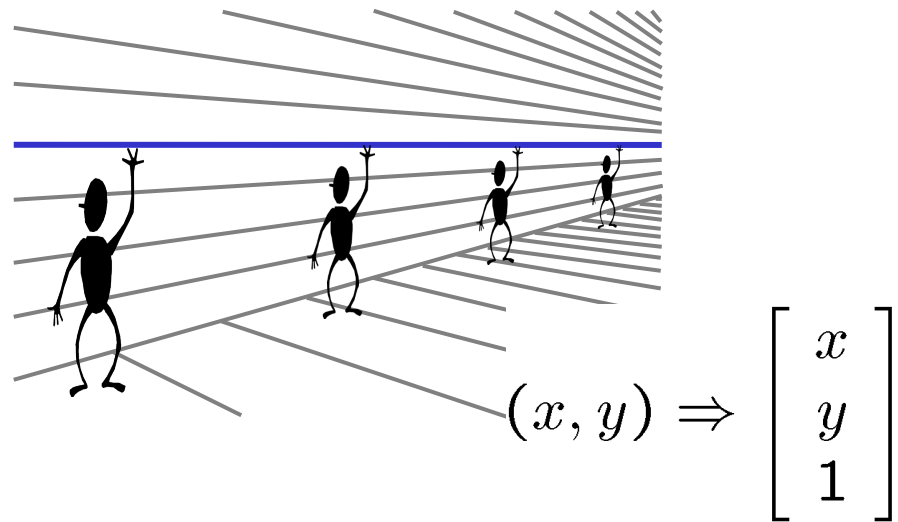
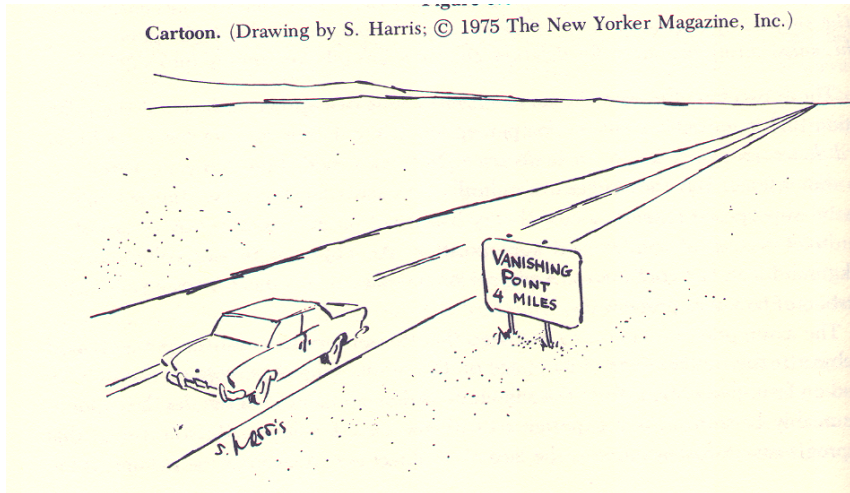
