts}}{\text{m}^2}\right)$$

(Reinhard)

Again, ignore the dA in the image; just think about a large finite area A.

Irradiance on a surface

- power accumulating on a surface per unit area, considering light arriving from all directions

$$E = \frac{P}{A} \qquad \left(\frac{\text{watts}}{\text{m}^2}\right)$$

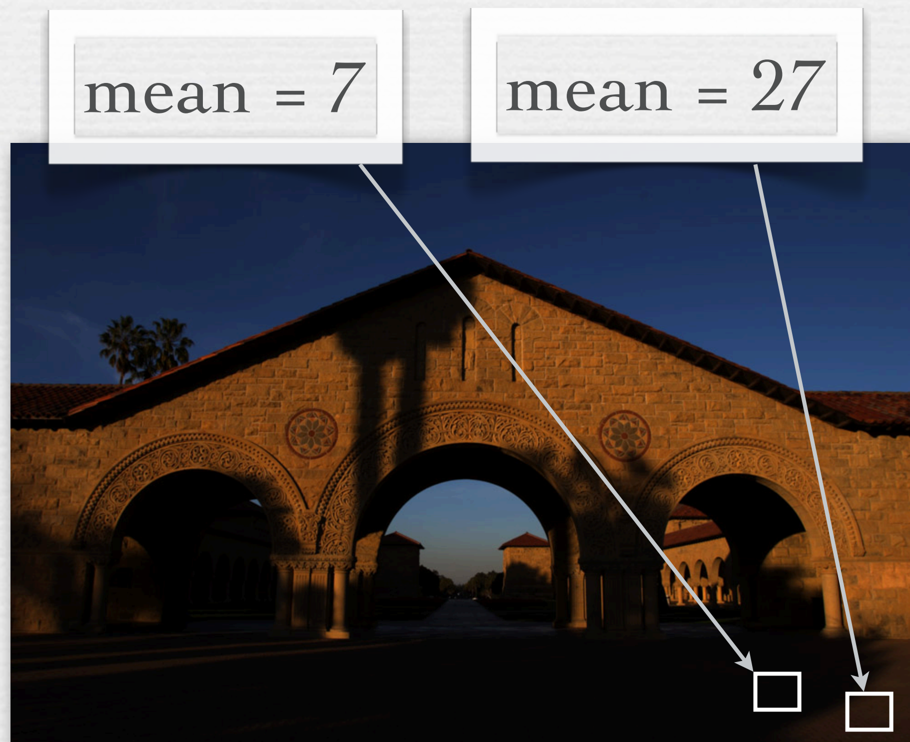
- related photometric unit is illuminance (measured in lux)
  - 1 lux = 1 lumen / m^2
  - British unit is footcandle = 1 candela held 1 foot from surface
- example
  - illuminance from a bright star = illuminance from a candle 900 meters away = 1/810,000 lux

How dark are outdoor shadows?

- luminance arriving on a surface from a full (overhead) sun is 300,000 × luminance arriving from the blue sky, but the sun occupies only a small fraction of the sky
- illuminance on a sunny day = 80% from the sun + 20% from blue sky, so shadows are 1/5 as bright as lit areas (2.3 f/stops)

(Marc Levoy)

JPEG file



RAW, linearly boosted

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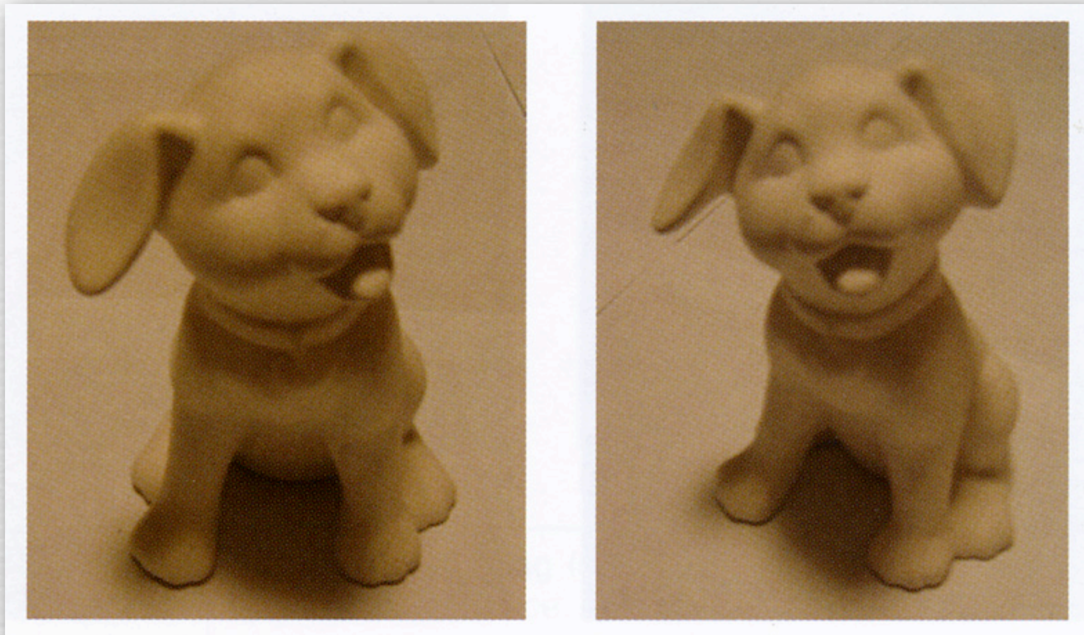
Reflection from diffuse surfaces



(Dorsey)

two viewpoints, same illumination

Johann Lambert
(1728-1777)

- rough surfaces reflect light uniformly in all directions
  - appearance is independent of viewing direction
  - if perfectly so, surface is called ideal diffuse (“Lambertian”)

Albedo

- fraction of light reflected from a diffuse surface
  - usually refers to an average across the visible spectrum

