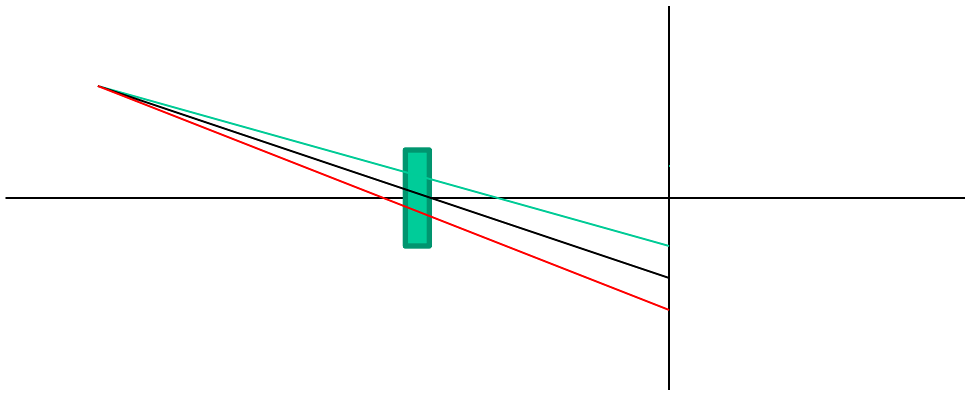
Today

Thin lens model

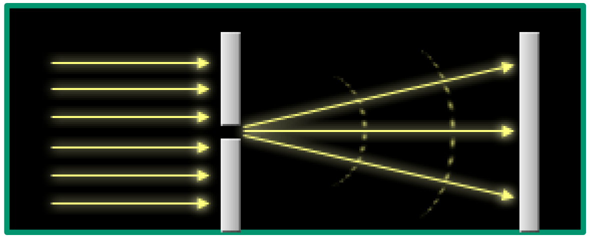
Radiometry

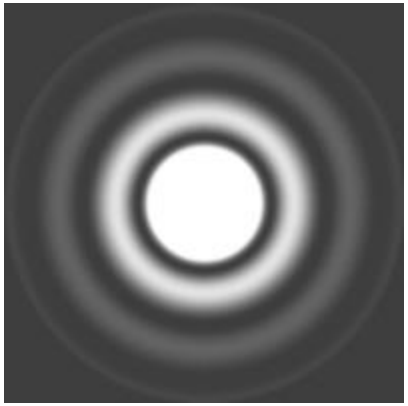
Problem of Pinhole Camera

Large aperture causes blur



Small aperture causes diffraction





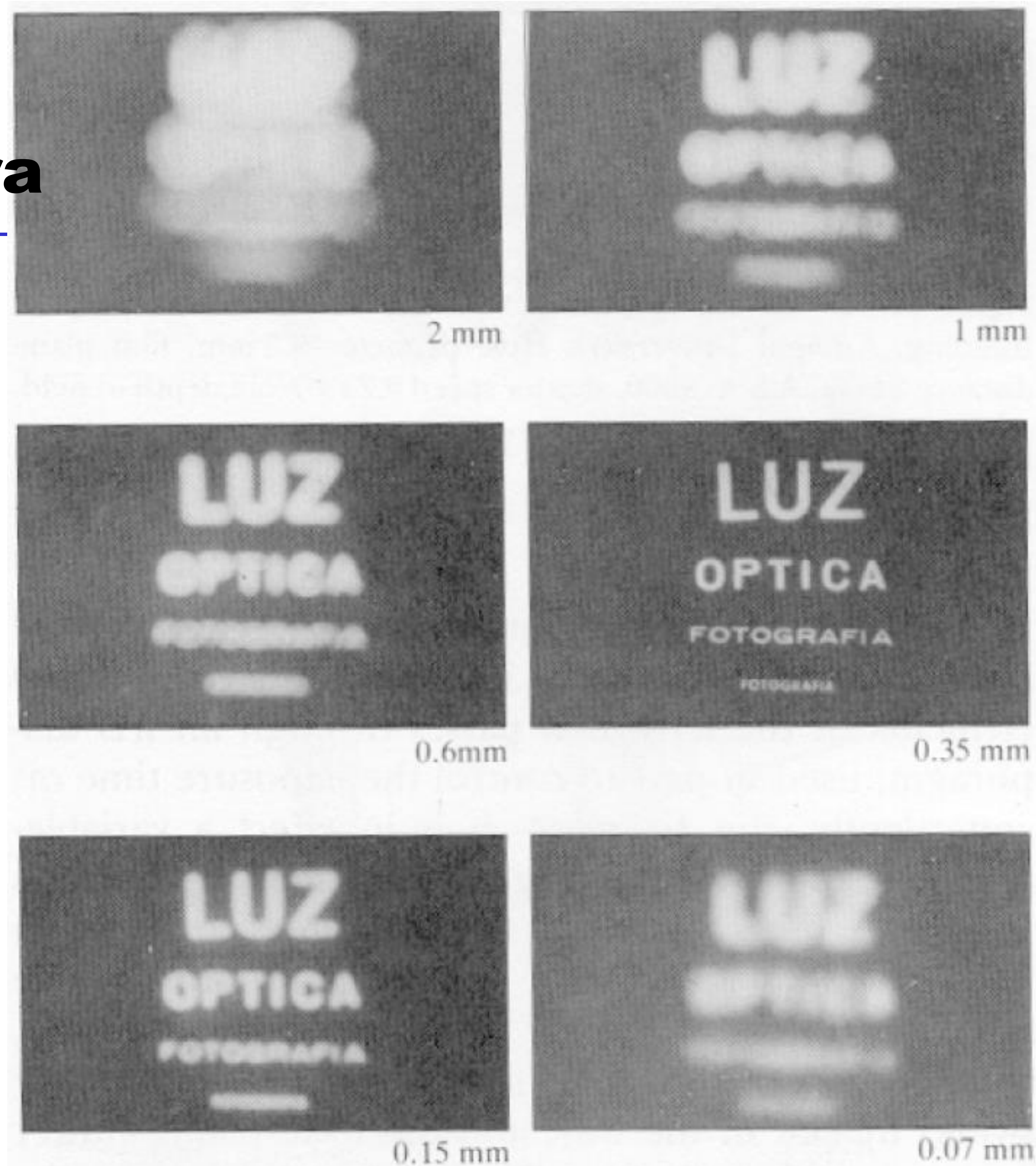
Images from http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm