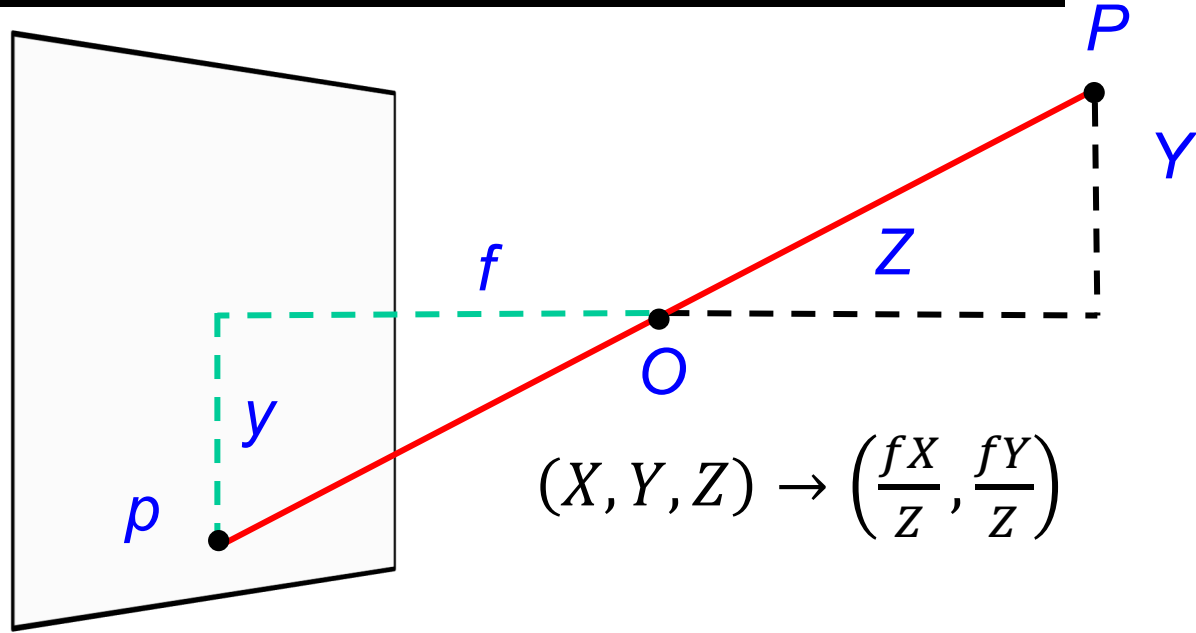
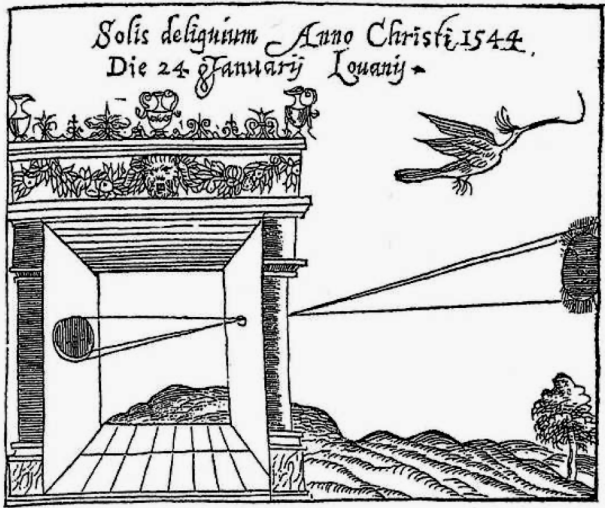