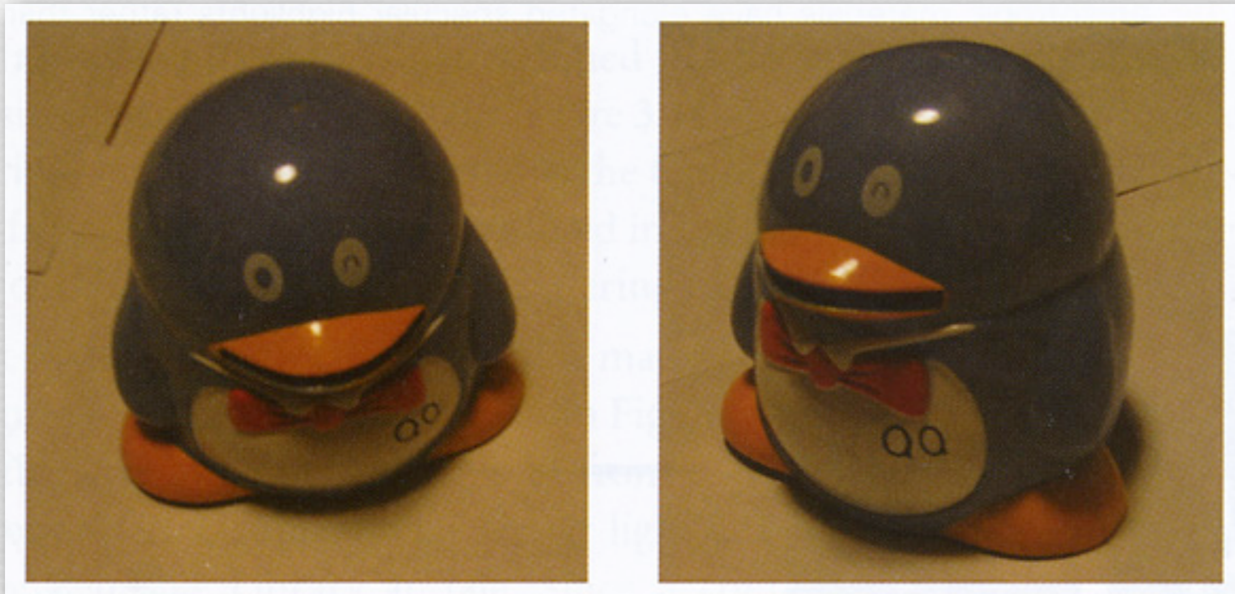
- examples

• clouds	80%
• fresh snow	80%
• old snow	40%
• grass	30%
• soil	15%
• rivers	7%
• ocean	3%

equality explains "whiteout" in blizzards

not including mirror reflections of the sun

Reflection from shiny surfaces



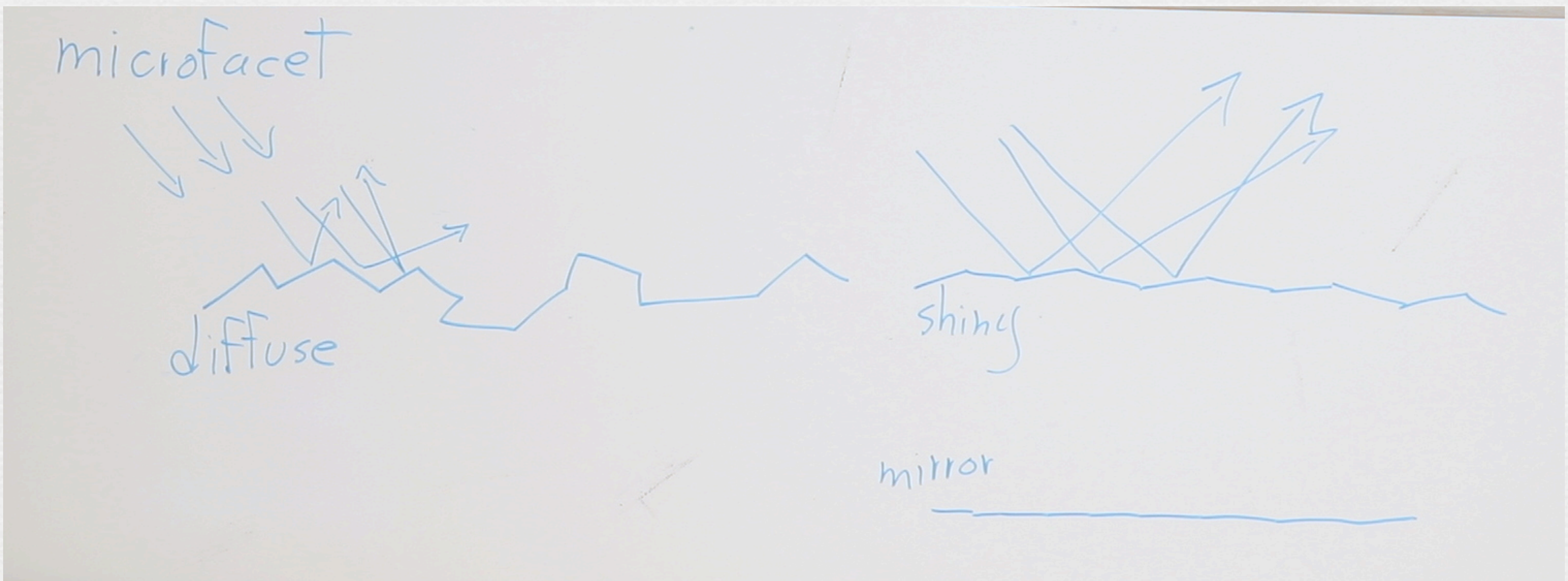
(Dorsey)

two viewpoints,
same illumination
(i.e. fixed to object)

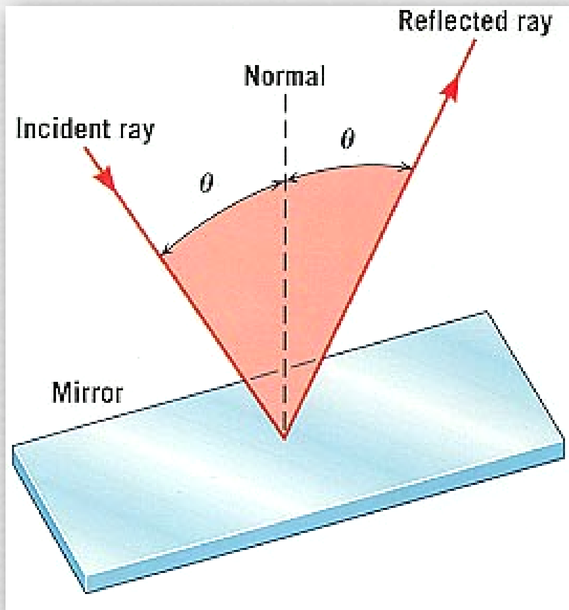
- rough surfaces are composed of flat microfacets (“asperities” according to Bouguer)
  - if most are randomly oriented, surface is diffuse
  - if most are aligned with the surface, it is shiny, with its *specular highlight* centered around the mirror direction (angle of reflection = angle of incidence)
  - location of highlight changes with movement of light or viewer

