Radiometry
Measuring Light

CS 554 – Computer Vision
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Bilkent University

How do we see?

- [Plato] – from our eyes flows a light similar to the light of the sun
- [Chalcidius, middle ages] “Therefore, when these three conditions concur, sight occurs, and through the eyes, which is the principal cause, the exterior light kindred to our own light, which both acts and assists, and the light that flows from visible bodies, flame or color without these the proposed effect [vision] cannot occur”

Adapted from Larry Davis

Difficulties with these theories

- Why we see faraway objects instantaneously when we open our eyes?
  - the visual spirit that leaves the eyes is exceptionally swift
- Why don’t the vision systems of different people looking at the same object interfere with each other
  - They just don’t
- What if the eyes are closed when the visual spirit returns
  - The soul has things times perfectly – this never happens

Adapted from Larry Davis

How do we see?

[Aristotle] objects create “material images” that are transported through the atmosphere and enter the eye

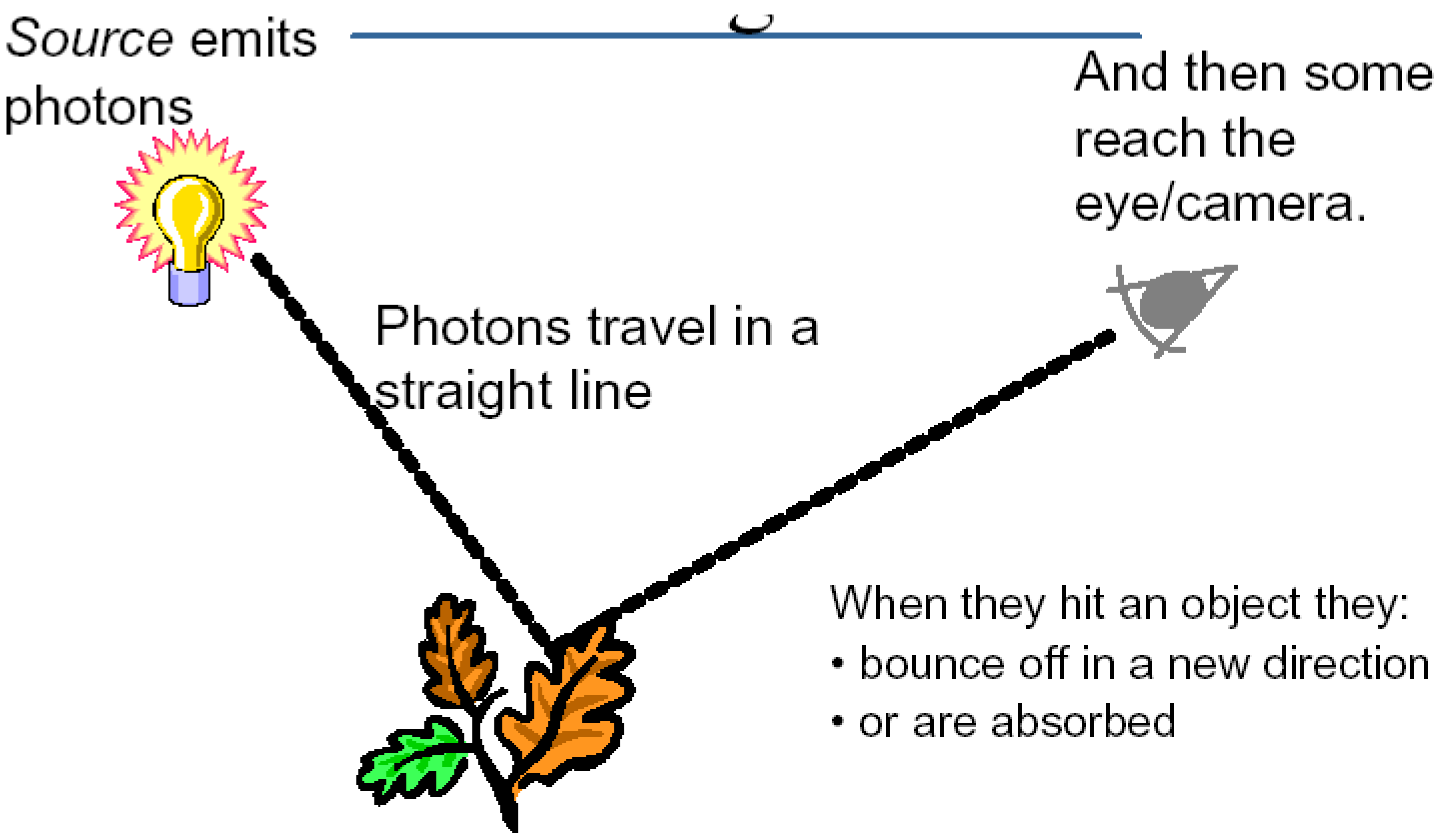
- but how do the material images of large objects enter the eye?

[Abu Ali al-Hassan ibn al-Hasan ibn al-Haytam - shortly Alhazen]

- Greatest optical scientist of the middle ages
- Pointillist theory of vision – we see a collection of points on the surfaces of objects
- Geometric theory to explain the 1-1 correspondence between the world and the image formed in our eyes

Adapted from Larry Davis

How do we see?

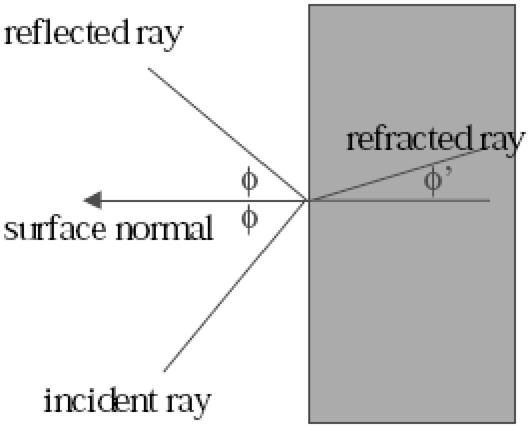


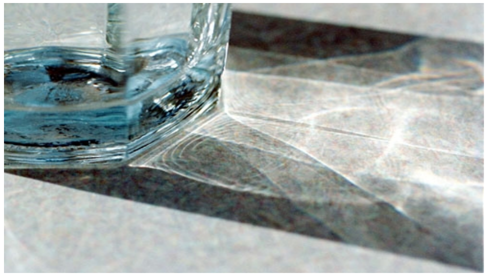
David Jacobs

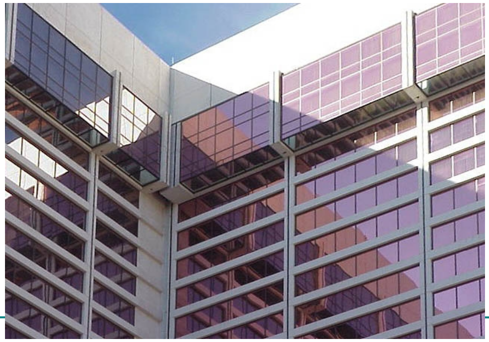
Adapted from Michael Black, Brown University

The interaction of light and matter

- Ray of light leaves the light source and travels along a straight line
- 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
    - it could be reflected in multiple directions at once
- If the object is our lens, then the useful light for imaging is the refracted light







Adapted from http://www.physics.utoledo.edu/%7Elsa/_color/lcsyl.htm

How do we see?

