Image Formation: Light and Shading

Introduction to Computer Vision

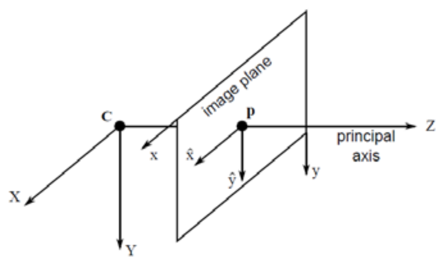
CSE 152

Lecture 3

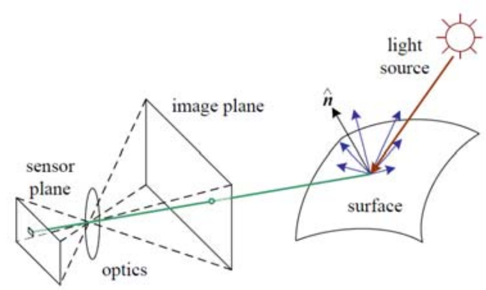
Announcements

- Homework 1 is due Apr 12, 11:59 PM
- Homework 2 will be assigned on Apr 12
- Reading:
  - Chapter 2: Light and Shading

Geometric image formation



Photometric image formation

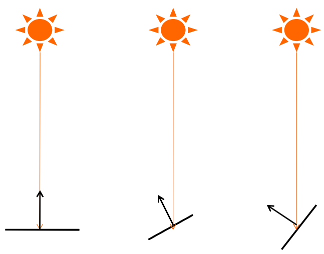


Radiometry

- Solid Angle
- Irradiance
- Radiance
- Bidirectional Reflectance Distribution Function (BRDF)

Appearance: lighting, surface reflectance, and shading

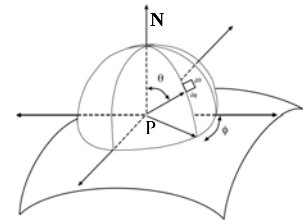
Foreshortening



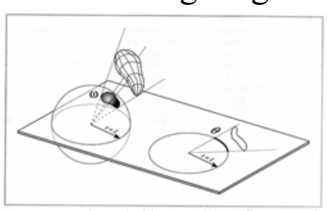
–The surface is foreshortened by the cosine of the angle between the normal and direction to the light.

A local coordinate system on a surface

- Consider a point **P** on the surface
- Light arrives at **P** from a hemisphere of directions defined by the surface normal **N**
- We can define a local coordinate system whose origin is **P** and with one axis aligned with **N**
- Convenient to represent in spherical angles.



Measuring Angle

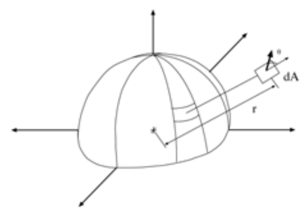


- The **solid angle** subtended by an object from a point P is the area of the projection of the object onto the unit sphere centered at P.
- Definition is analogous to projected angle in 2D
- Measured in *steradians*, sr
- If I'm at P, and I look out, solid angle tells me how much of my view is filled with an object

Solid Angle

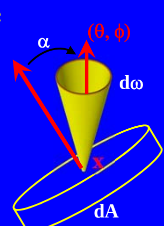
- By analogy with angle (in radians), the solid angle subtended by a region at a point is the area projected on a unit sphere centered at that point
- The solid angle subtended by a patch area dA is given by

$$d\omega = \frac{dA\cos\theta}{r^2}$$



Radiance

- Power is energy per unit time (watts)
- **Radiance: Power traveling at some point in a specified direction, per unit area perpendicular to the direction of travel, per unit solid angle**
- Symbol: L(**x**,θ,φ)
- Units: watts per square meter per steradian : $W/m^2/sr$ = $W\ m^{-2}\ sr^{-1}$



$$L = \frac{P}{(dA\cos\alpha)d\omega}$$

Power emitted from patch, but radiance in direction different from surface normal

Irradiance

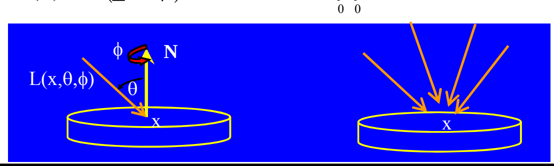
- How much light is arriving at a surface?
- Units of irradiance: $W/m^2 = W\ m^{-2}$
- This is a function of incoming angle.
- A surface experiencing radiance L(x,θ,φ) coming in from solid angle dω experiences **irradiance**:

$$E(x) = L(\underline{x},\theta,\phi)\cos\theta d\omega$$

- Crucial property:
  Total **Irradiance** arriving at the surface is given by adding irradiance over all incoming angles
  Total irradiance is

$$\int_{hemisphere} L(\underline{x},\theta,\phi)\cos\theta d\omega$$

$$= \int_0^{2\pi}\int_0^{\pi/2} L(\underline{x},\theta,\phi)\cos\theta\sin\theta d\theta d\phi$$