Microfacet distributions

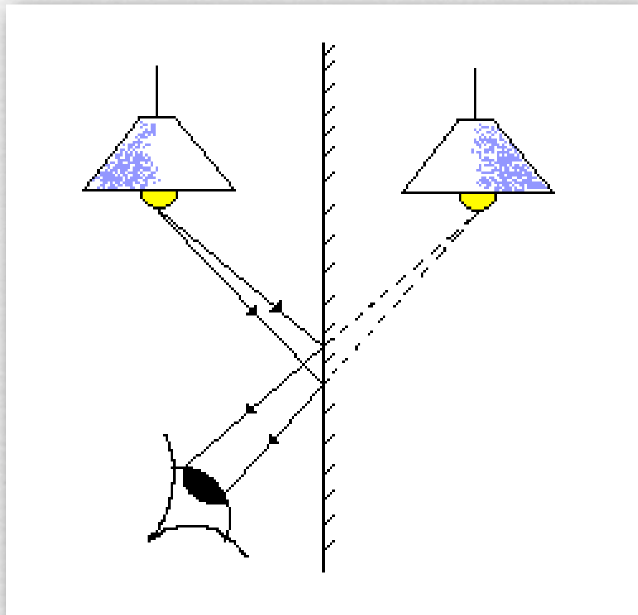
- see previous slide for explanation



Mirror reflections



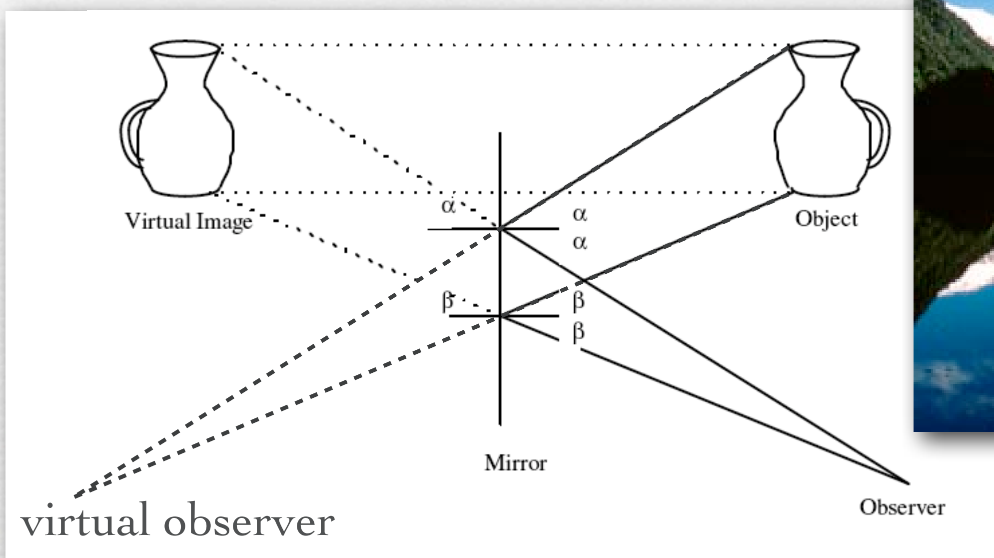
(Joseph Alward)

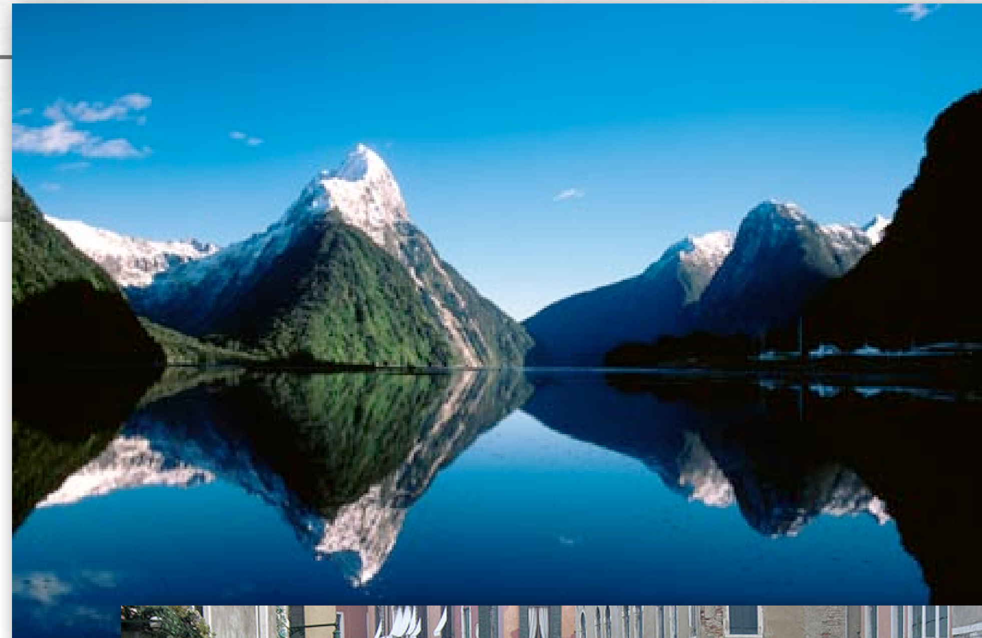


(ectc.org.uk)

- the focus distance of objects seen in mirrors is more than the distance from you to the mirror!