- The phenomena of refraction was known to Ptolemy
- Alhazen's problem – since light from a surface point reaches the entire surface of the eye, how is it that we see only a single image of point
  - he assumed that only the ray that enters perpendicular to the eye effects vision
  - the other rays are more refracted and therefore weakened
  - But in fact the optical properties of the lens combine all of these rays into a single focused point under favorable conditions

Adapted from Larry Davis

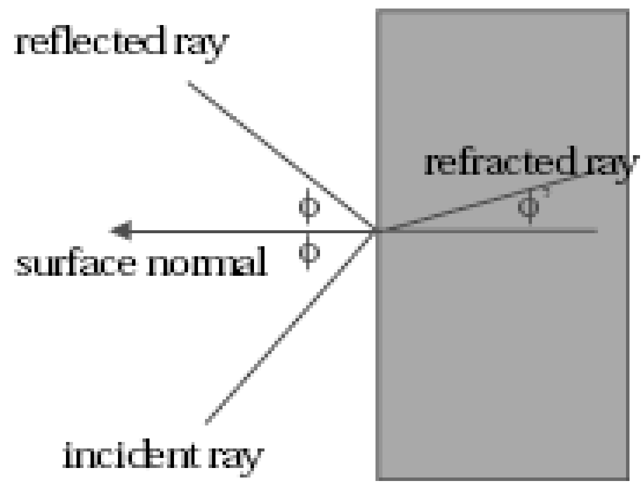
Snell's law

- If ϕ is the angle of incidence and ϕ' is the angle of refraction then

$$\frac{\sin\phi}{\sin\phi'} = \frac{v}{v'}$$

where v and v' are the refractive indices of the two media

- Refractive index is the ratio of speed of light in a vacuum to speed of light in the medium

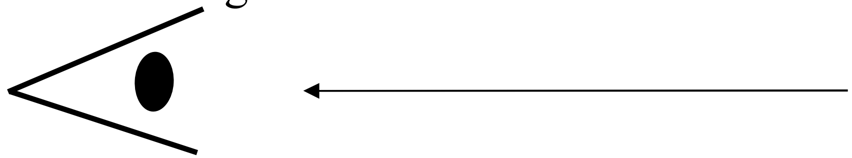


Refractive indices
glass - 1.52
water - 1.333
air - 1.000 - mercifully, or there would be no physical basis for vision!

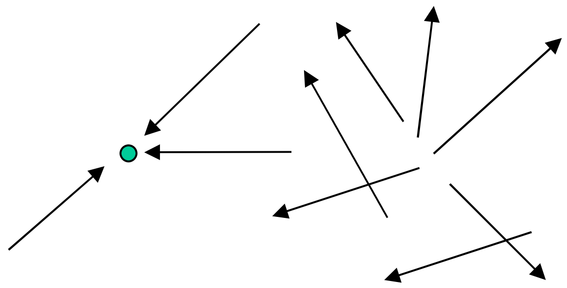
Adapted from Larry Davis

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 arriving at every point in space and from every direction



Adapted from Seitz

Light sources

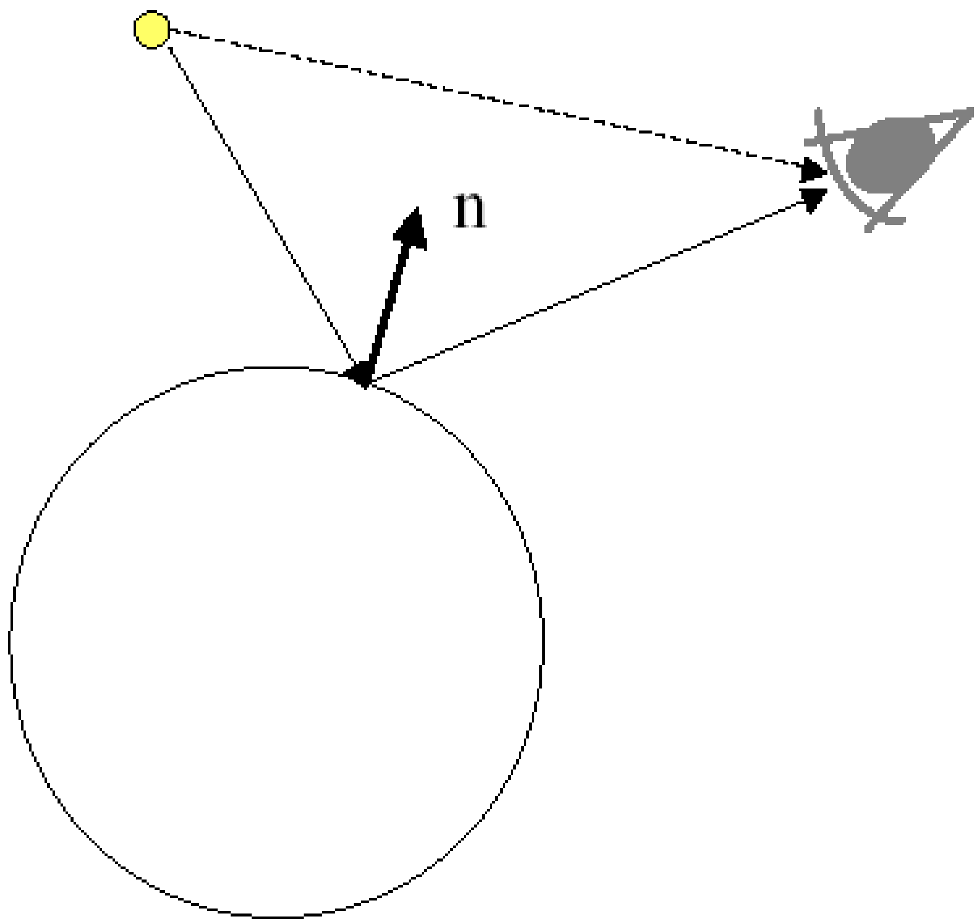
- Basic types
  - point source
  - directional source
    - a point source that is infinitely far away
  - area source
    - a union of point sources
- More generally
  - a light field can describe any distribution of light sources

Adapted from Seitz

Light

Imagine a perfect mirror sphere in a perfectly dark room. Illuminate it with a *point light source.*

What do you see?