Camera's sensor

- Measured pixel intensity is a function of irradiance integrated over
  - pixel's area
  - over a range of wavelengths
  - for some period of time

$$I = \int_t \int_\lambda \int_x \int_y E(x, y, \lambda, t) s(x, y) q(\lambda) dy dx d\lambda \, dt$$

Light at surfaces

Many effects when light strikes a surface -- could be:

- transmitted
  - Skin, glass
- reflected
  - mirror
- scattered
  - milk
- travel along the surface and leave at some other point
- absorbed
  - sweaty skin

Assume that

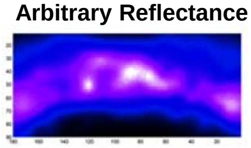
- surfaces don't fluoresce
  - e.g., scorpions, detergents
- surfaces don't emit light (i.e., are cool)
- all the light leaving a point is due to that arriving at that point

Surface Reflectance Models

Common Models

- Lambertian
- Phong
- Physics-based
  - Specular [Blinn 1977], [Cook-Torrance 1982], [Ward 1992]
  - Diffuse [Hanrahan, Kreuger 1993]
  - Generalized Lambertian [Oren, Nayar 1995]
  - Thoroughly Pitted Surfaces [Koenderink et al 1999]
- Phenomenological
  - [Koenderink, Van Doorn 1996]

Arbitrary Reflectance



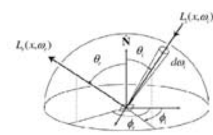
- Non-parametric model
- Anisotropic
- Non-uniform over surface
- BRDF Measurement *[Dana et al, 1999], [Marschner]*

Specialized

- Hair, skin, threads, paper [Jensen et al]

Lambertian (Diffuse) Surface

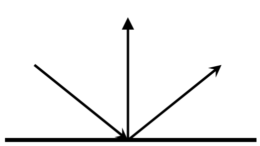
- BRDF is a constant called the albedo. $\rho(\underline{x}; \theta_{in}, \phi_{in}; \theta_{out}, \phi_{out}) = K$
- Emitted radiance is NOT a function of outgoing direction – i.e., constant in all directions.
- For lighting coming in single direction ω_i, emitted radiance is proportional to cosine of the angle between normal and light direction

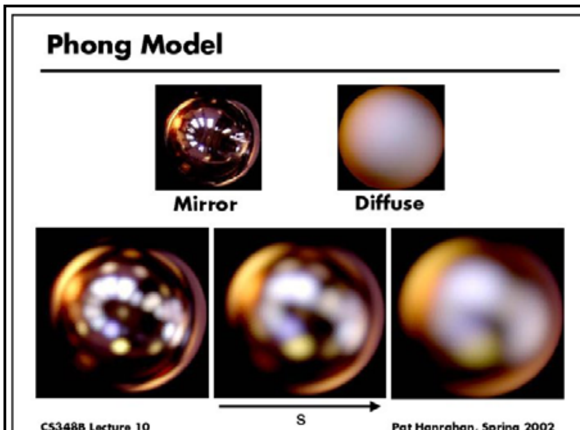


$$L_r(x,\omega_r) = \int_{H^2} f_r(x, \omega_i \to \omega_r) L_i(x, \omega_i) \cos\theta_i \, d\omega_i$$

$$L_r = KN \cdot \omega_i$$

Specular Reflection: Smooth Surface





Non-Lambertian reflectance

General BRDF: e.g. Velvet

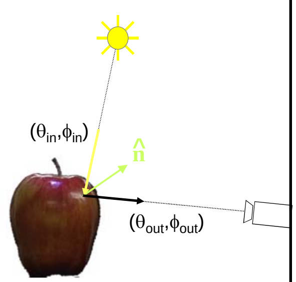
Portrait of Sir Thomas Morre, Hans Holbein the Younger, 1527

[After Koenderink et al, 1998]

BRDF

With assumptions in previous slide

- **Bi-directional Reflectance Distribution Function**
  $\rho(\theta_{in}, \phi_{in} ; \theta_{out}, \phi_{out})$
- **Ratio of emitted radiance to incident irradiance (units: sr^{-1})**
- **Function of**
  - **Incoming light direction:** θ_{in}, ϕ_{in}
  - **Outgoing light direction:** θ_{out}, ϕ_{out}



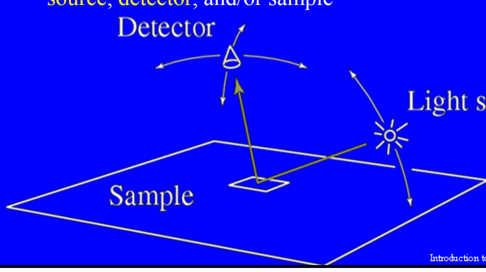
$$\rho\left(\underline{x};\theta_{in},\phi_{in};\theta_{out},\phi_{out}\right)=\frac{L_o\left(\underline{x};\theta_{out},\phi_{out}\right)}{L_i\left(\underline{x};\theta_{in},\phi_{in}\right)\cos\theta_{in}d\omega}$$

Where ρ is sometimes denoted f_r.