Problem of Pinhole Camera

Pinhole too big - many directions are averaged, blurring the image

Pinhole too small - diffraction effects blur the image

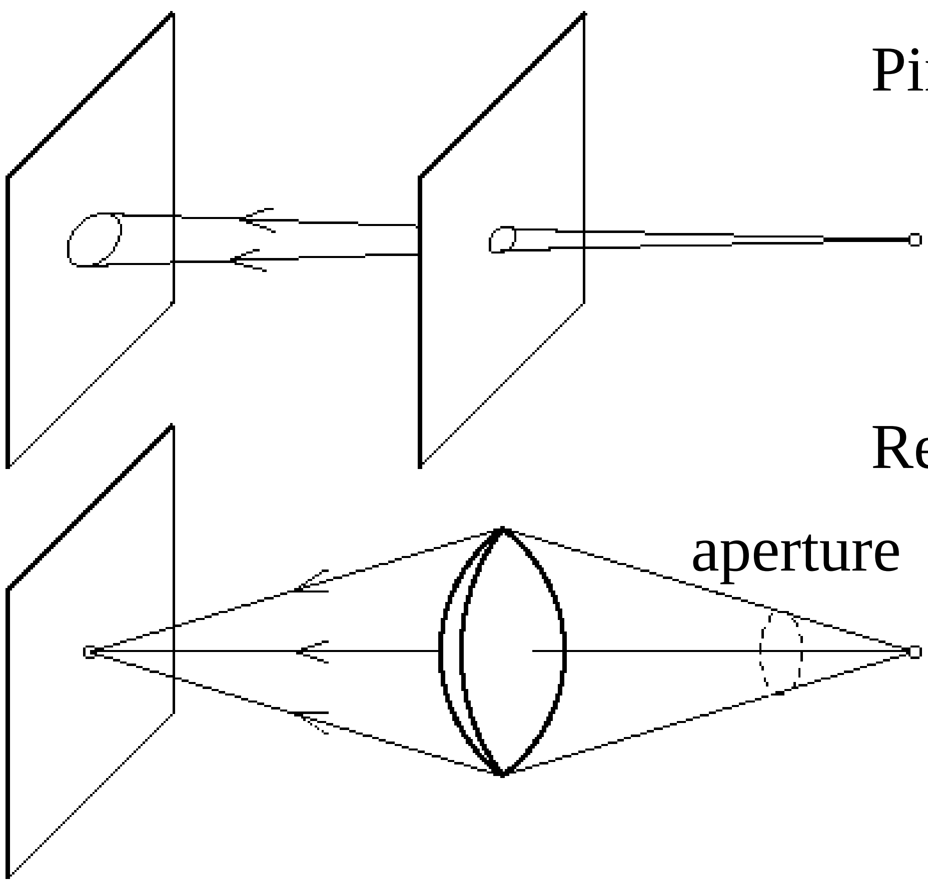
Generally, pinhole cameras are *dark*, because a very small set of rays from a particular point hits the screen.



The Reason for Lenses

The lens focuses light rays from the same point: make it brighter

Pinhole without lens



Regular camera with lens

Refraction of Light

Rays transitioning between materials are bent around normal

- every material has an index of refraction

$$n = \frac{c}{v}$$

Material	Index of Refraction
vacuum	1.0
ice	1.309
water	1.333
ethyl alcohol	1.36
glass	1.5–1.6
diamond	2.417

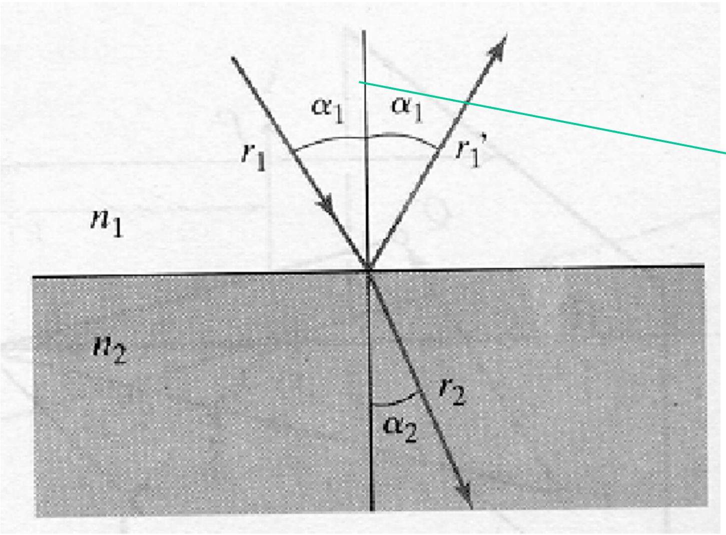
Refraction of Light

Rays transitioning between materials are bent around normal

- every material has an index of refraction

$$n = \frac{c}{v}$$

Snell's law



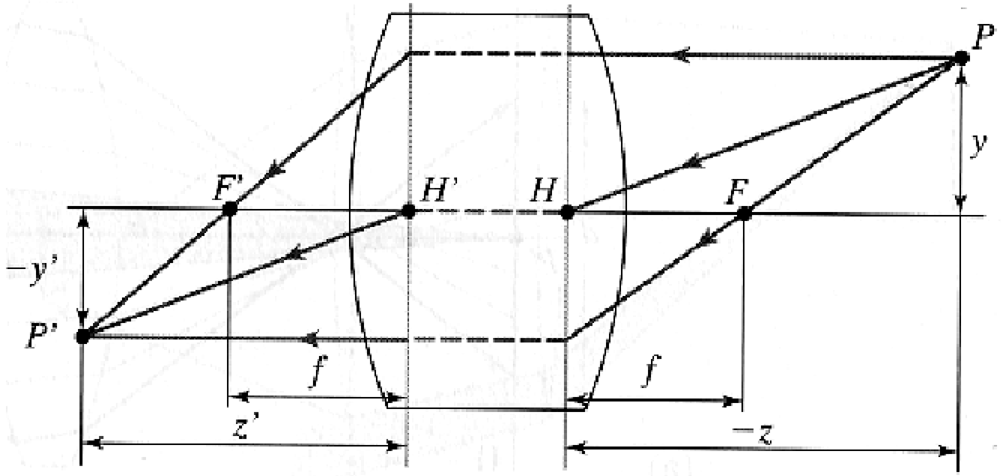
$$n_1 \sin(\alpha_1) = n_2 \sin(\alpha_2)$$

r1: incident ray
r1': reflected ray
r2: refracted ray

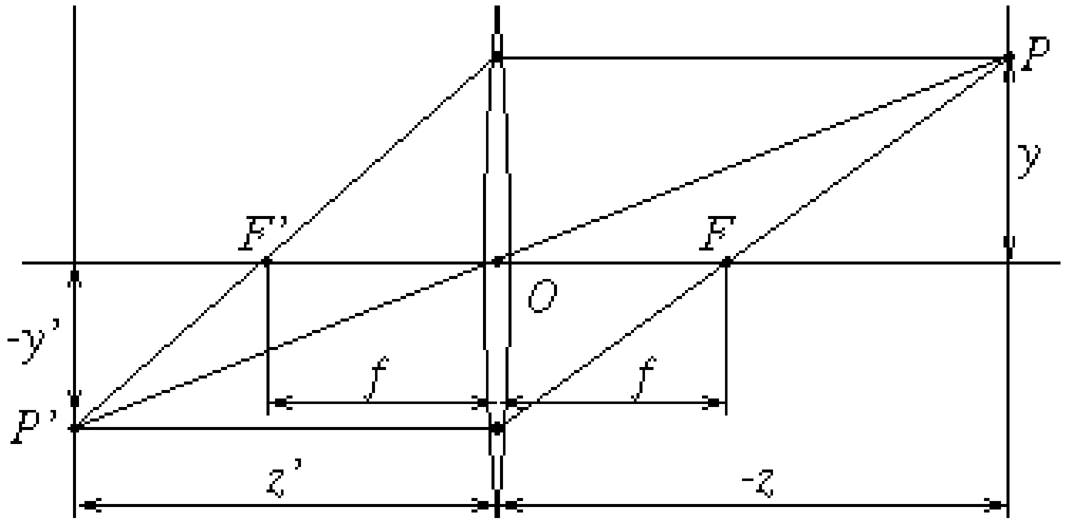
Normal direction

All of them are on the same plane!