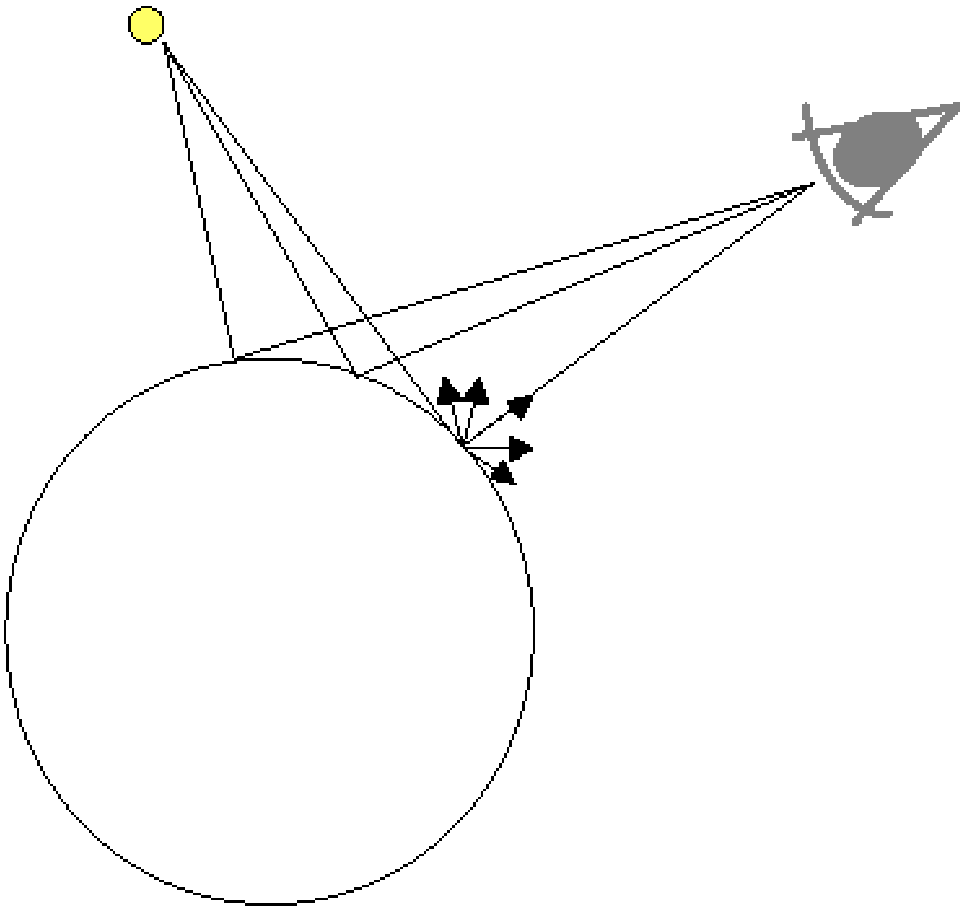


Adapted from Michael Black, Brown University

Light

Imagine the sphere now painted with a flat white paint.

What do you see?



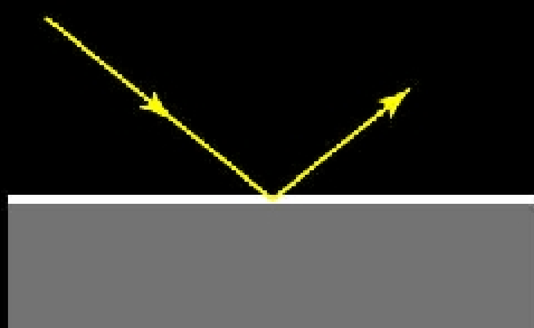
Adapted from Michael Black, Brown University

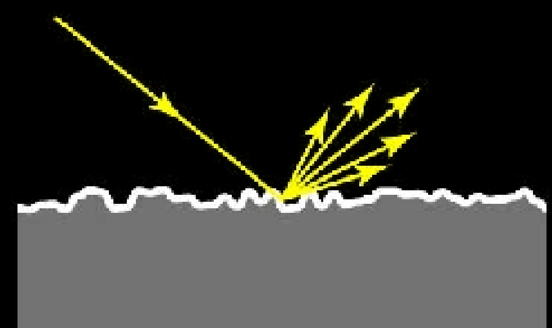
from Steve Marschner

Materials

conductor

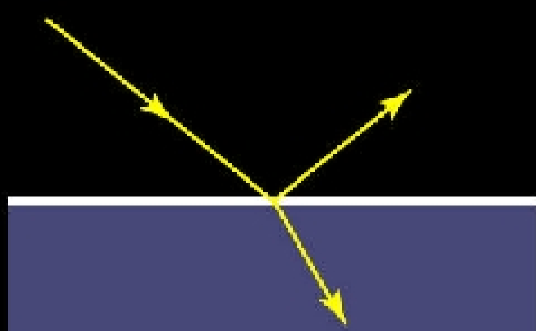
conductor plus microgeometry



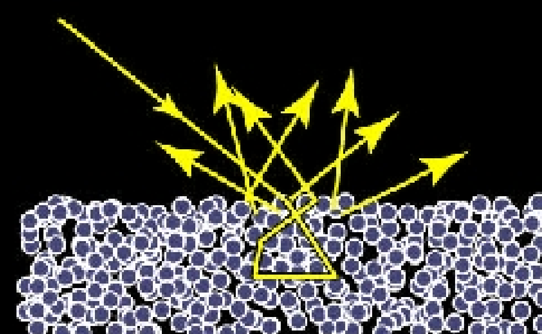


from Steve Marschner

insulator



insulator plus microgeometry



Light

- First, language for describing light
  - Striking a surface;
  - Leaving a surface.
- Next, how do we model the relationship between the two.
  - This depends on the material;
  - Eg., cloth or mirror.

Adapted from Michael Black, Brown University

Foreshortening

If two different sources result in exactly the same amount of radiation arriving along each incoming direction, they must have the same effect on the surface. Because they are indistinguishable from the surface.

- As a source is tilted with respect to the direction in which the illumination travelling it looks smaller to a patch of surface viewing the source.

Crucial consequence: a big source viewed at a glancing angle, must produce the same effect as a small source viewed frontally. (resp. receiver)

Adapted from David Forsyth, UC Berkeley

Radiance, L

The distribution of light in space is a function of position and direction

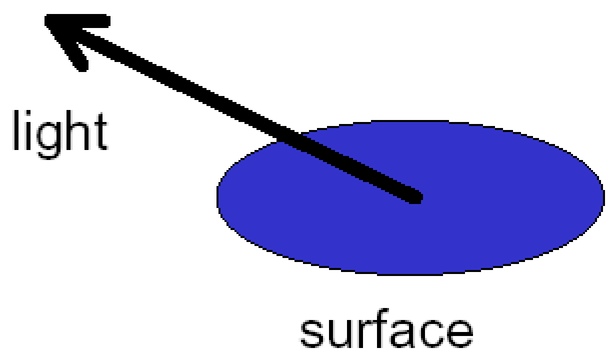
e.g. Consider a shining torch with a narrow beam in an empty room at night
we need to know
where the torch is shining
in what direction it is shining

The appropriate unit for measuring the distribution of of light in space is radiance

Radiance, L

- Amount of light radiated from a surface into a given solid angle per unit area (watts per square meter per *steradian*).
- Note: the area is the foreshortened area, as seen from the direction that the light is being emitted.

Informally: "Brightness"



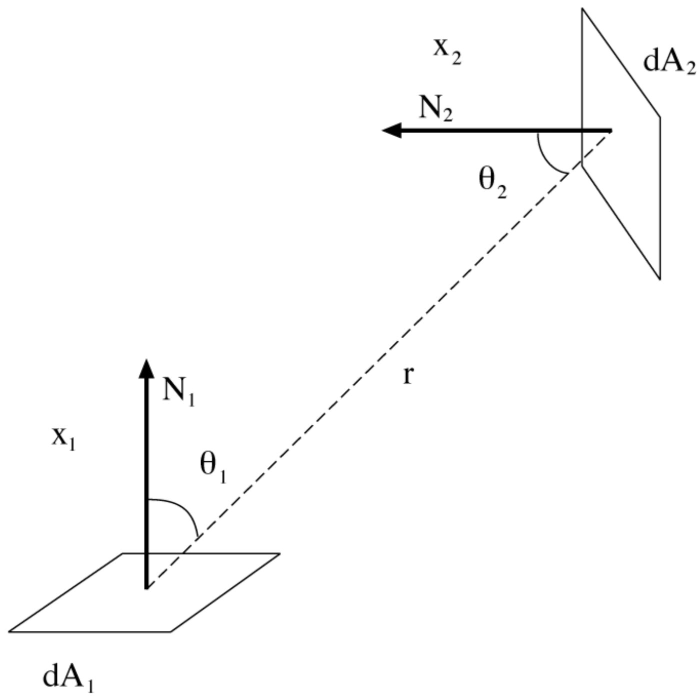
Jacobs

Adapted from Michael Black, Brown University

Radiance

A small surface patch viewing a source frontally collects more energy than the same patch viewing a source a nearly tangent direction.