Mirror reflections





- scenes reflected in water are not copies of the scenes!
  - the reflection shows the underside of the bridge

A. She's look at you (the painter). If you can see her face in the mirror, she is looking at your face, not at herself!

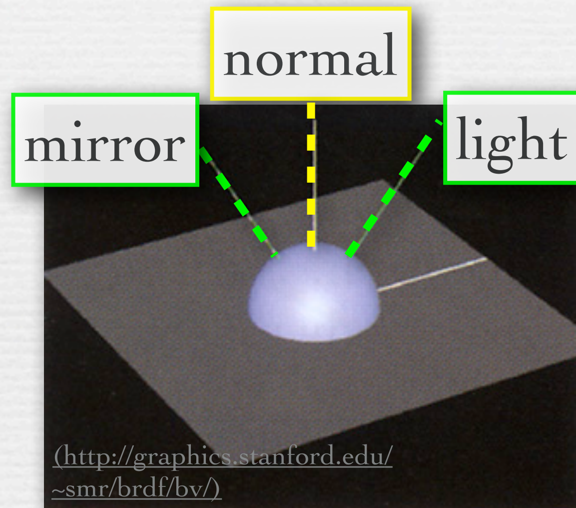
Diego Velázquez, Venus at her Mirror, 1647

Q. Who is Venus looking at in the mirror?

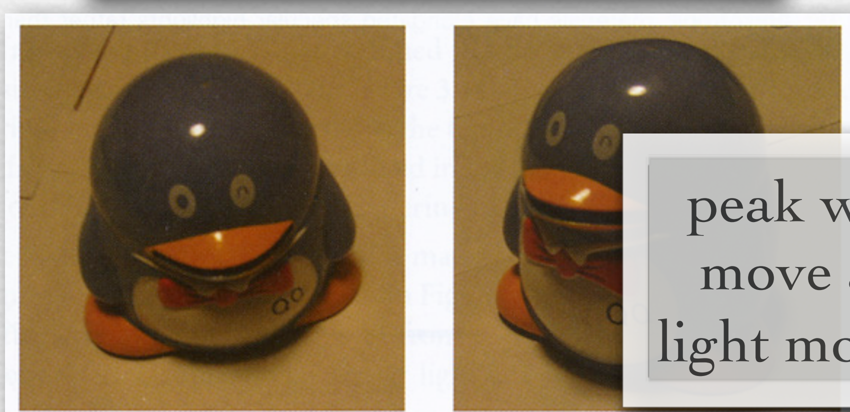
Goniometric diagram

- depiction of reflectance (fraction of light reflected) as a function of one of the relevant angles or directions
- shown here is reflectance as a function of viewing direction, for a fixed incoming direction of light

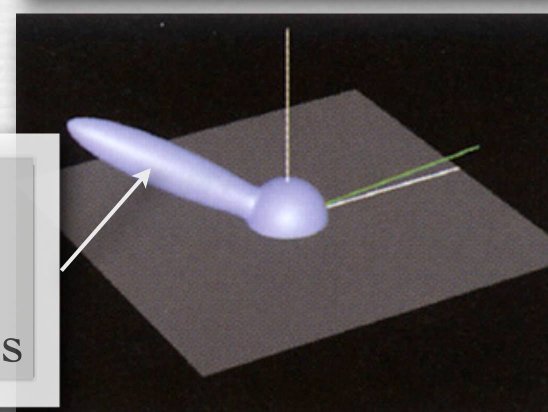
diffuse surface



shiny surface

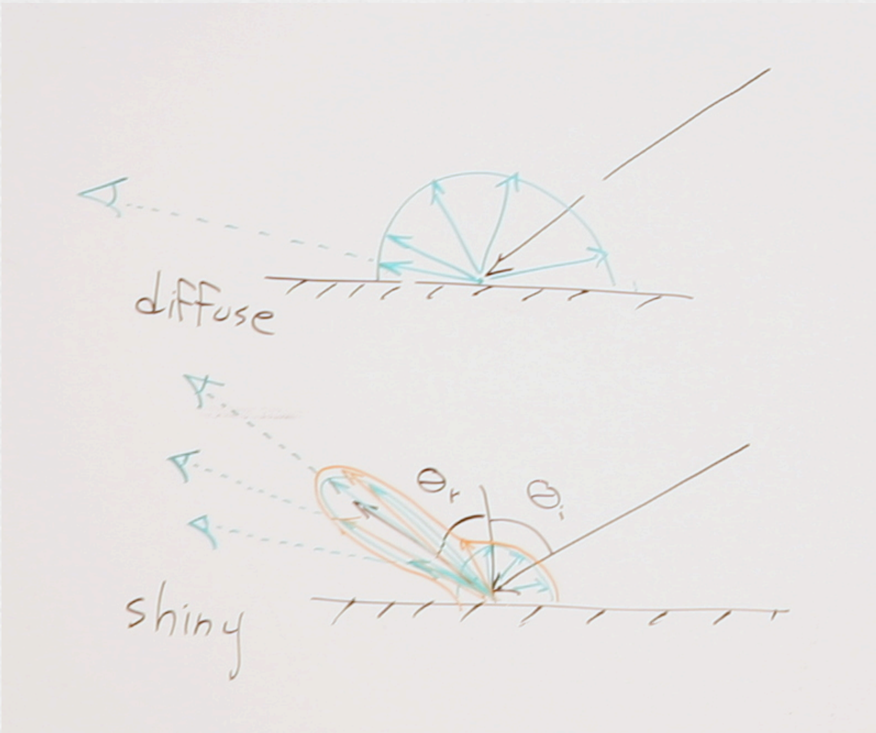


peak will move as light moves

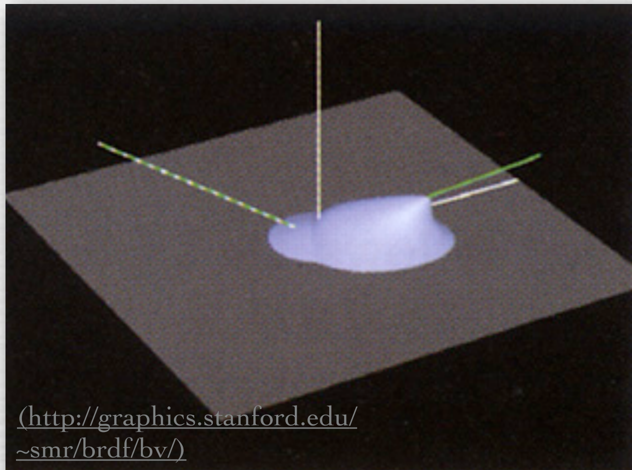


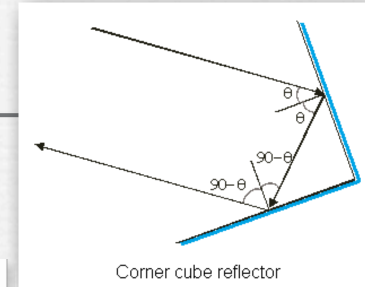
Goniometric diagrams in flatland

- the incoming light is the long black vector at right in both drawings
- for the given incoming light direction, the fraction of light reflected in each viewing direction is given by the lengths of the green arrows
- in the shiny case, there is a diffuse component, whose reflectance is equal across all viewing directions, and a specular component, which is strongest in the mirror direction (angle of reflection θ_r equals angle of incidence θ_i); the total reflectance, hence the final goniometric diagram, is the sum of these two components, i.e. the orange envelope



What unusual material property does this goniometric diagram depict?