Lens



Thick lens



Thin lens

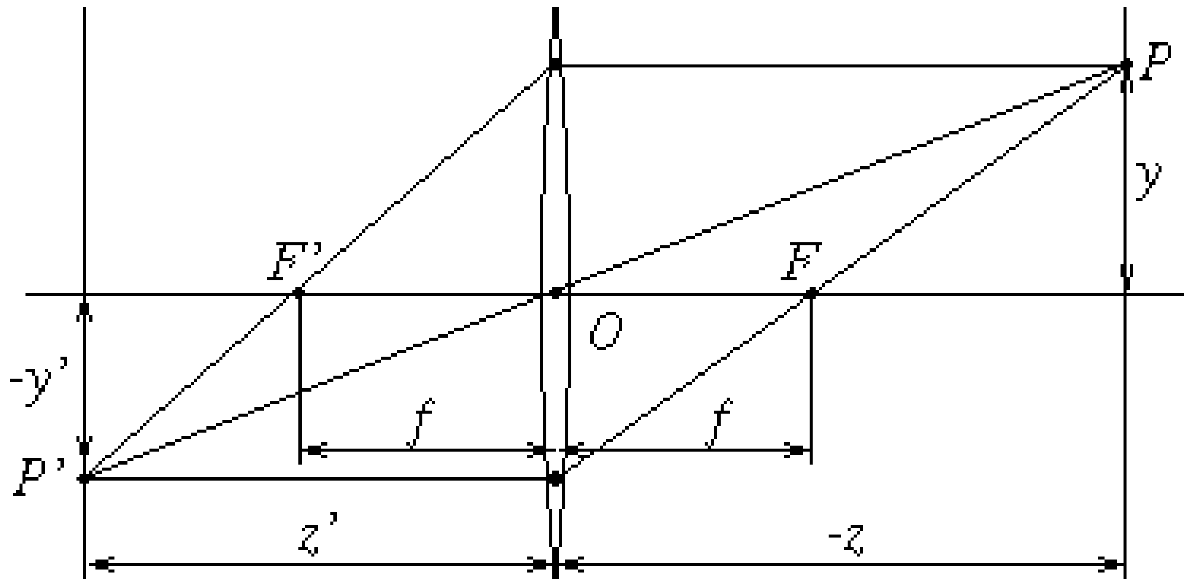
Basic Optics: Thin Lens Model

Pinhole is an abstract model. In practice, we have a thin lens model

Thin lens: a lens with a thickness negligible compared to the focal length

Terminology:

- O: optical center
- Z: object distance
- Z': image distance
- F: primary focal point
- F': secondary focal point
- f: focal length
- R: the radius of the curvature of the lens surface
    - assume the two surfaces having the same R



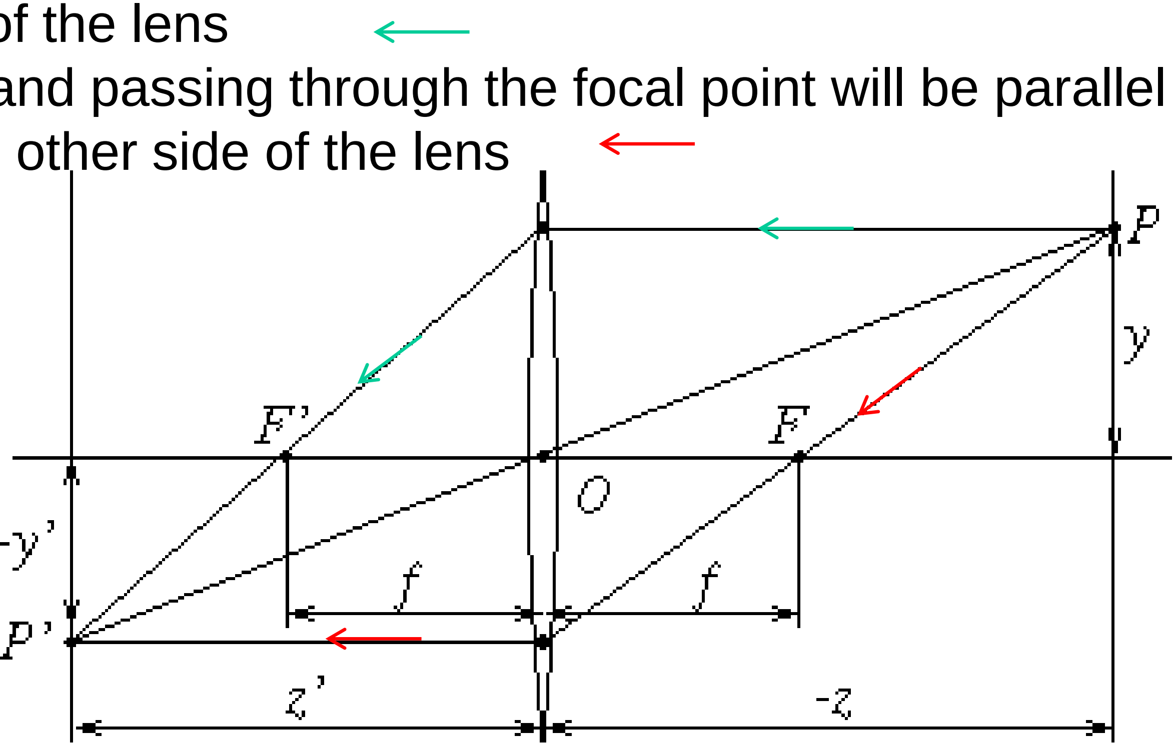
$$f = \frac{R}{2(n-1)}$$

Note: f in the thin lens model is different from that in the pinhole model

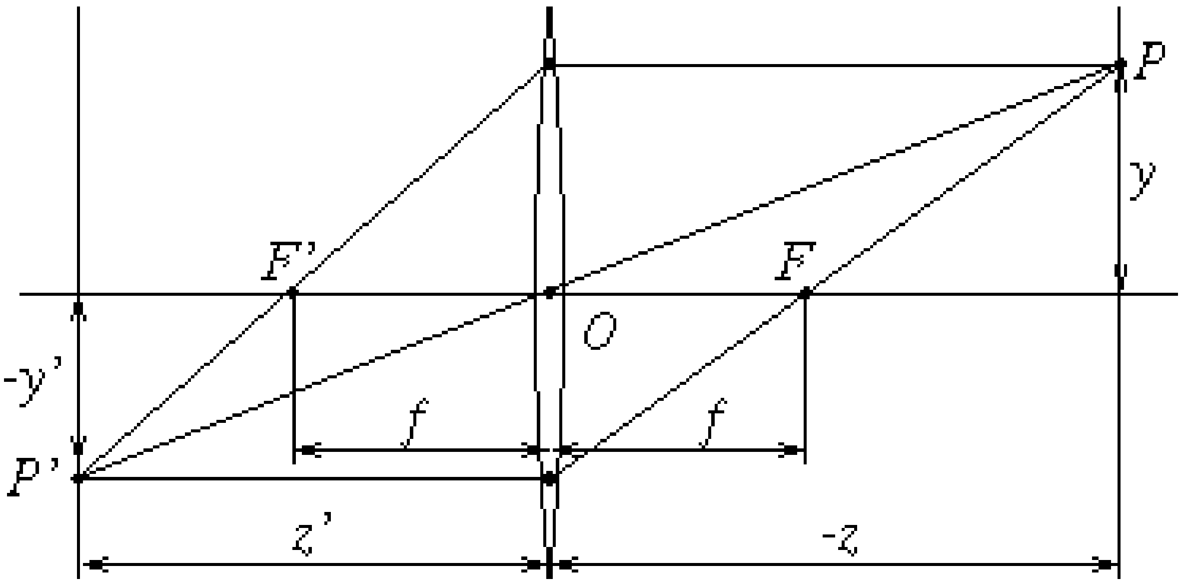
Basic Optics: Thin Lens

Properties of thin lens:

- A ray passing through O does not change direction: same as pinhole
- Rays entering the lens parallel to the optical axis will intersect at the focal point on the other side of the lens
- Rays entering the lens and passing through the focal point will be parallel to the optical axis at the other side of the lens