The amount of energy a patch collects from a source depends both on how large the source looks from the patch, and how large the patch looks from the source



Radiance is constant along straight lines

For two points P1 and P2, the radiance leaving P1 in the direction of P2 is the same as the radiance arriving at P2 from the direction of P1

Adapted from David Forsyth, UC Berkeley

Light at surfaces

When light strikes a surface, it may be
- absorbed
- transmitted (skin)
- scattered (milk)
- reflected (mirror)

Usually the combination of these effects occur

e.g. Light arriving at skin can be
- scattered at various depths into tissue
- reflected from blood or from melanin
- absorbed
- scattered tangential to the skin within a film of oil then escape at some distant point

Adapted from David Forsyth, UC Berkeley

Light at surfaces

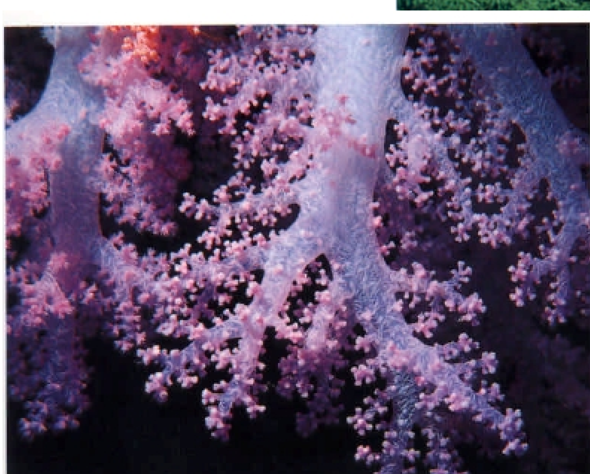
Some surfaces absorb light at one wavelength and then radiate light at different wavelength as a result --> fluorescence

-scorpions fluoresce visible light under x-ray illumination
-human teeth fluoresce faint blue under ultraviolet light
-nylon clothes in discotheques

Color in Nature

ew Zealand. *Photo: L. Rodgers*

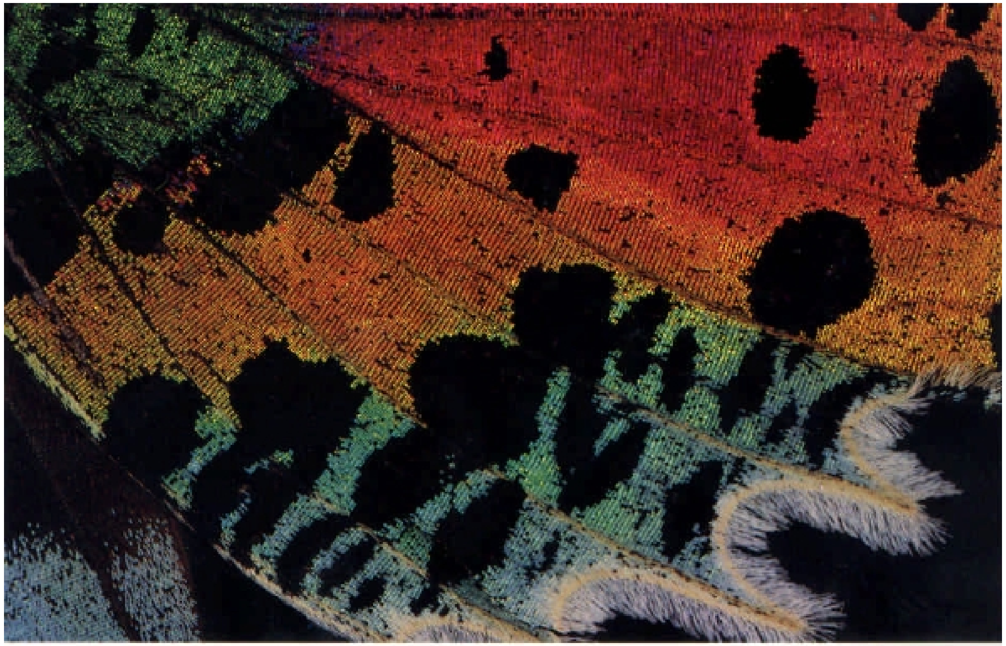
PL. 1.3 Blue ocean, Fiji. *Photo: W. Farrant*



PL. 1.19 Soft coral, Maldives. *Photo: P. Farrant*

Adapted from the book chapter on Color in Nature

Color in Nature



PL. 10.9 Urania moths have iridescent scales containing layers of chitin, air spaces and a backing of melanin. *Photo: P. Farrant*

PL. 10.5 In pigeons, relatively large granules of melanin produce some interference colours. *Photo: P. Farrant.*

Adapted from the book chapter on Color in Nature

Simplifying assumptions

The radiance leaving a point on a surface is due only to radiance arriving at this point

all light leaving a surface at a given wavelength is due to light arriving at that wavelength

the surfaces do not generate light internally and treat sources separately

Irradiance

What is the relationship between incoming illumination and reflected light?

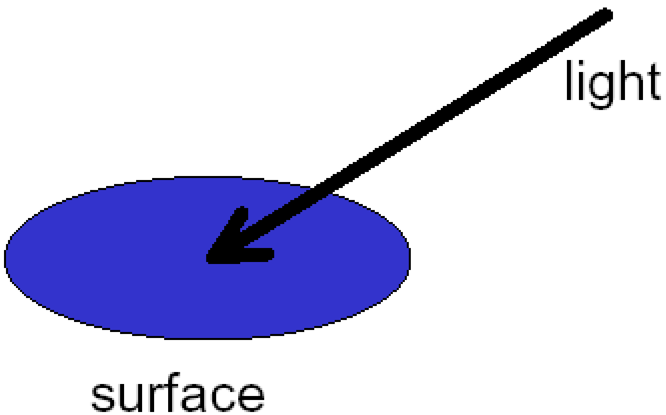
-it is a function of both the direction in which light arrives at a surface and the direction in which it leaves.

-The appropriate function to represent incoming power is irradiance

-Total power arriving at the surface is given by adding irradiance over all incoming angles --- this is why it's a natural unit

Irradiance, E

- Light power per unit area (watts per square meter) incident on a surface.
- If surface tilts away from light, same amount of light strikes bigger surface (foreshortening) (less irradiance).



Jacobs

Adapted from Michael Black, Brown University

The BRDF

- 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?