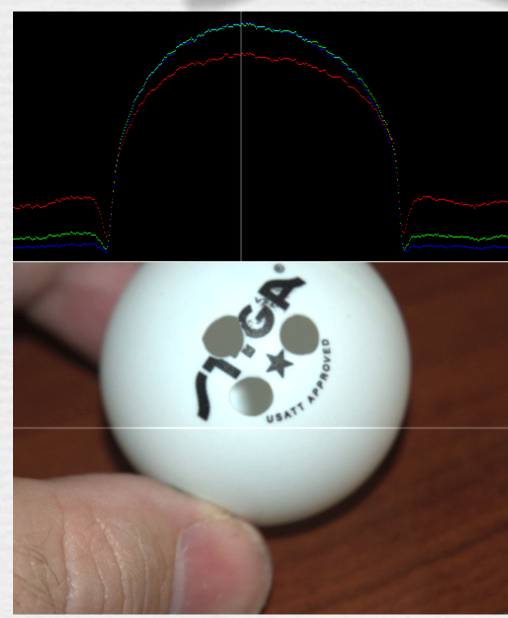


a full moon is roughly lit from the camera's viewpoint

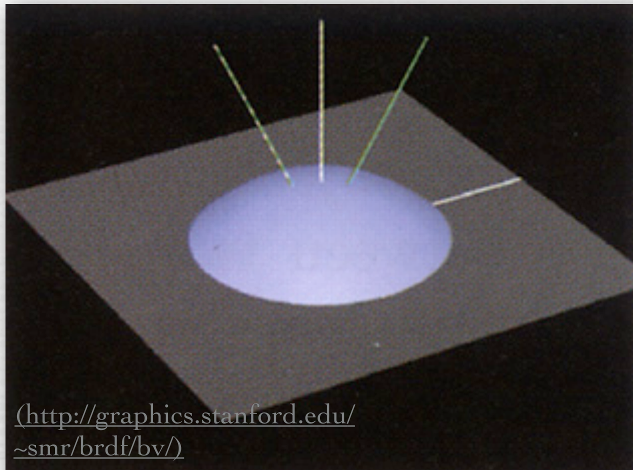
so is a flash photograph

- A. retroreflectivity
- the maria of the moon is retroreflective and gray
- a diffuse object, lit from the camera's viewpoint, falls off as cos θ

(NASA)



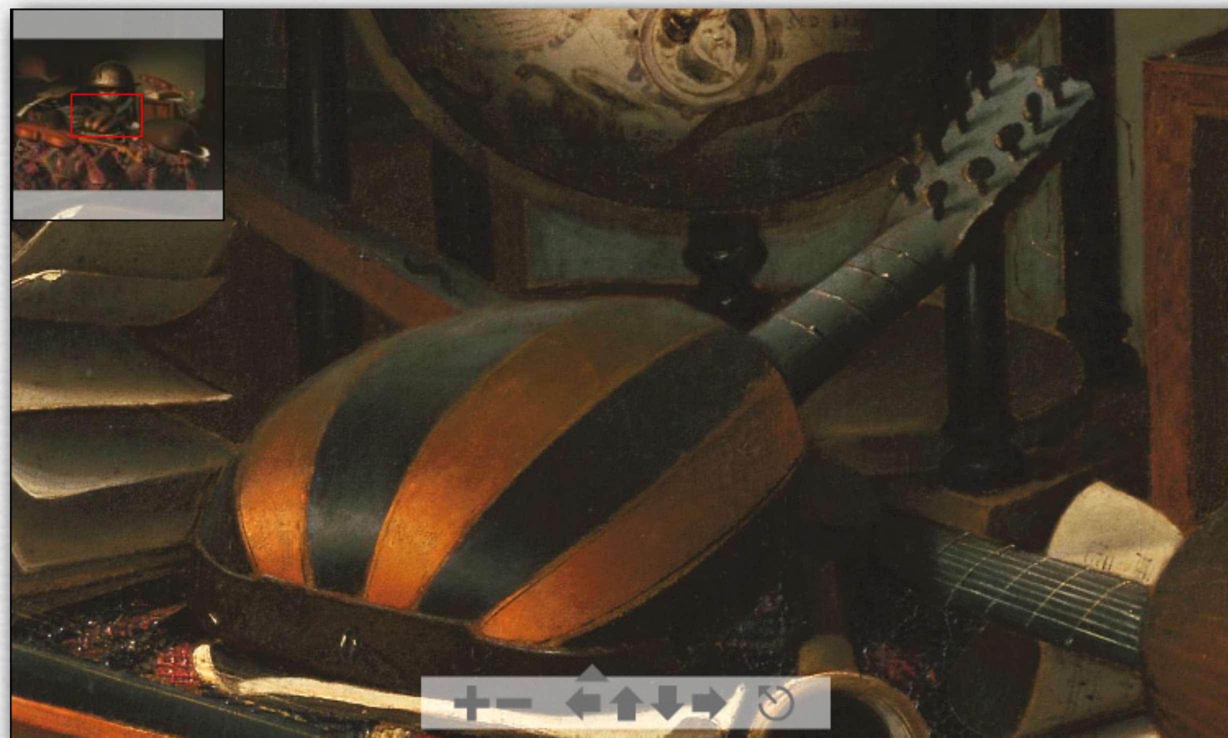
What about this goniometric diagram?