Basic Optics: Thin Lens Model



$$\frac{1}{z'} + \frac{1}{|z|} = \frac{1}{f}$$

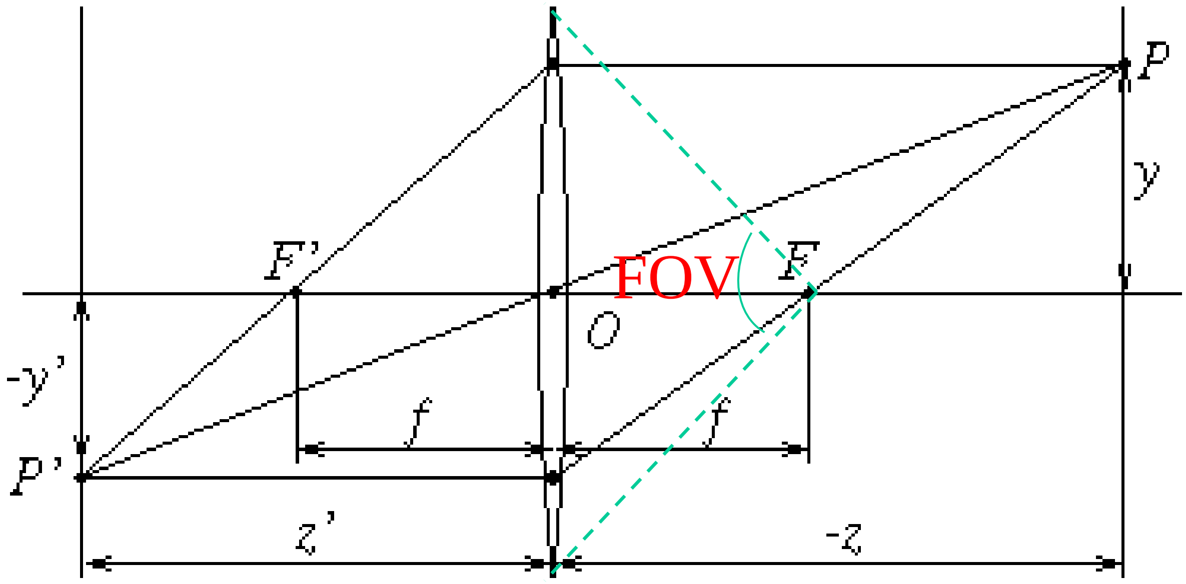
Increasing the object distance will

- Reduce the image distance z'
- Reduce the image size

Increasing the focal length will

- Increase the image size

Basic Optics: Thin Lens: Field of View



Human:

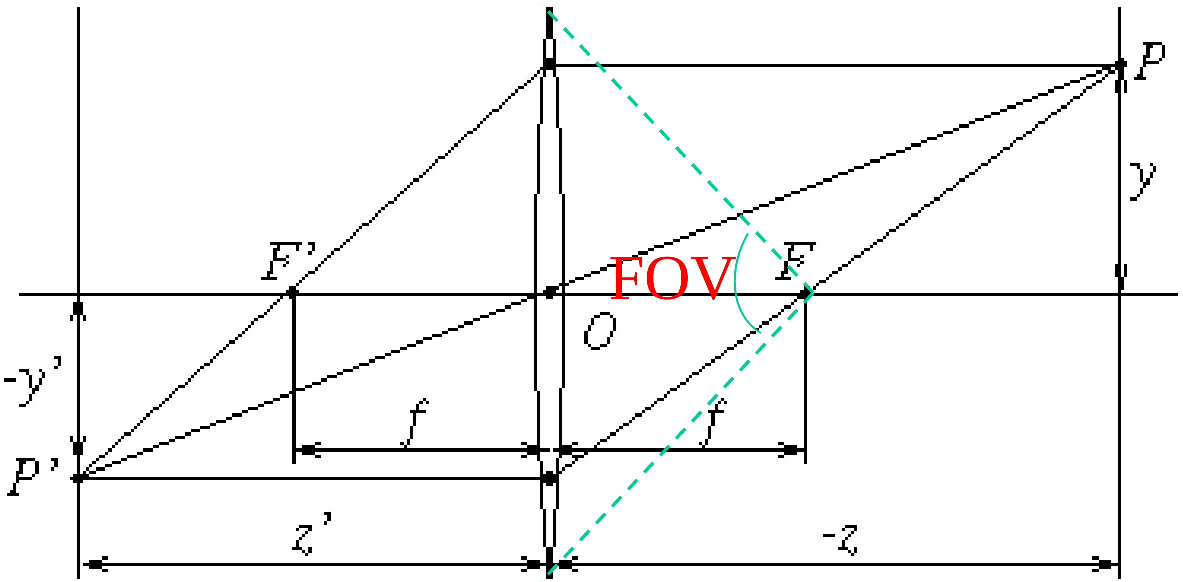
- 180° horizontal FOV and 100° degree vertical FOV
- 120° horizontal FOV for binocular vision

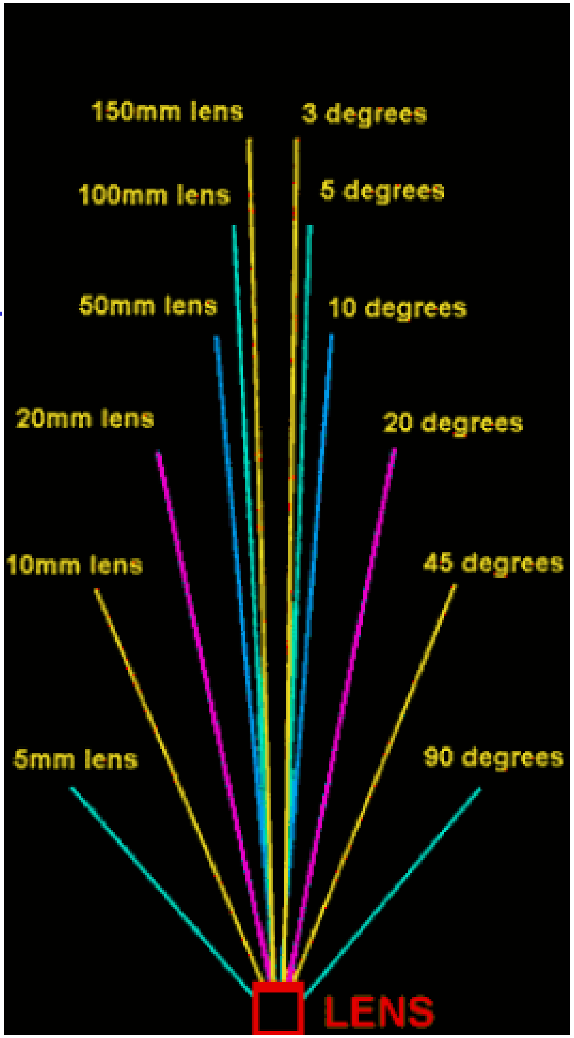
Animals: varies

- 360° FOV for some birds

Pinhole camera: 360° FOV

Basic Optics: Thin Lens





Field of View: $\omega = 2arctan\frac{d}{f}$

F-number: *f/d* → Large focal length or smaller lens will give a small FOV

Normal lens: *f* is almost equal to the diagonal size of the film or CCD array (36*24mm) → $f = 50\ mm$