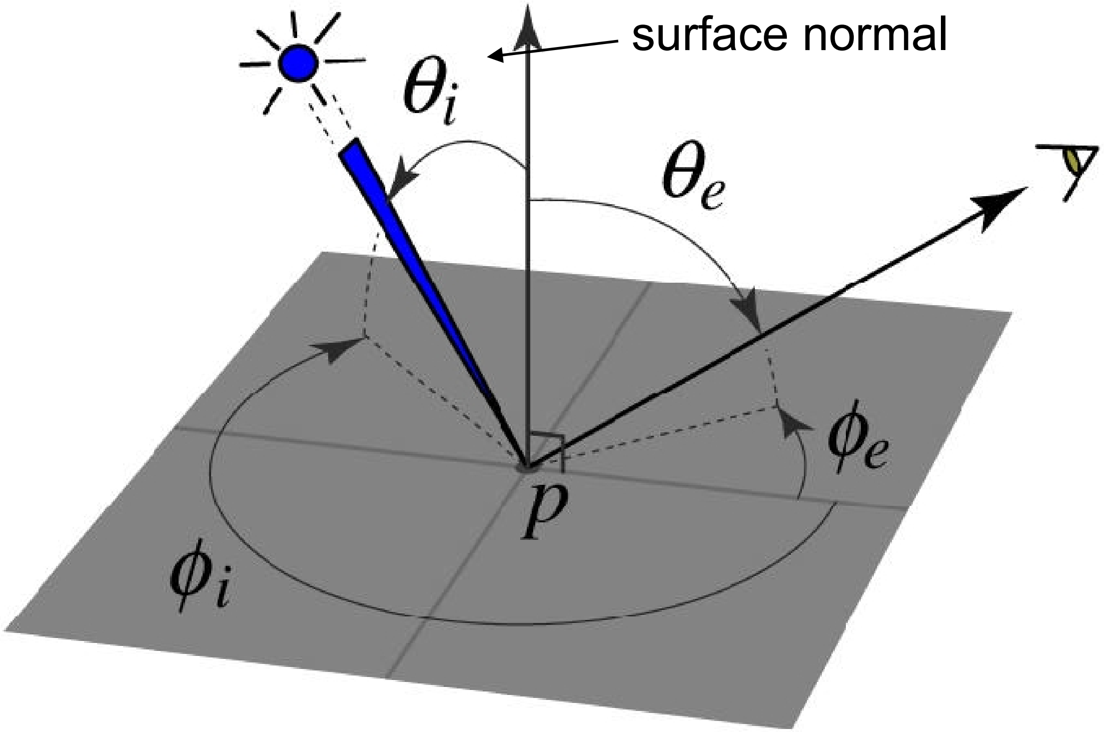
- Assuming that
  - surfaces don't fluoresce
  - surfaces don't emit light (i.e. are cool)
  - all the light leaving a point is due to that arriving at that point

- Can model this situation with the Bidirectional Reflectance Distribution Function (BRDF)
- the ratio of the radiance in the outgoing direction to the incident irradiance

Adapted from David Forsyth, UC Berkeley

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?

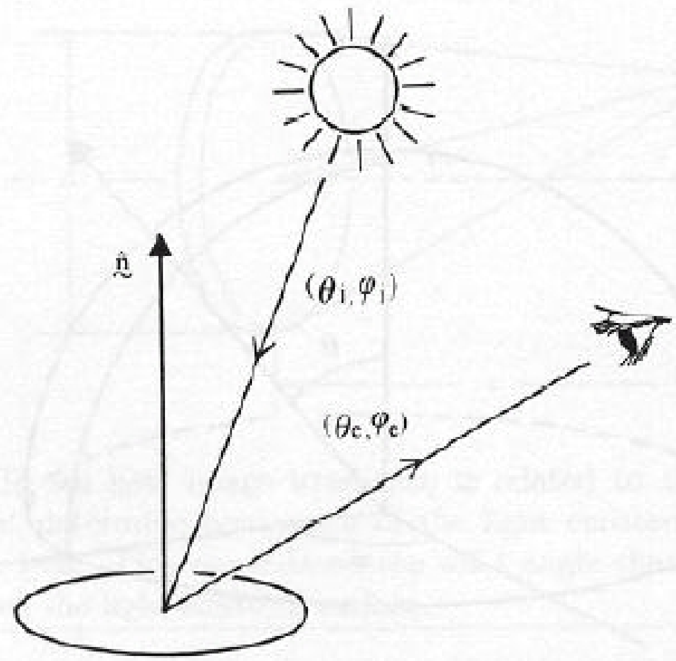


Answer given by the BRDF: $\rho(\theta_i, \phi_i, \theta_e, \phi_e)$

Adapted from Seitz

The BRDF

Scene Radiance



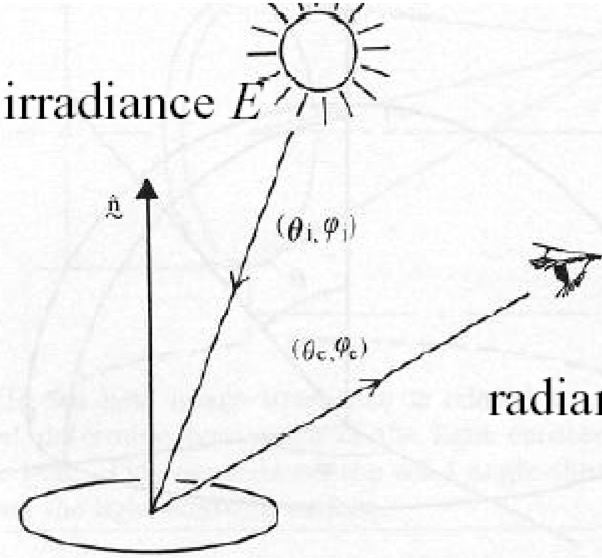
Horn, 1986

Figure 10-7. The bidirectional reflectance distribution function is the ratio of the radiance of the surface patch as viewed from the direction (θ_e, ϕ_e) to the irradiance resulting from illumination from the direction (θ_i, ϕ_i).

BRDF says how show bright a surface appears when viewed from one direction when lit from another.

Adapted from Michael Black, Brown University

The BRDF



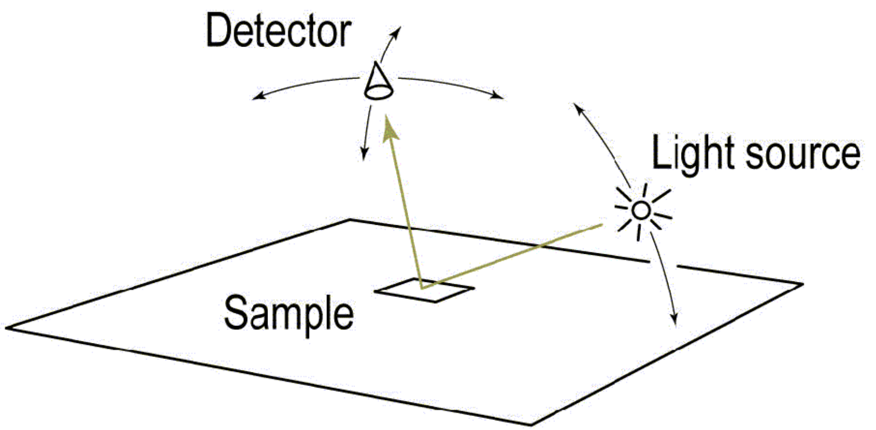
Horn, 1986

Figure 10-7. The bidirectional reflectance distribution function is the ratio of the radiance of the surface patch as viewed from the direction (θ_e, ϕ_e) to the irradiance resulting from illumination from the direction (θ_i, ϕ_i).