Ways to measure BRDF's

Gonioreflectometers

- Three degrees of freedom spread among light source, detector, and/or sample



Gonioreflectometers

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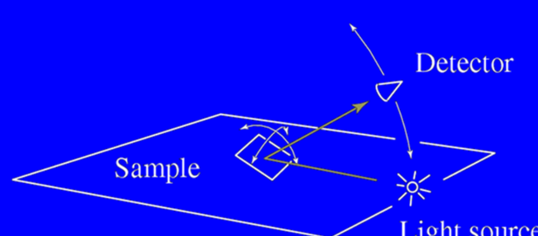


Isotropic BRDF

$$f(\theta_o, \varphi_o, \theta_i, \varphi_i) = f(\theta_o, \theta_i, \varphi_i - \varphi_o)$$

From Hertzmann & Seitz, CVPR'03

Isotropic BRDF's are symmetric about the surface normal. If the surface is rotated about the normal for the same incident and emitting directions, the value of the BRDF is the same.

Anisotropic BRDF

From Hertzmann & Seitz, CVPR'03

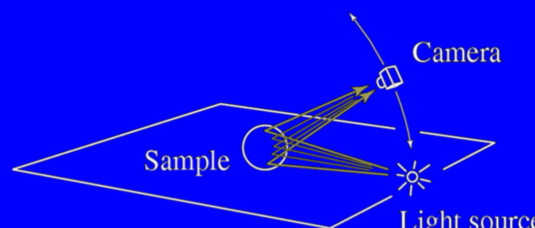
Gonioreflectometers

- Can add fourth degree of freedom to measure anisotropic BRDFs

4 degree-of-freedom gantry

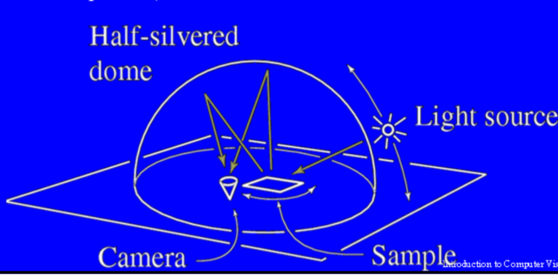
Marschner's Image-Based BRDF Measurement

- For uniform BRDF, capture 2-D slice corresponding to variations in normals



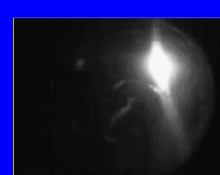
Ward's BRDF Measurement Setup

- Collect reflected light with hemispherical (should be ellipsoidal) mirror [SIGGRAPH 92]



Ward's BRDF Measurement Setup

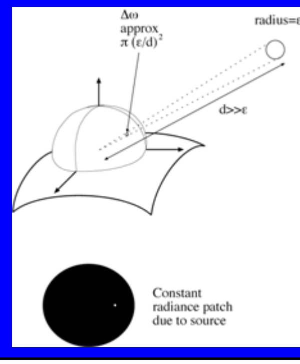
- Result: each image captures light at all exitant angles



Light sources and shading

- How bright (or what color) are objects?
- One more definition: Exitance of a source is
  - the internally generated power radiated per unit area on the radiating surface
- Also referred to as radiant emittance
- Similar to irradiance
  - Same units, $W/m^2 = W\ m^{-2}$

Radiosity due to a point source

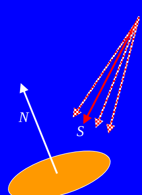


- small, distant sphere radius ε and exitance E, which is far away subtends solid angle of about

$$\pi\left(\frac{\varepsilon}{d}\right)^2$$

Standard nearby point source model

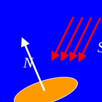
$$\rho_d(x)\left(\frac{N(x)^T S(x)}{r(x)^2}\right)$$



- N is the surface normal
- ρ is diffuse (Lambertian) albedo
- S is source vector - a vector from x to the source, whose length is the intensity term
  - works because a dot-product is basically a cosine

Standard distant point source model

- Issue: nearby point source gets bigger if one gets closer
  - the sun doesn't for any reasonable meaning of closer
- Assume that all points in the model are close to each other with respect to the distance to the source. Then the source vector doesn't vary much, and the distance doesn't vary much either, and we can roll the constants together to get:



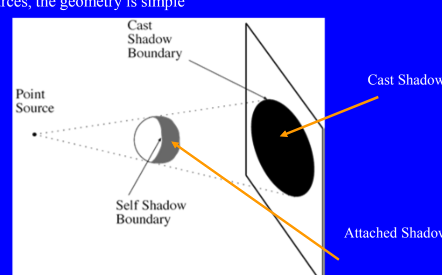
$$\rho_d(x)\left(N(x)^T S(x)\right)$$

Lighting at infinity

- Direction is a three vector **s**, with |**s**| = *1*.
- Described as function on a sphere: radiance as a function of direction r(**s**)
- Single point source is a delta function at some direction
- Multiple point sources: sum of delta functions

Shadows cast by a point source

- A scene point that can't see the source is in shadow
- For point sources, the geometry is simple



Shading models

Local shading model

- Surface has incident radiance due only to sources visible at each point
- Advantages:
  - often easy to manipulate, expressions easy
  - supports quite simple theories of how shape information can be extracted from shading
- Used in vision & real time graphics

Global shading model

- surface radiosity is due to radiance reflected from other surfaces as well as from surfaces
- Advantages:
  - usually very accurate
- Disadvantage:
  - extremely difficult to infer anything from shading values
- Rarely used in vision, often in photorealistic graphics

Image sensors

Two types :

1. CCD
2. CMOS

CCD

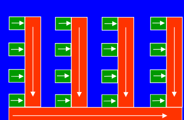
Separate photo sensor at regular positions
no scanning

Charge-coupled devices (CCDs)

interline transfer and frame transfer

photosensitive

storage



CMOS

Each photo sensor has its own amplifier

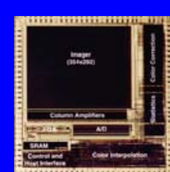
More noise (reduced by subtracting ‘black’ image)

Lower sensitivity (lower fill rate)

Uses standard CMOS technology

Allows other components to be put on chip

‘Smart’ pixels



CCD vs. CMOS

- Mature technology
- Specific technology
- High production cost
- High power consumption
- Higher fill rate
- Blooming
- Sequential readout

- Recent technology
- Standard IC technology
- Cheap
- Low power
- Less sensitive
- Per pixel amplification
- Random pixel access
- Smart pixels
- On chip integration with other components

Color Cameras

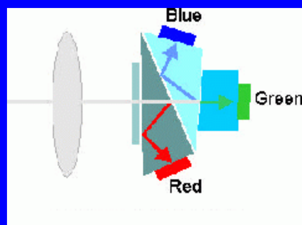
We consider 3 concepts:

1. Prism (with 3 sensors)
2. Filter mosaic
3. Filter wheel

… and X3

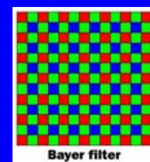
Prism color camera

Separate light in 3 beams using dichroic prism
Requires 3 sensors & precise alignment
Good color separation

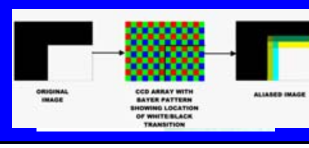


Filter mosaic

Coat filter directly on sensor



Demosaicing (obtain full color & full resolution image)



Filter wheel

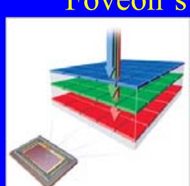
Rotate multiple filters in front of lens
Allows more than 3 color bands

Only suitable for static scenes

Prism vs. mosaic vs. wheel

approach	Prism	Mosaic	Wheel
# sensors	3	1	1
Separation	High	Average	Good
Cost	High	Low	Average
Framerate	High	High	Low
Artifacts	Low	Aliasing	Motion
Bands	3	3	3 or more
	High-end cameras	Low-end cameras	Scientific applications

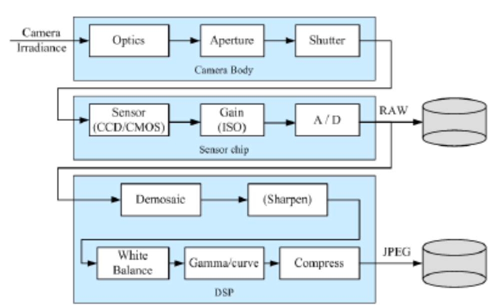
"newer" color CMOS sensor
Foveon's X3 – Sigma, Fujifilm



smarter pixels

better image quality

Digital Camera



Next Lecture

- Photometric Stereo
- Reading:
  - Section 2.2.4: Photometric Stereo
    - Shape from Multiple Shaded Images