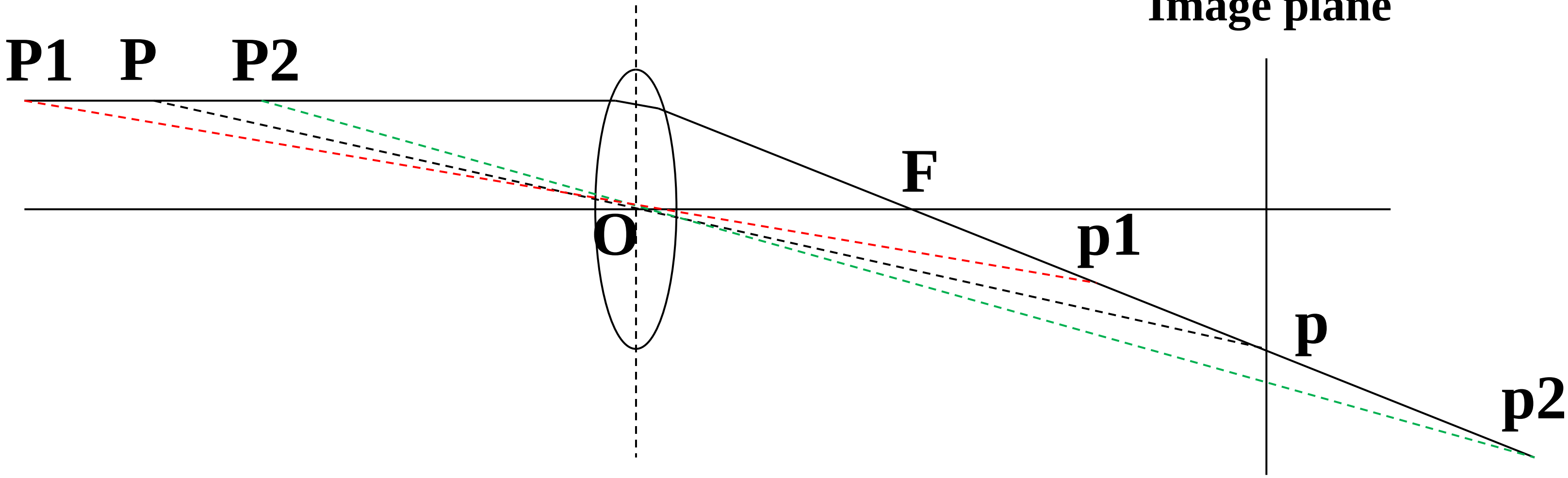
Wide-angle lens: *f* is shorter than 50mm (e.g., 35mm)

Telephoto lens: *f* is longer than 50mm (e.g., >85mm)

Depth of Field & Out of Focus

http://www.azuswebworks.com/photography/dof.html

$$\frac{1}{z'} + \frac{1}{|z|} = \frac{1}{f}$$

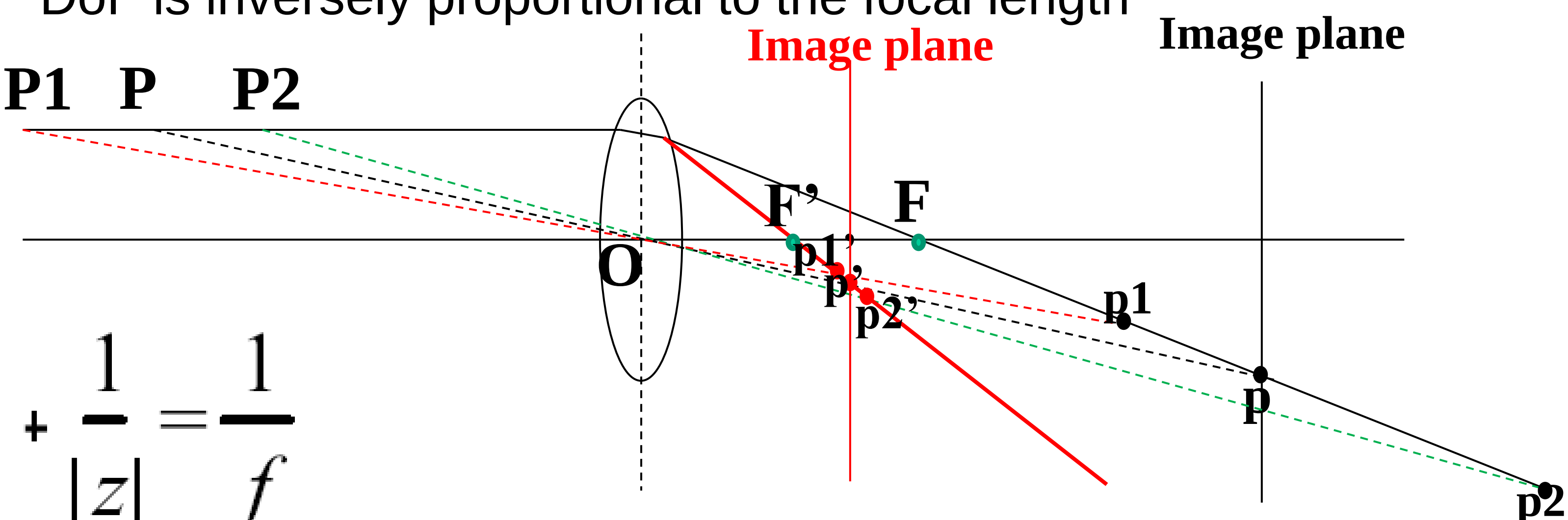


Depth of Field (DoF) & Out of Focus

- DoF is proportional to object distance
  - Objects far away from the camera have a large DOF

- DoF is inversely proportional to the aperture

- DoF is inversely proportional to the focal length



$$\frac{1}{z'} + \frac{1}{|z|} = \frac{1}{f}$$

More information on DoF: http://www.azuswebworks.com/photography/dof.html

Note on the Focal Length for Thin Lens

Increase *f* will

- Increase image size
- Decrease the FOV
- Decrease the DoF

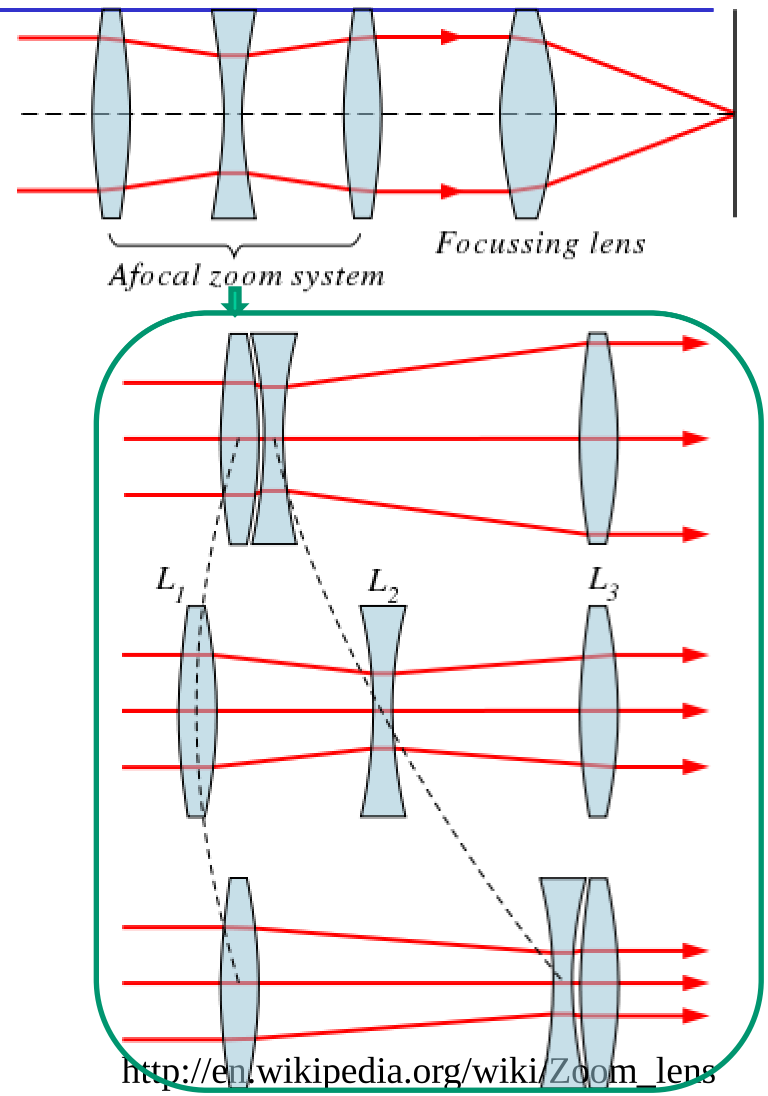
Note on the Focal Length for Thin Lens

Increase *f* will

- Increase image size
- Decrease the FOV
- Decrease the DoF

In practice: changing focal length in camera with zoom lens is implemented by a lens array:

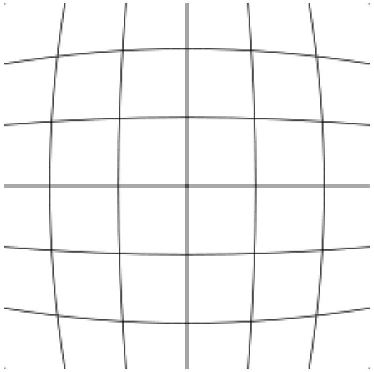
- An afocal zoom system changes the size of the beam
- A standard fixed-f lens focuses the light



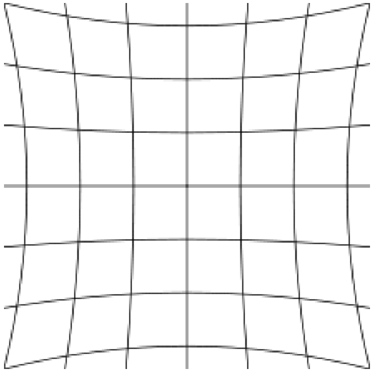
http://en.wikipedia.org/wiki/Zoom_lens

Aberration – Why We Need Expensive Lens?

Geometrical aberrations: Radial distortion



Barrel



Pincusion

Good application: fisheye

Can be corrected with known parameters

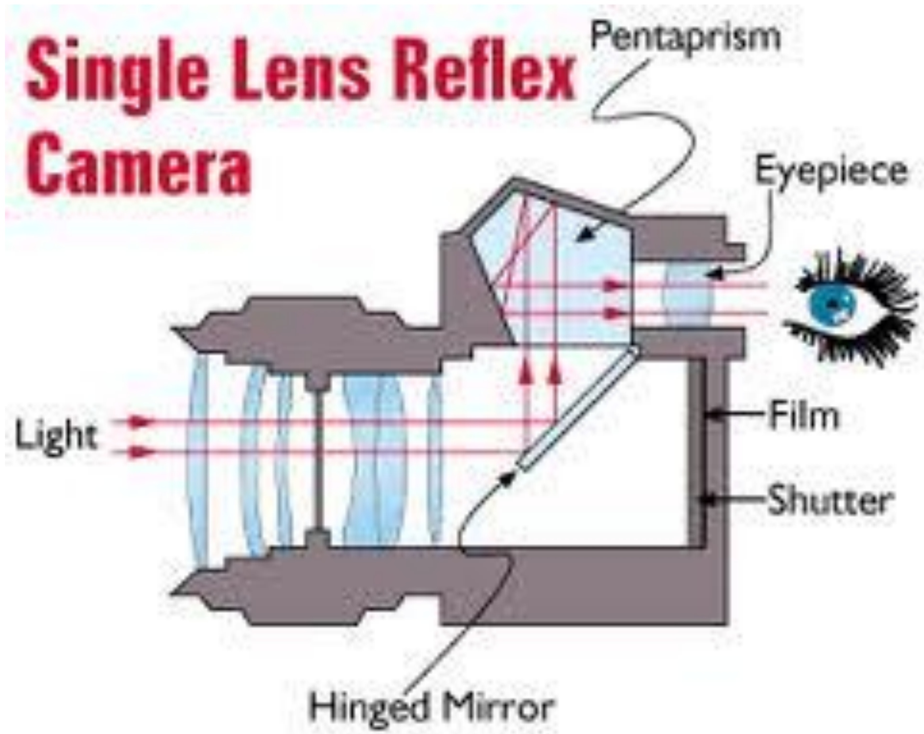
Chromatic aberrations:

Rays of different wavelengths focus at different planes

Cannot be fully corrected

Thanks wiki for the pictures

Camera


Single Lens Reflex Camera
Pentaprism
Eyepiece
Light
Film
Shutter
Hinged Mirror

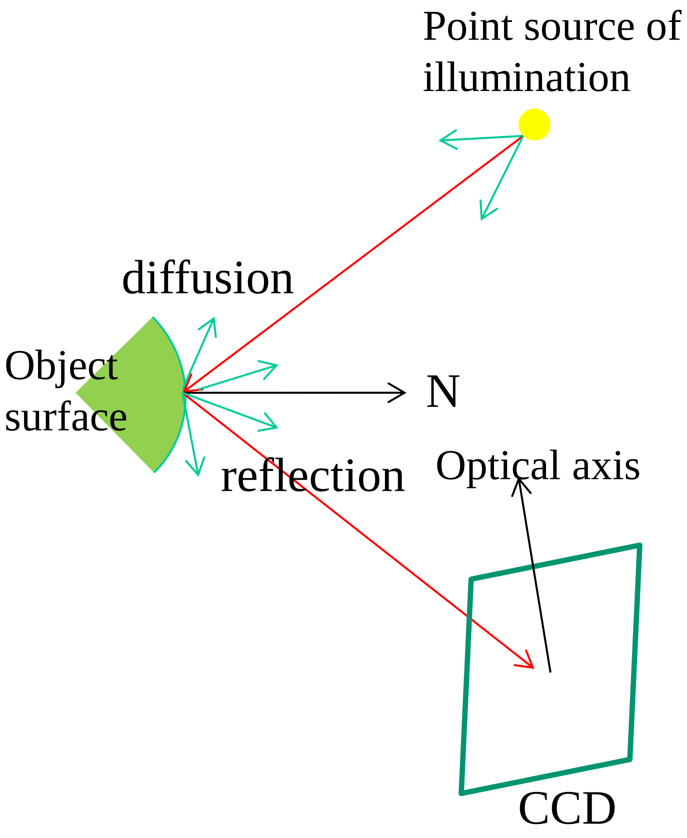
Next: Radiometry

Read Chapter 2 of Forsyth & Ponce

Radiometry

Imaging process

- **Light reaches surfaces**
  - from a light source
  - from another surface
- **Surfaces reflect light**
- **Sensor element receives light energy**
  - linear in the middle of range
  - nonlinear at the two ends



Reflection at a surface

Assumptions:

- 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

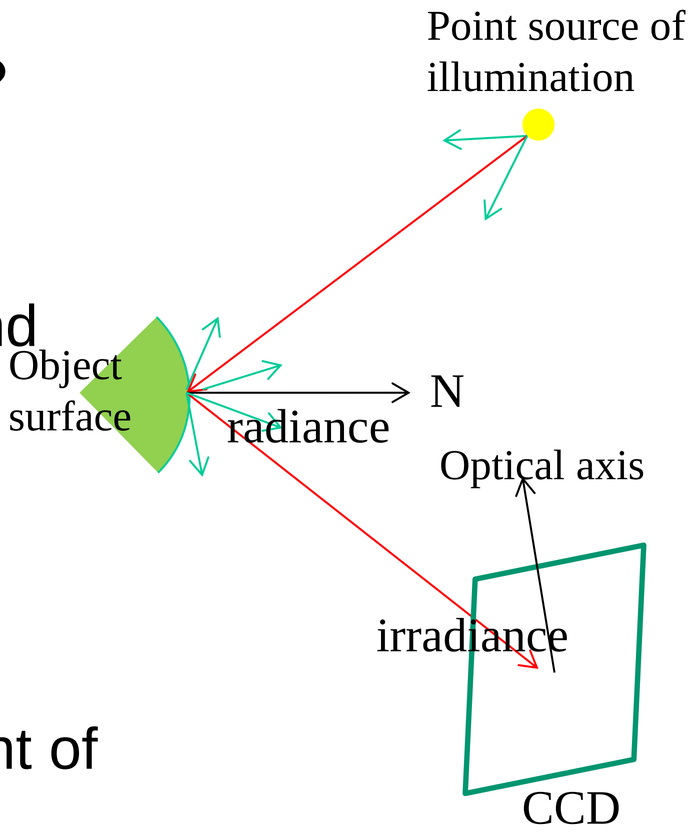
Many effects when light strikes a surface