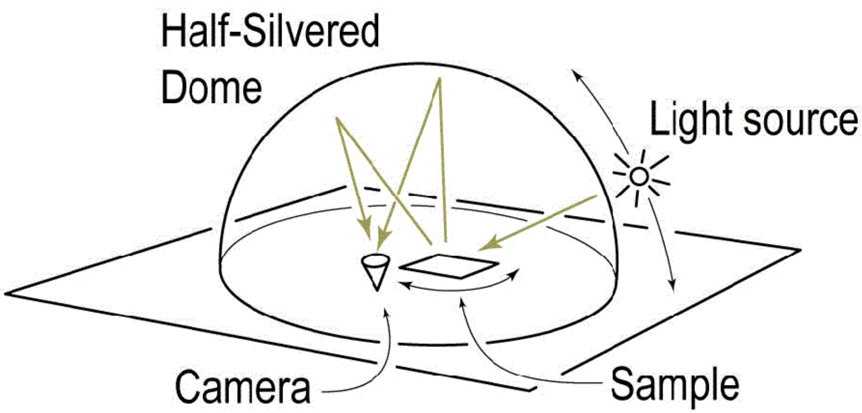
$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e) = \frac{L(\theta_e, \phi_e)}{E(\theta_i, \phi_i)}$$

Adapted from Michael Black, Brown University

Measuring the BRDF



traditional

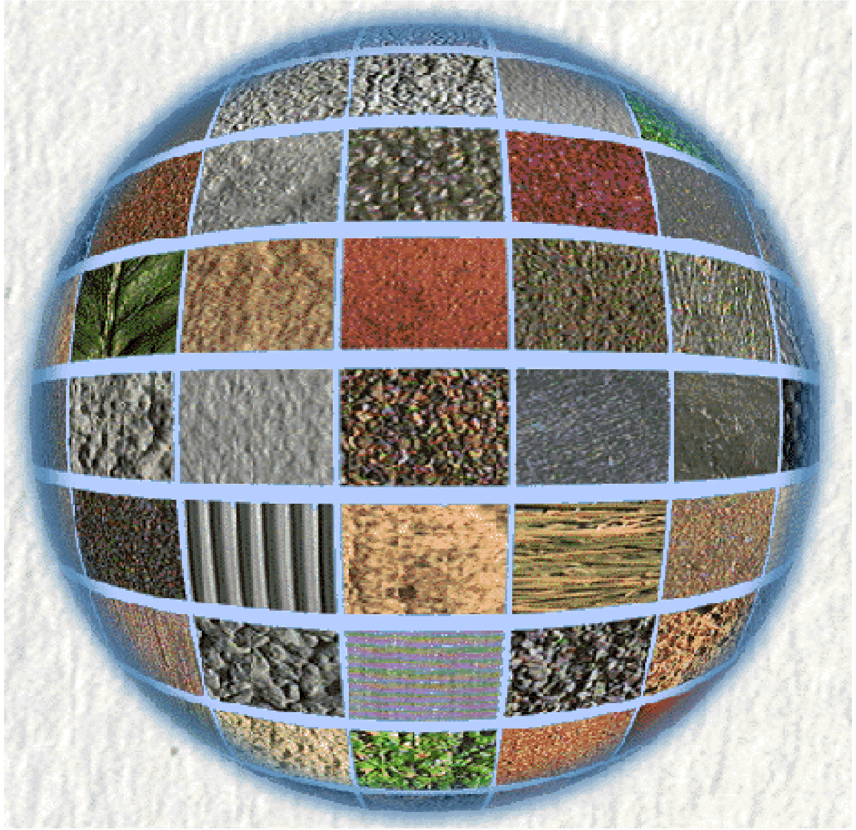


design by Greg Ward

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

Adapted from Seitz

Columbia-Utrecht Database



- Captured BRDF models for a variety of materials
  - http://www.cs.columbia.edu/CAVE/curet/.index.html

Adapted from Seitz

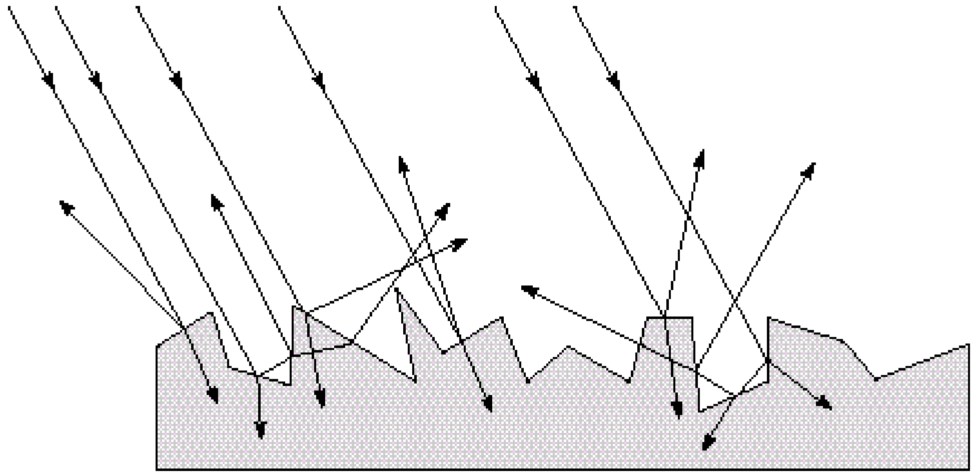
Radiosity

- Radiance depends on angle
  - Torch beam
  - Compact disc

- What about a cotton cloth
  - The dependency of reflected light on angle is weak or non-existent

- When the radiance leaving a surface is independent of exit angle radiosity is the appropriate unit
  - The total power leaving a point on a surface per unit area on the surface

Diffuse reflection

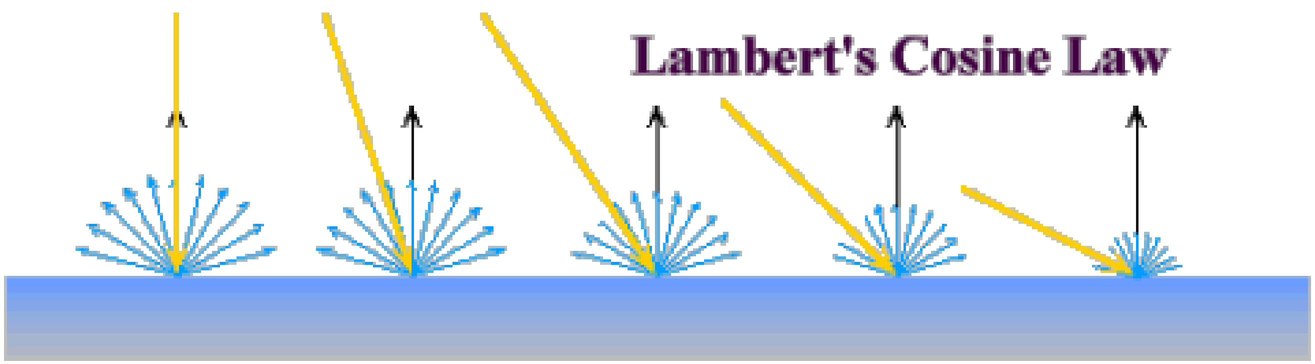


- Diffuse reflection
  - Dull, matte surfaces like chalk or latex paint
  - Microfacets scatter incoming light randomly
  - Effect is that light is reflected equally in all directions