Cameras, Light and Shading

CS 543 / ECE 549 – Saurabh Gupta

Spring 2020, UIUC

<http://saurabhg.web.illinois.edu/teaching/ece549/sp2020/>

Recap



Overview

- Cameras with lenses
 - Depth of field
 - Field of view
 - Lens aberrations
- Brightness of a pixel
 - Small taste of radiometry
 - In-camera transformation of light
 - Reflectance properties of surfaces
 - Lambertian reflection model
 - Shape from shading

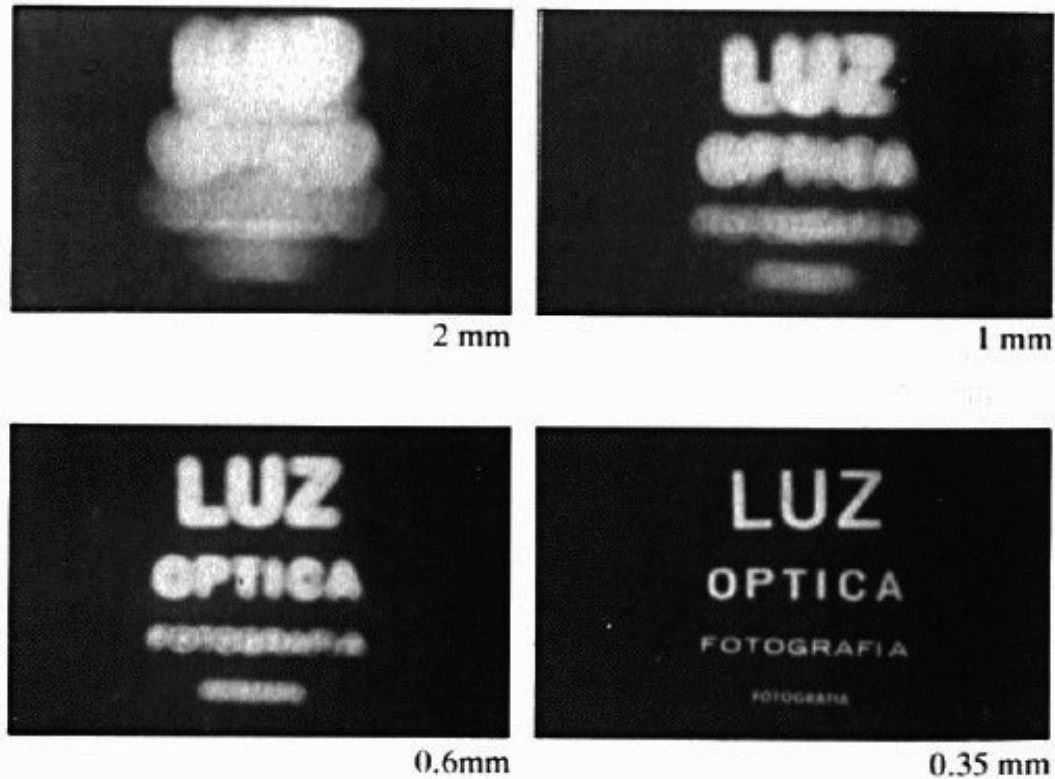
Building a Real Camera



Home-made pinhole camera



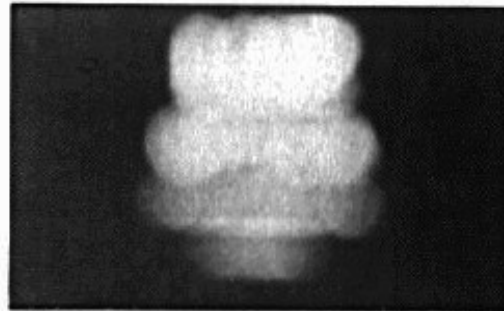
Shrinking the aperture



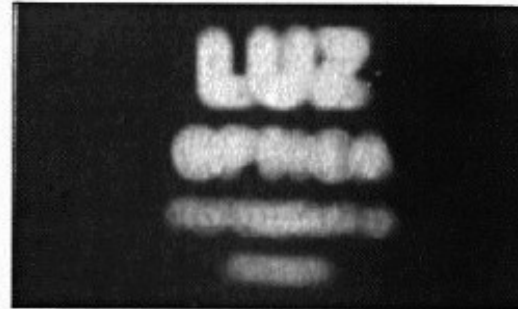
Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects...