- Absorbed
- Transmitted
  - –transparent media
- Reflected (specular)
  - –mirror
  - –Scattered

Basic Radiometry

Questions:

- how "bright" will surfaces be?
- what is "brightness"?
  - measuring light
  - interactions between light and surfaces



The brightness is affected by

- Illumination
- Surface radiance **($wsr^{-1}m^{-2}$)**: amount of radiation in a specific direction
- Image irradiance **(wm^{-2})**: power of light per unit area a CCD array element receives

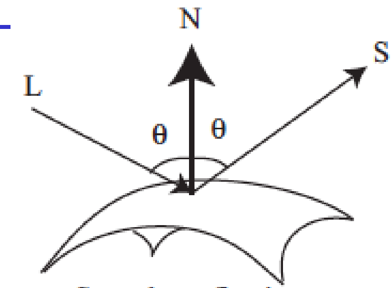
Important Reflection Modes

Specular reflection (mirror like)

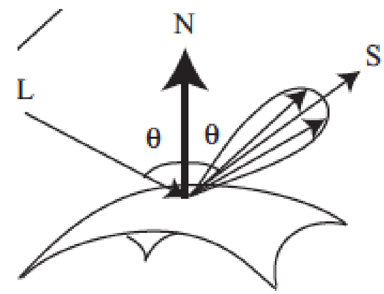
- Pure mirror:
  - incoming, outgoing directions and normal are coplanar
  - incoming, outgoing angles to normal are equal
- Most specular surfaces:
  - some light leaves the surface along directions near to the specular direction as well

Diffuse reflection

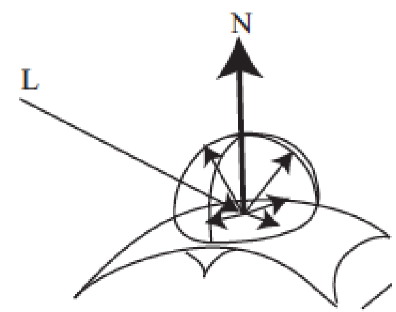
- Light leaves in equal amounts in each direction
  - so surface looks equally bright from each viewing direction
  - Application: diffusion umbrella



Specular reflection

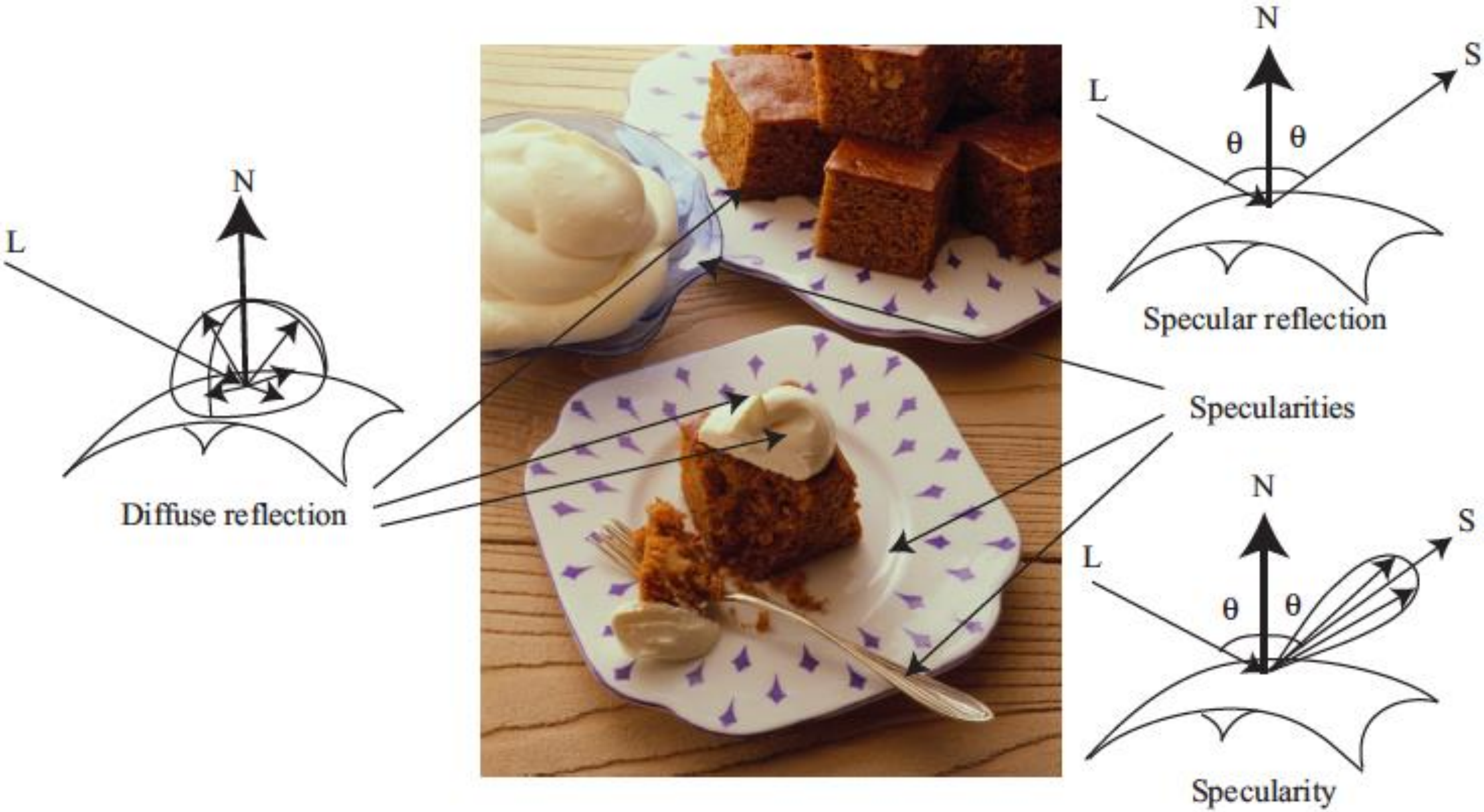


Specularity



Diffuse reflection

Important Reflection Modes



Specularities

Mirrors are bright
- Reflect most incoming light

Most specular surfaces aren't pure mirrors
- The only significant specular reflection is the light source
- Result: small, bright patches on specular surfaces
  - Move when the light source moves
  - Move when the viewing direction moves
  - Shape, motion depend on local geometry of the surface

Specular albedo
- percentage of incoming light that is specularly reflected

Diffuse Reflection

Light leaves the surface evenly in all directions

- E.g., cotton cloth, carpets, matte paper, matte paints, most "rough" surfaces

Described by one parameter: Albedo (reflection coefficient)

- percentage of light arriving that leaves
- range 0-1
  - practical range is 0.05-0.9
  - Albedo of earth is 0.3-0.35

Light leaving is (Albedo)x(Light arriving)

- Does not depend on the observation direction
- Ambiguity: A surface could be dark because
  - It reflects a small percentage of the light arriving
  - There isn't very much light arriving

How much light arrives: Lambertian Reflection

Assume source is far away

- So light travels in parallel rays
- (Light arriving) proportional to (number of rays striking surface)

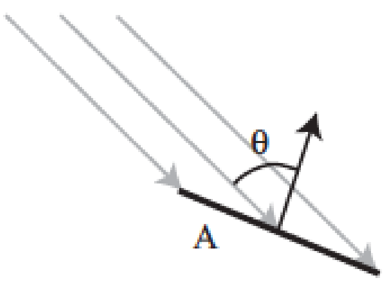
Lambertian reflection: Ideal diffuse reflection