(http://graphics.stanford.edu/~smr/brdf/bv/)

- A. dusty scatterer
- appears brighter as the viewer moves to grazing angles

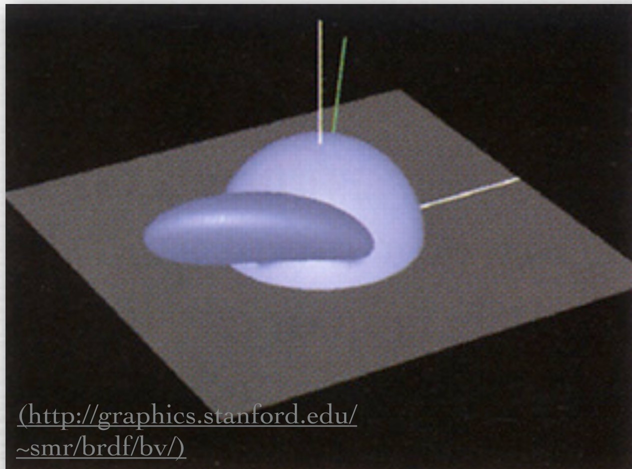
(famsf.org)

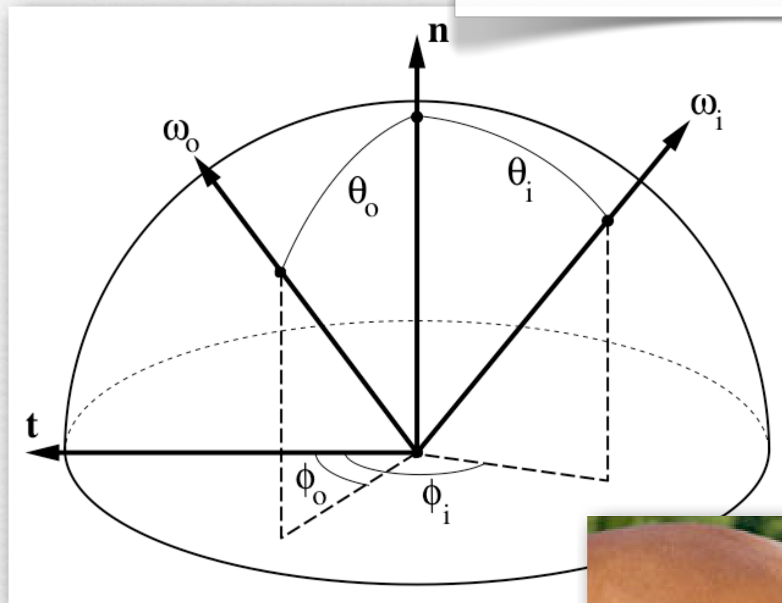


Bartolomeo Bettera,
Still Life with Musical Instruments,
17th century

And this goniometric diagram?

θ's denote declination;
ϕ's denote azimuth


(http://graphics.stanford.edu/~smr/brdf/bv/)

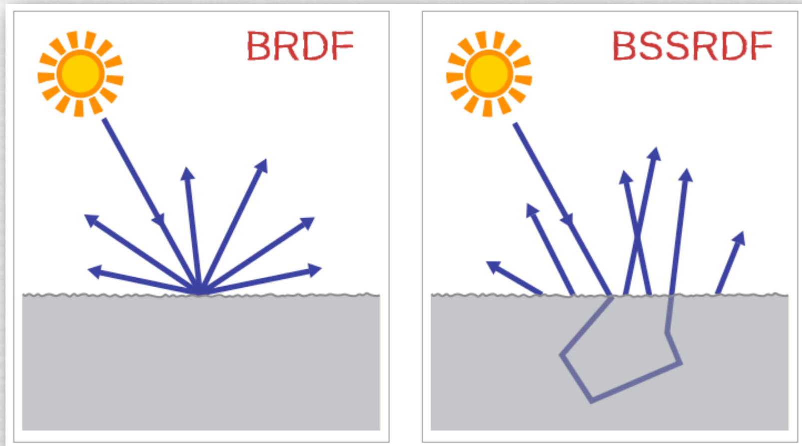


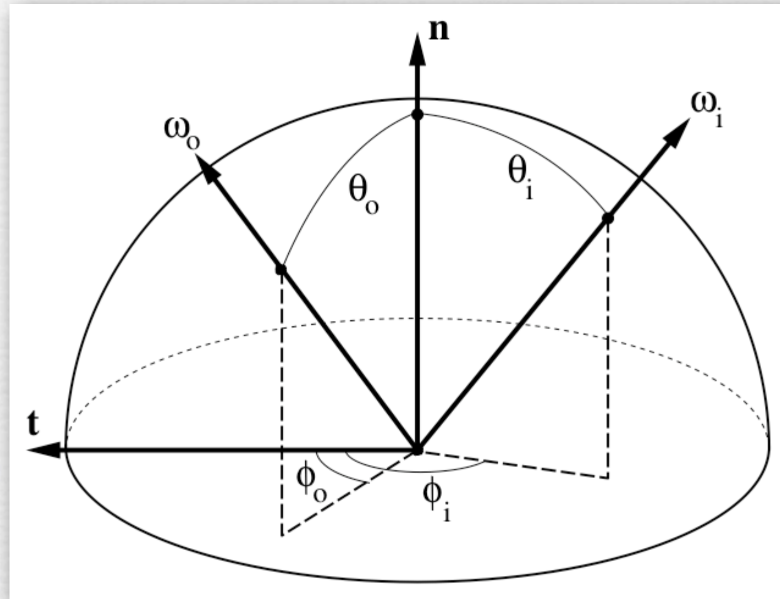
- A. anisotropic reflection
  - highlight not radially symmetric around mirror direction (typical but not strictly required)
  - diagram changes shape with azimuthal rotation of the light (required but not shown above)
- typically produced by directionally textured materials


(horsemanmagazine.com)

BRDFs and BSSRDFs

(wikipedia)





(http://graphics.stanford.edu/~smr/brdf/bv/)

- Bidirectional Reflectance Distribution Function (BRDF, 4D function)

$$f_r(\theta_i, \phi_i, \theta_r, \phi_r) \qquad \left(\frac{1}{sr}\right)$$

- Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF, 8D function)

$$\rho(x_i, y_i, \theta_i, \phi_i, x_r, y_r, \theta_r, \phi_r) \qquad \left(\frac{1}{sr}\right)$$

BRDFs versus BSSRDFs

(Henrik Wann Jensen)

BRDF

BSSRDF

- subsurface scattering is critical to the appearance of human skin
  - cosmetics hide blemishes, but they also prevent subsurface scattering