Shrinking the aperture



2 mm



1 mm



0.6mm



0.35 mm



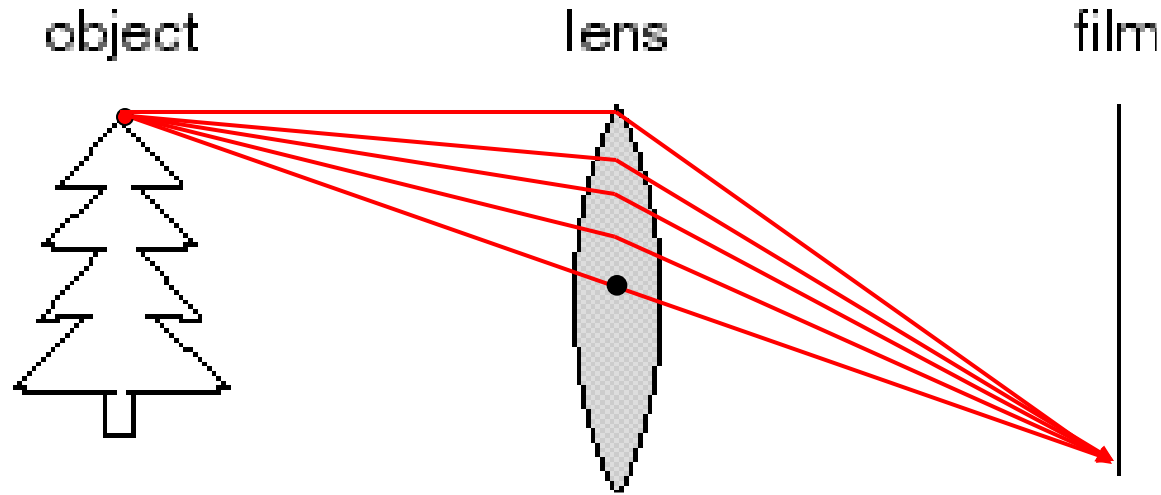
0.15 mm



0.07 mm

Adding a lens

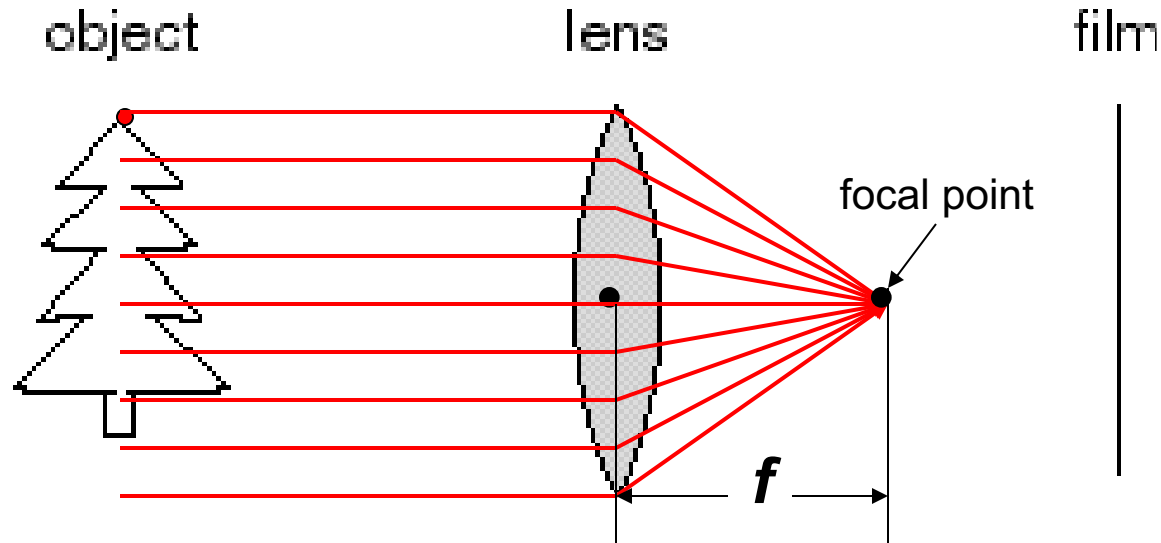
Adding a lens



A lens focuses light onto the film

- Thin lens model:
 - Rays passing through the center are not deviated (pinhole projection model still holds)