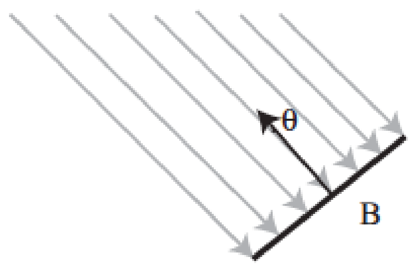
- Surface radiance follows the Lambert's cosine law

$$I_R = \rho \mathbf{L} \cdot \mathbf{N}$$

I_R: surface radiance; ρ: surface albedo;

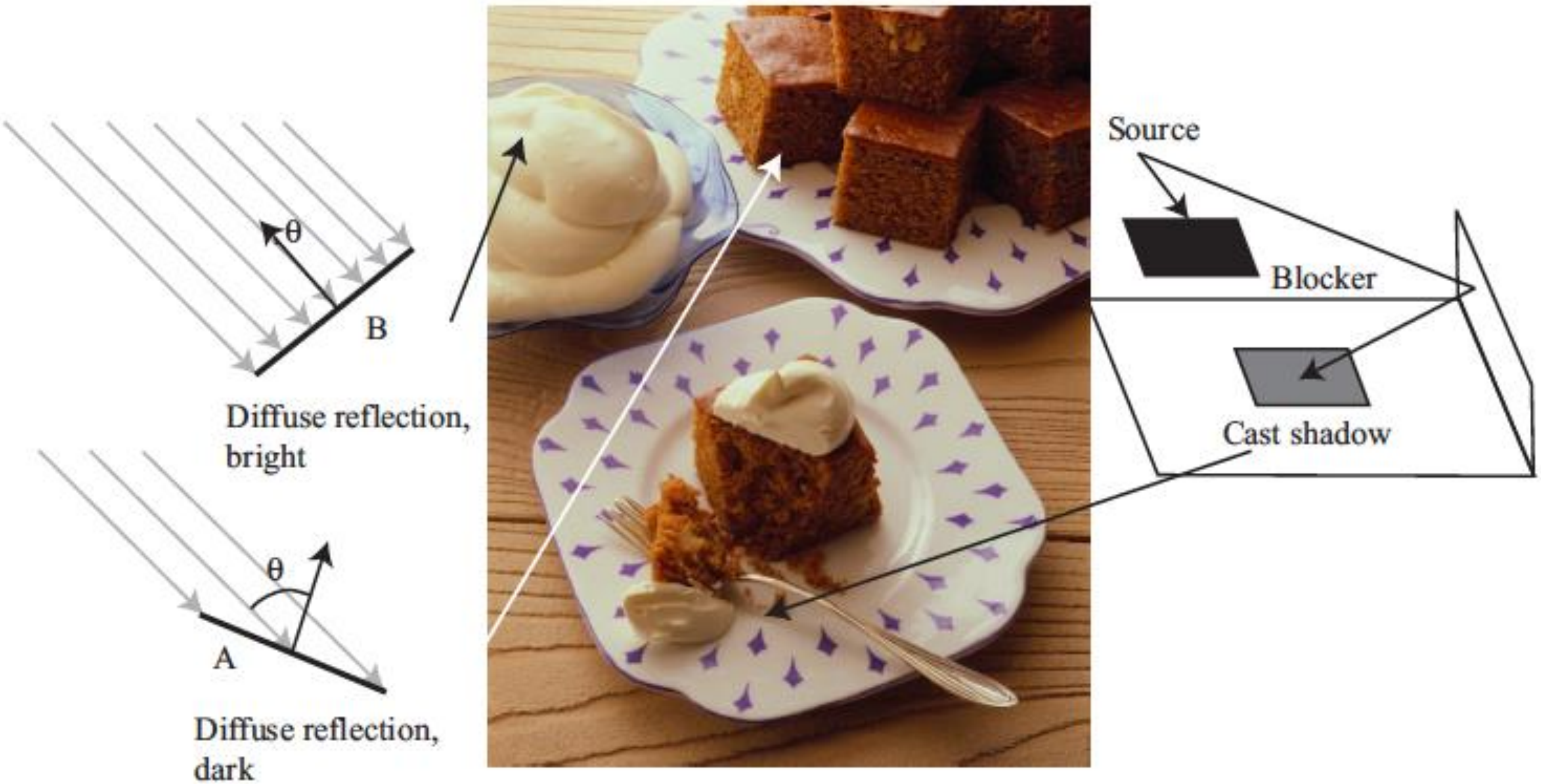
$\mathbf{L}$: intensity and direction of incoming light; $\mathbf{N}$: surface normal





Which surface will be brighter with the same number of rays arriving?

How much light arrives: Lambertian Reflection

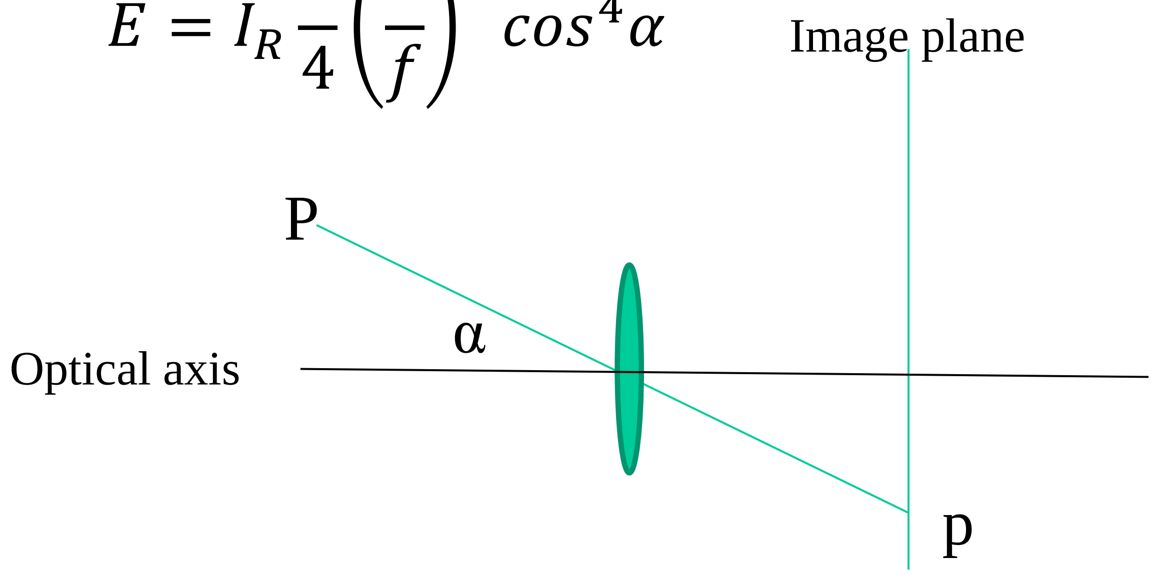


Fundamental Equation of Radiometric Image Formation

What is the relationship between the surface radiance and image irradiance?

For a thin lens with diameter d and focal length f, we have

$$E = I_R \frac{\pi}{4}\left(\frac{d}{f}\right)^2 \cos^4\alpha$$



For small angular aperture (FOV), the image irradiance is proportional to the surface radiance.

Fundamental Equation of Radiometric Image Formation

illumination ➡ intensity

$$I = \beta\rho\frac{\pi}{4}\left(\frac{d}{f}\right)^2 cos^4\alpha\,\mathbf{L}\cdot\mathbf{N}$$

↓

Sensor determined

Notes: Radiometry

Image brightness is affected by

- amount of light arriving at surface
- surface type (diffuse, specular) and amount reflected at surface
- camera sensitivity

➡ Low albedo surface in bright light vs high albedo surface in low light: each might reflect about the same amount

Most surfaces can be modeled as diffuse + specular

- generally, find and remove specularities
- treat the rest as diffuse