Fresnel equations

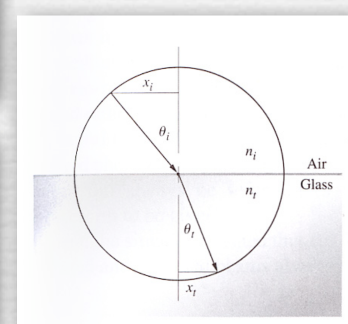
- a model of reflectance derived from physical optics (light as waves), not geometrical optics (light as rays)

Augustin-Jean Fresnel
(1788-1827)

(wikipedia)

$$R_s = \left[\frac{\sin(\theta_t - \theta_i)}{\sin(\theta_t + \theta_i)}\right]^2 = \left(\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right)^2 = \left[\frac{n_1 \cos\theta_i - n_2\sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1 \cos\theta_i + n_2\sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}\right]^2$$

$$R_p = \left[\frac{\tan(\theta_t - \theta_i)}{\tan(\theta_t + \theta_i)}\right]^2 = \left(\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right)^2 = \left[\frac{n_1\sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2 \cos\theta_i}{n_1\sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2 \cos\theta_i}\right]^2$$

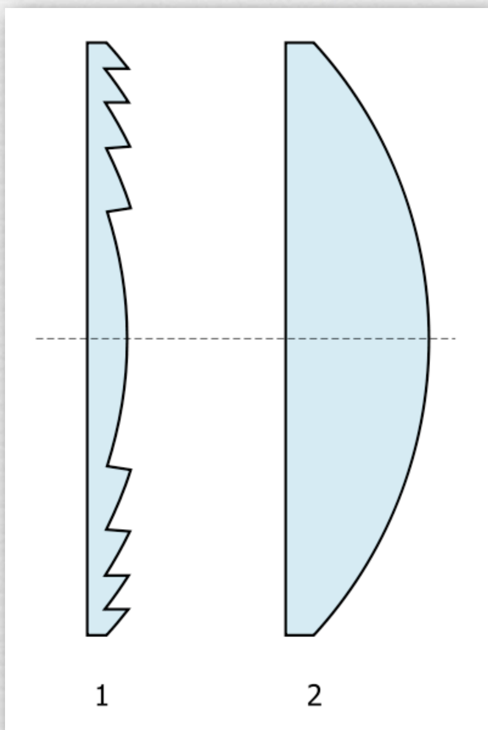


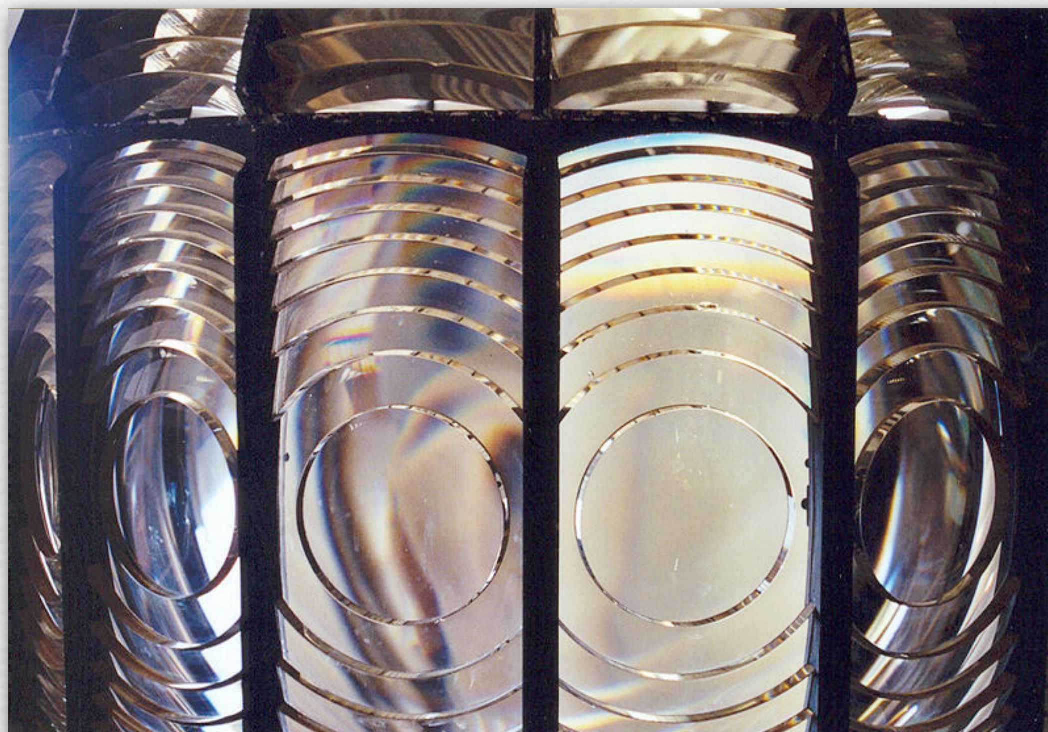
(Hecht)

- effects
  - conductors (metals) - specular highlight is color of metal
  - non-conductors (dielectrics) - specular highlight is color of light
  - specular highlight becomes colorless at grazing angles
  - even diffuse surfaces become specular at grazing angles

Fresnel Lens

- same refractive power (focal length) as a much thicker lens
- good for focusing light, but not for making images