Adding a lens

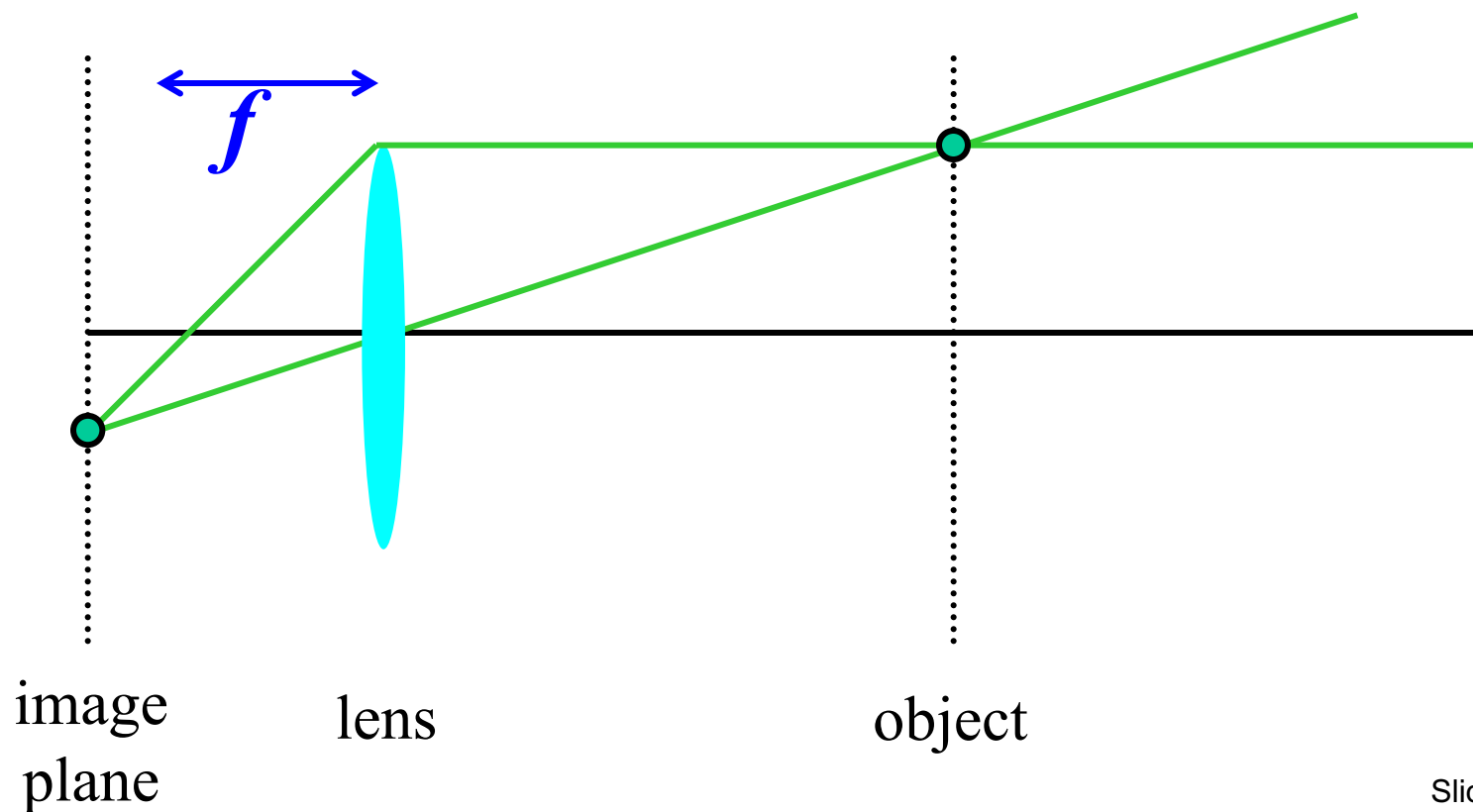


A lens focuses light onto the film

- Thin lens model:
 - Rays passing through the center are not deviated (pinhole projection model still holds)
 - All rays parallel to the optical axis pass through the *focal point*
 - All parallel rays converge to points on the *focal plane*