Adapted from Seitz

Diffuse reflection

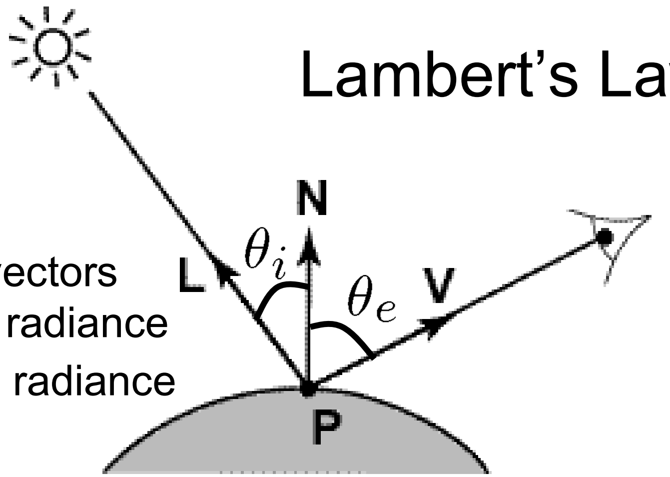
- Diffuse reflection governed by **Lambert's law**
  - Viewed brightness does not depend on viewing direction
  - Brightness *does* depend on direction of illumination
  - This is the model most often used in computer vision



Adapted from Seitz

Diffuse reflection

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



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

k_d is called **albedo**

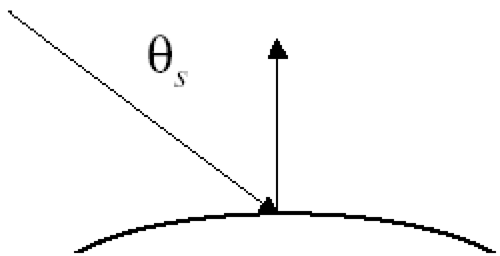
BRDF for **Lambertian surface**

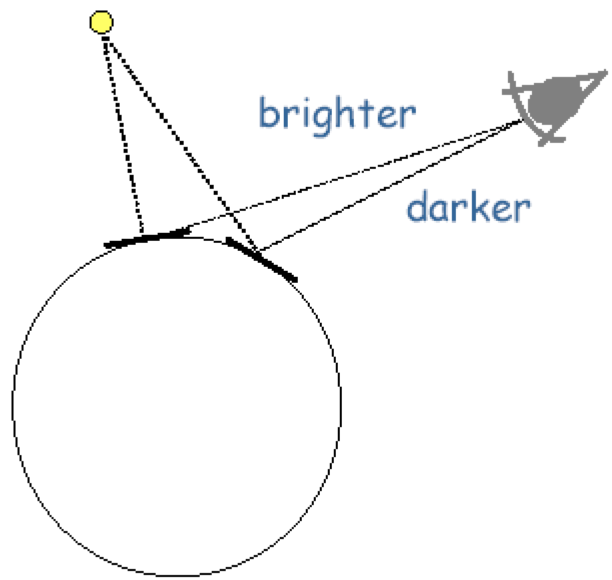
$$\rho(\theta_i, \phi_i, \theta_e, \phi_e) = k_d cos\theta_i$$

Adapted from Seitz

Special Cases: Lambertian

Matte (*Lambertian*) surface illuminated by a *point* light source.



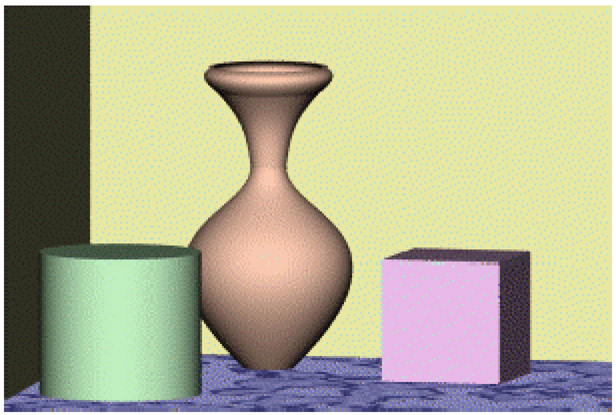


foreshortening depending on the angle of incidence.

reflection is the same in all directions

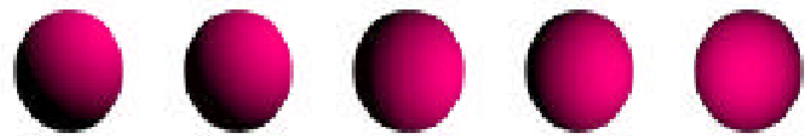
Adapted from Michael Black, Brown University

Lambertian Examples



Scene

(Oren and Nayar)



Lambertian sphere as the light moves.

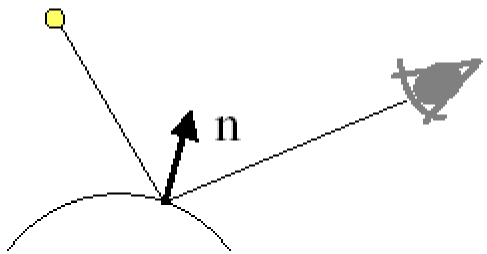
(Steve Seitz)

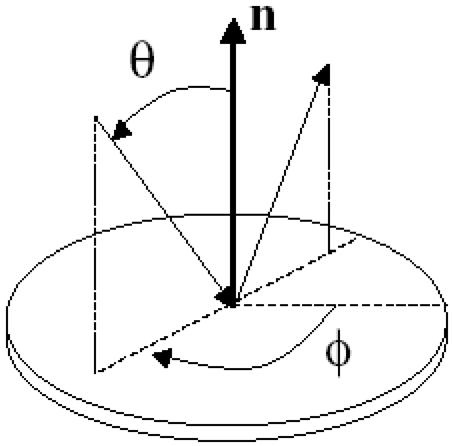
Adapted from Michael Black, Brown University

Specular surfaces

- radiation arriving along a direction leaves along the specular direction
- reflect about surface normal