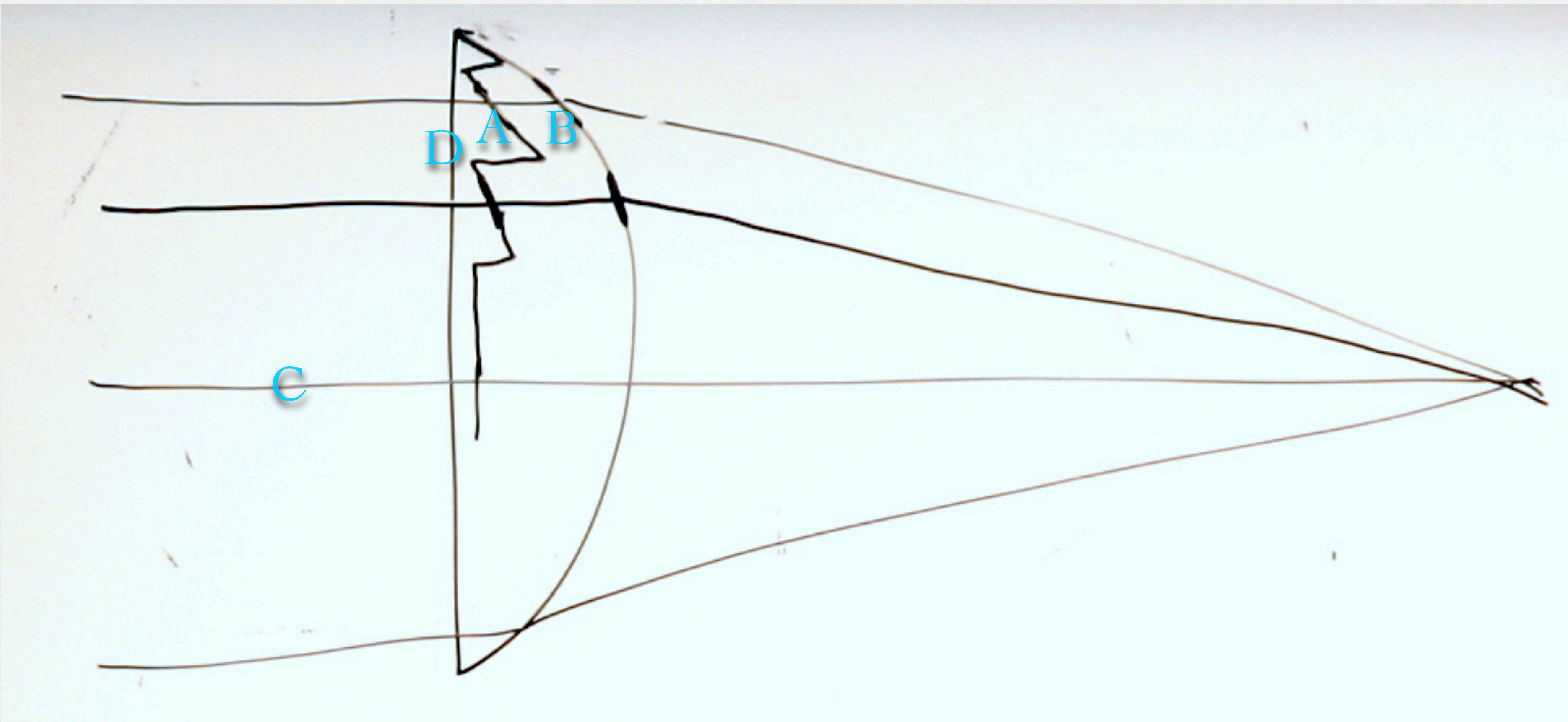




(wikipedia)

The geometry of a Fresnel lens

- each Fresnel segment (A) is parallel to that part of the original lens (B) which is at the same ray height (distance from the optical axis (C)), but it's closer to the planar surface (D), making the lens physically thinner, hence lighter and cheaper



Tyler Westcott, Pigeon Point Lighthouse in light fog,
photographed during the annual relighting of its historical 1KW lantern, 2008
(Nikon D40, 30 seconds, ISO 200, not Photoshopped)

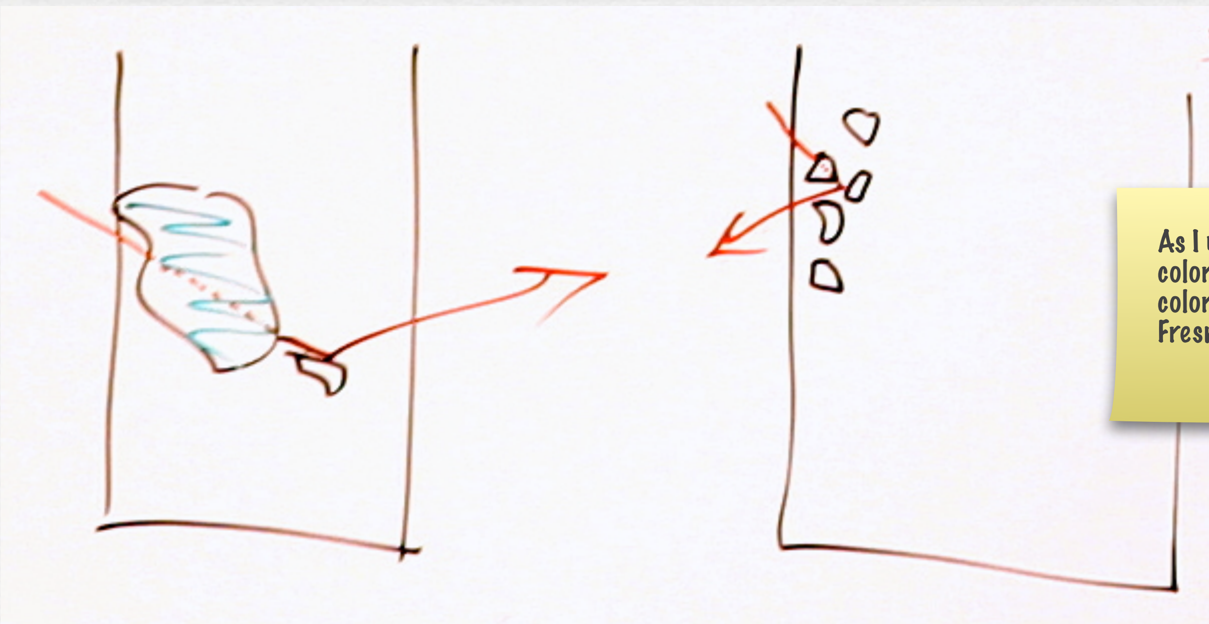
Parting puzzle

- Q. These vials represent progressive stages of pounding chunks of green glass into a fine powder; why are they getting whiter?

(Gary Meyer)

Passage of light through chunks of colored glass

- with large chunks, the light becomes green as soon it passes through one large chunk of glass; eventually it strikes a chunk at a grazing angle, which reflects it totally and out of the vial
- with smaller chunks, the light rather quickly strikes a chunk at a grazing angle and reflects out of the vial, before passing through many chunks, which would change it to green



As I mentioned in class, white paint is composed of small colorless (i.e. transparent) crystals (of titanium dioxide) in a colorless binder liquid. Its apparent whiteness is entirely due to Fresnel grazing-angle reflection from the sides of the crystals.

Slide credits

- Stone, M., *A Field Guide to Digital Color*, A.K. Peters, 2003.
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