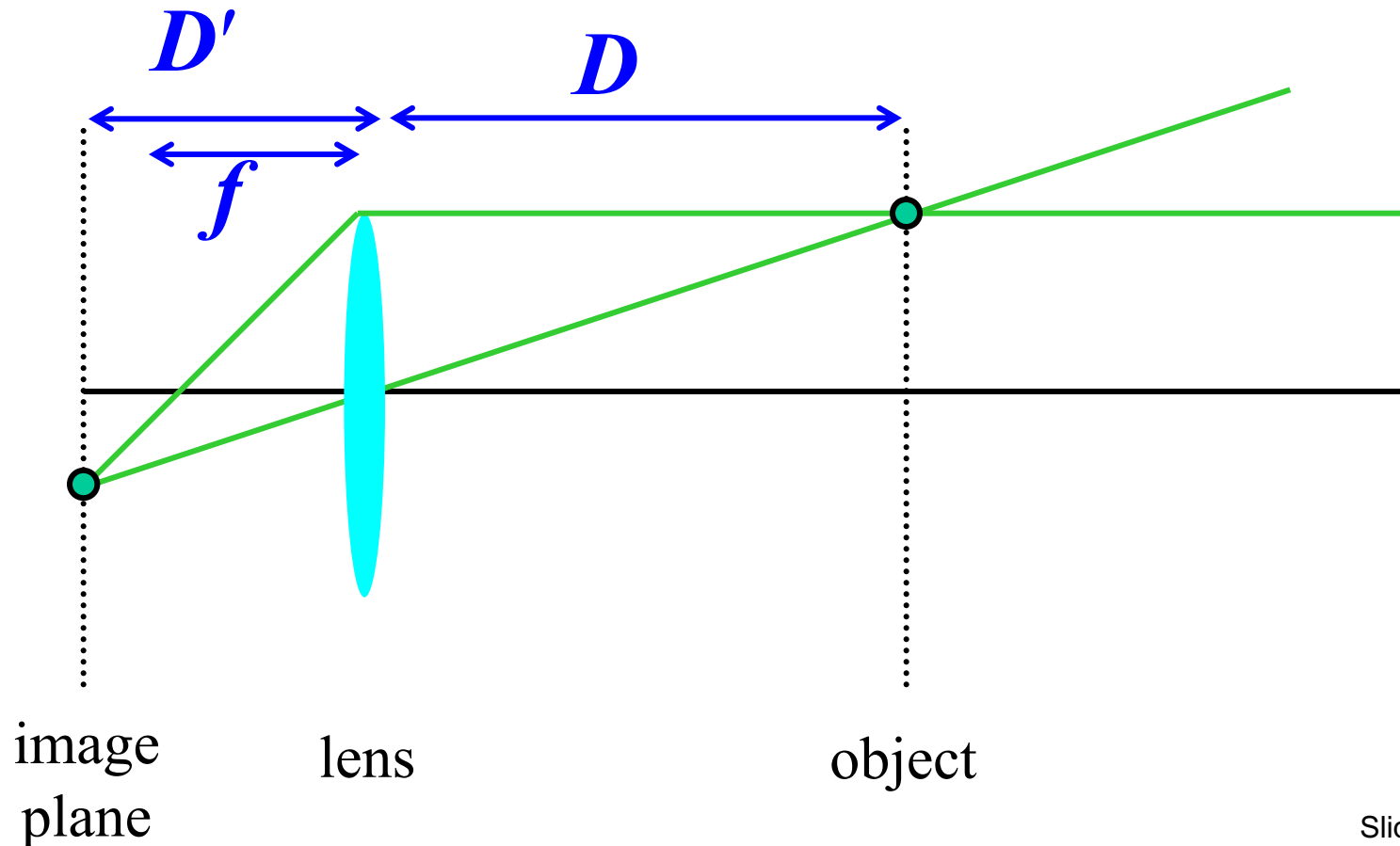
Thin lens formula

- Where does the lens focus the rays coming from a given point in the scene?