$$L(\theta_e, \varphi_e) = E(\theta_e, \varphi_e - \pi)$$



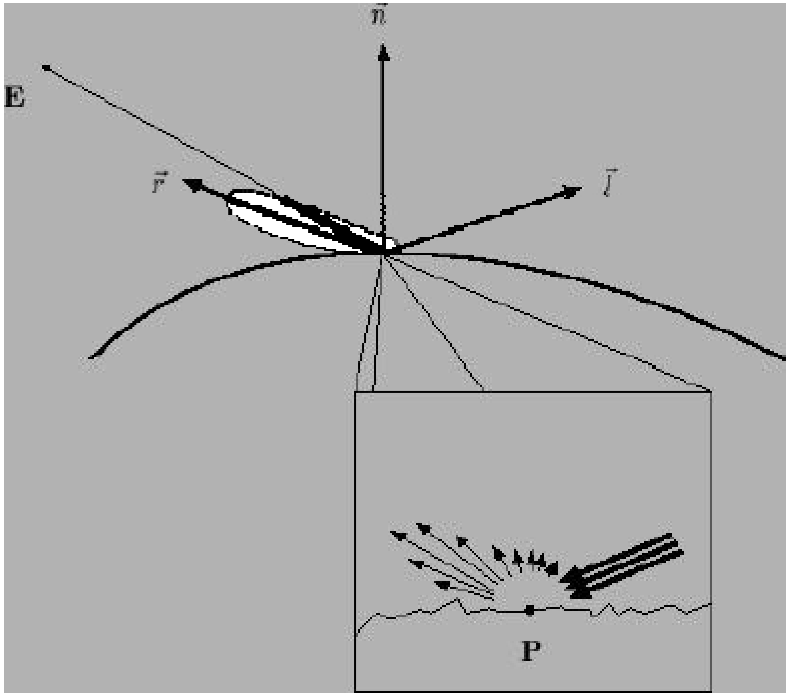


Adapted from Michael Black, Brown University

Specular surfaces

–some fraction is absorbed, some reflected

–on real surfaces, energy usually goes into a lobe of directions

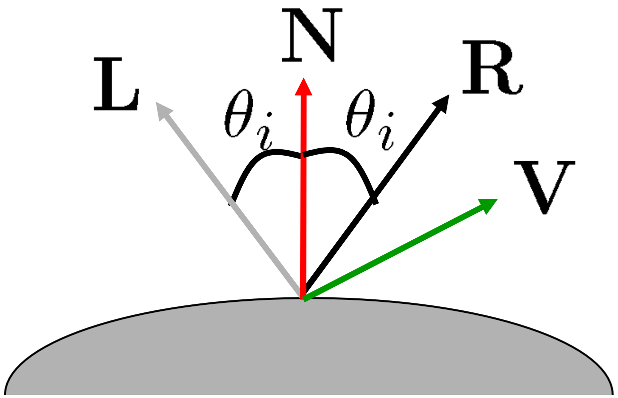


(http://graphics.cs.ucdavis.edu/GraphicsNotes/Shading/Shading.html)

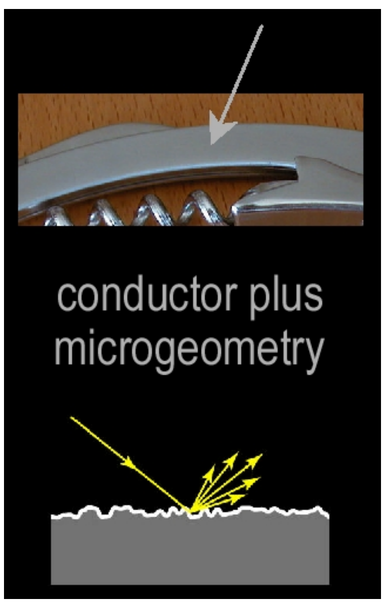
Adapted from Michael Black, Brown University

Specular reflection

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

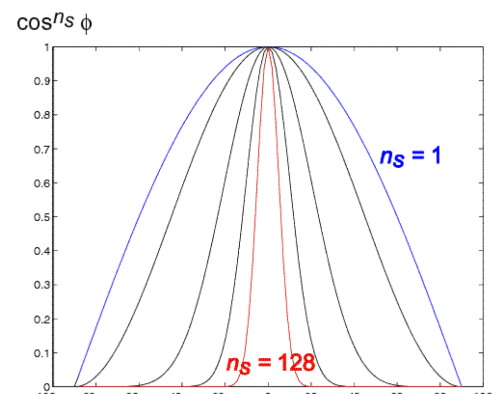


$$I_e = \begin{cases} I_i & \text{if } \mathbf{V} = \mathbf{R} \\ 0 & \text{otherwise} \end{cases}$$



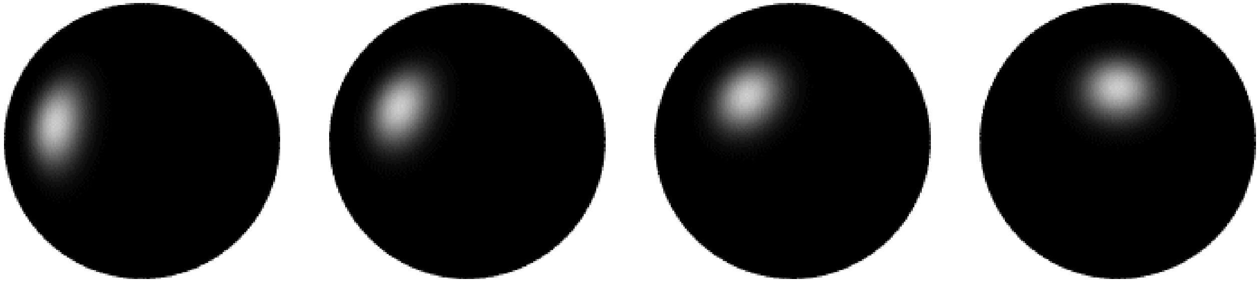
- Near-perfect mirrors have a **highlight** around **R**
  - common model:

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

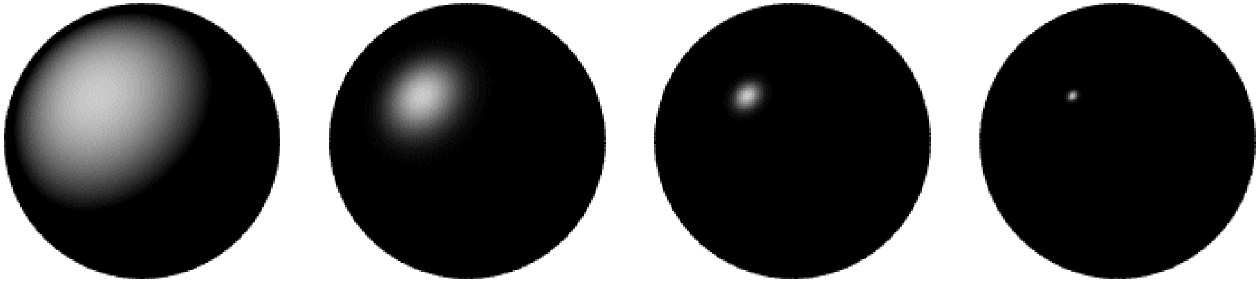


Adapted from Seitz

Specular reflection



- Moving the light source



- Changing n_s

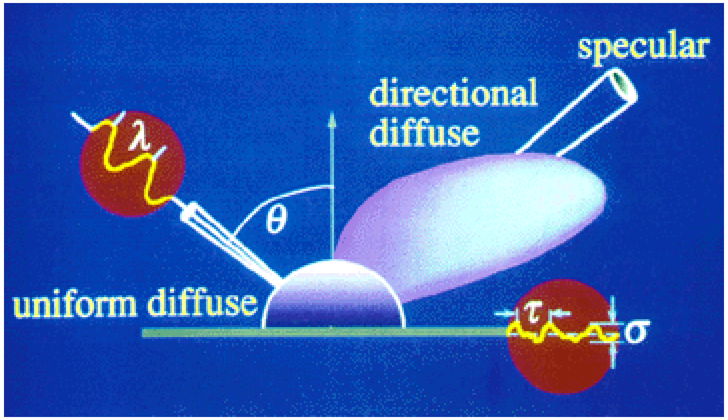
Adapted from Seitz

Phong illumination model

- Phong approximation of surface reflectance
  - Assume reflectance is modeled by three components
    - Diffuse term
    - Specular term

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

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



Adapted from Seitz