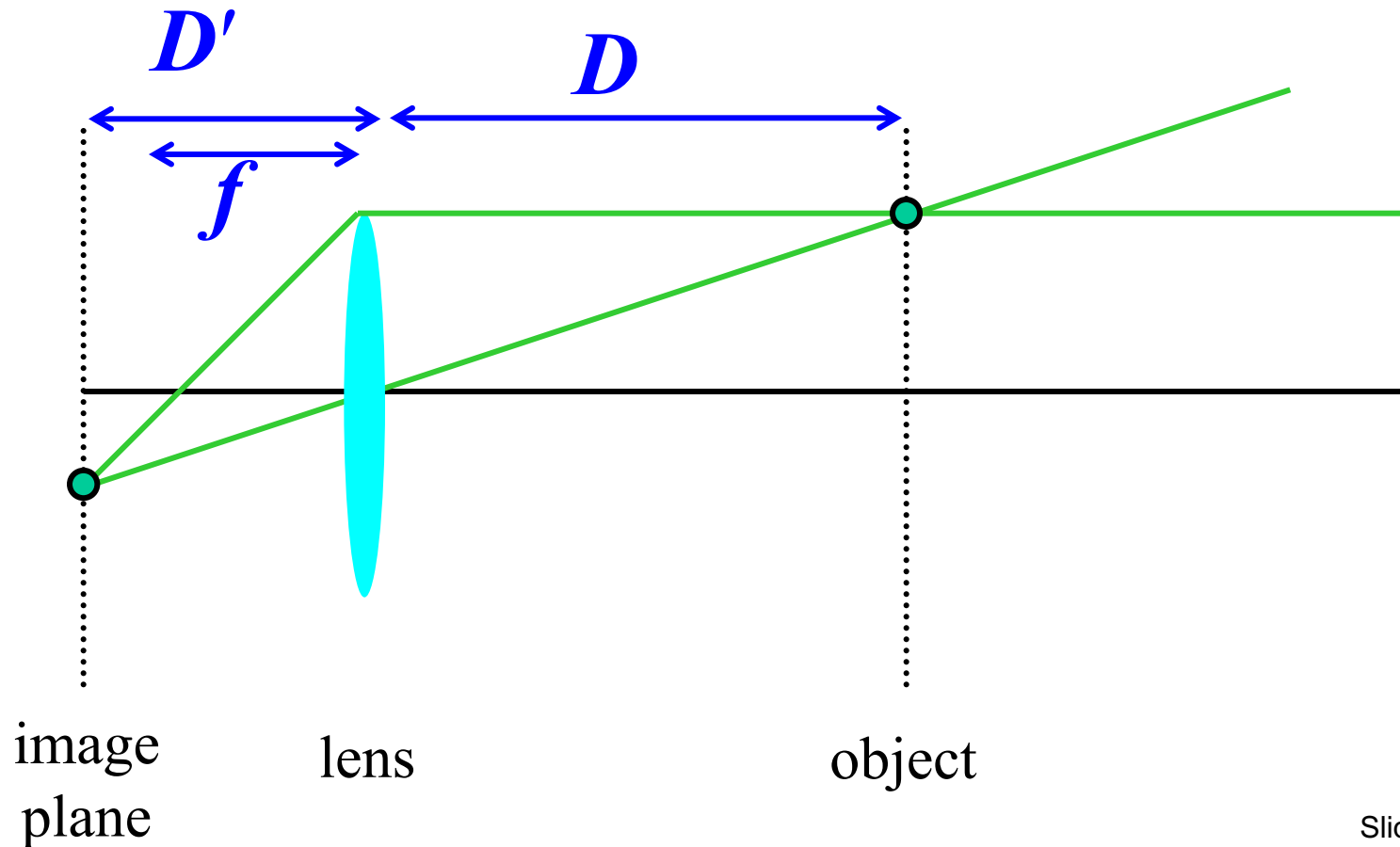
Thin lens formula

- What is the relation between the focal length (f), the distance of the object from the optical center (D), and the distance at which the object will be in focus (D')?



Thin lens formula

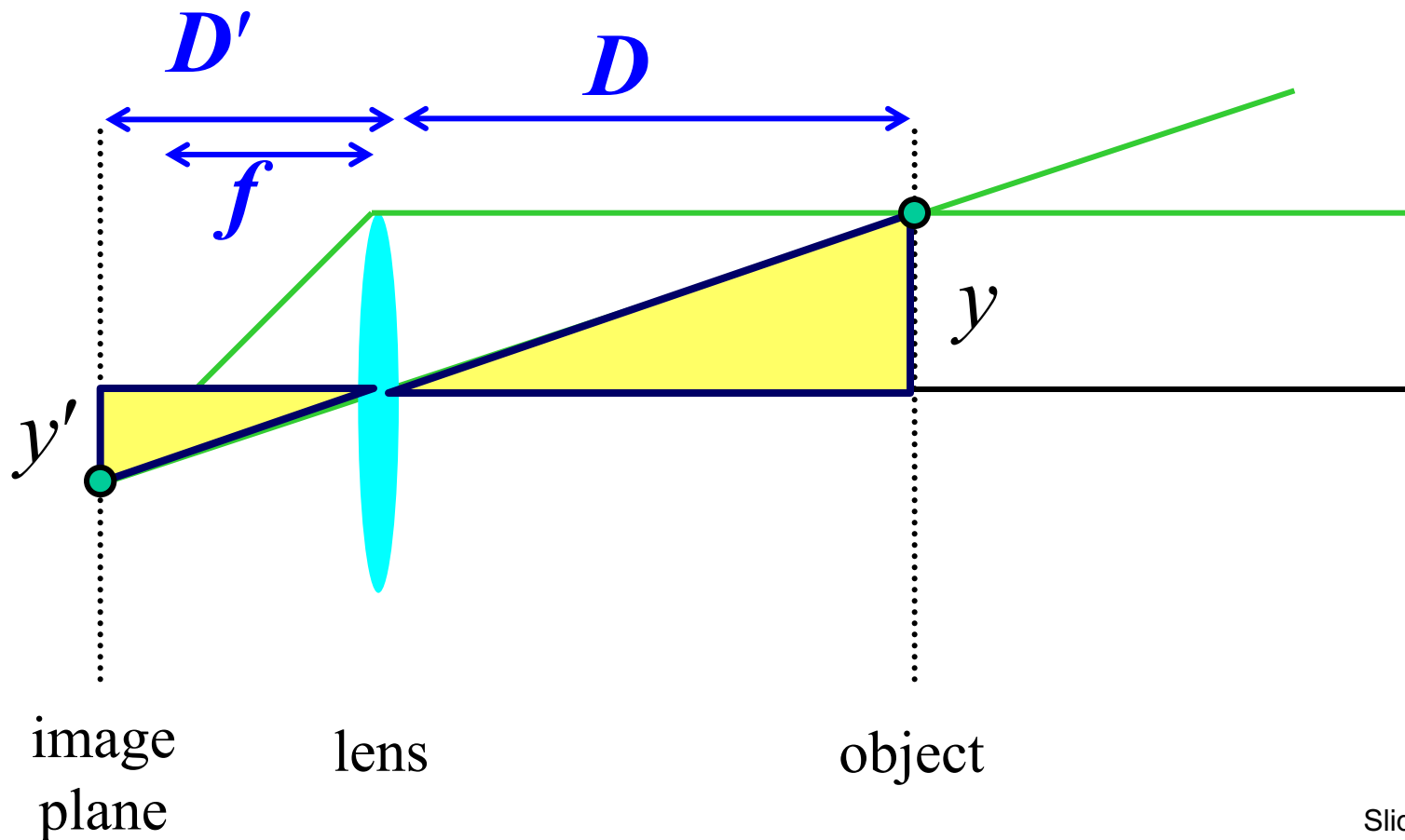
Similar triangles everywhere!



Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$

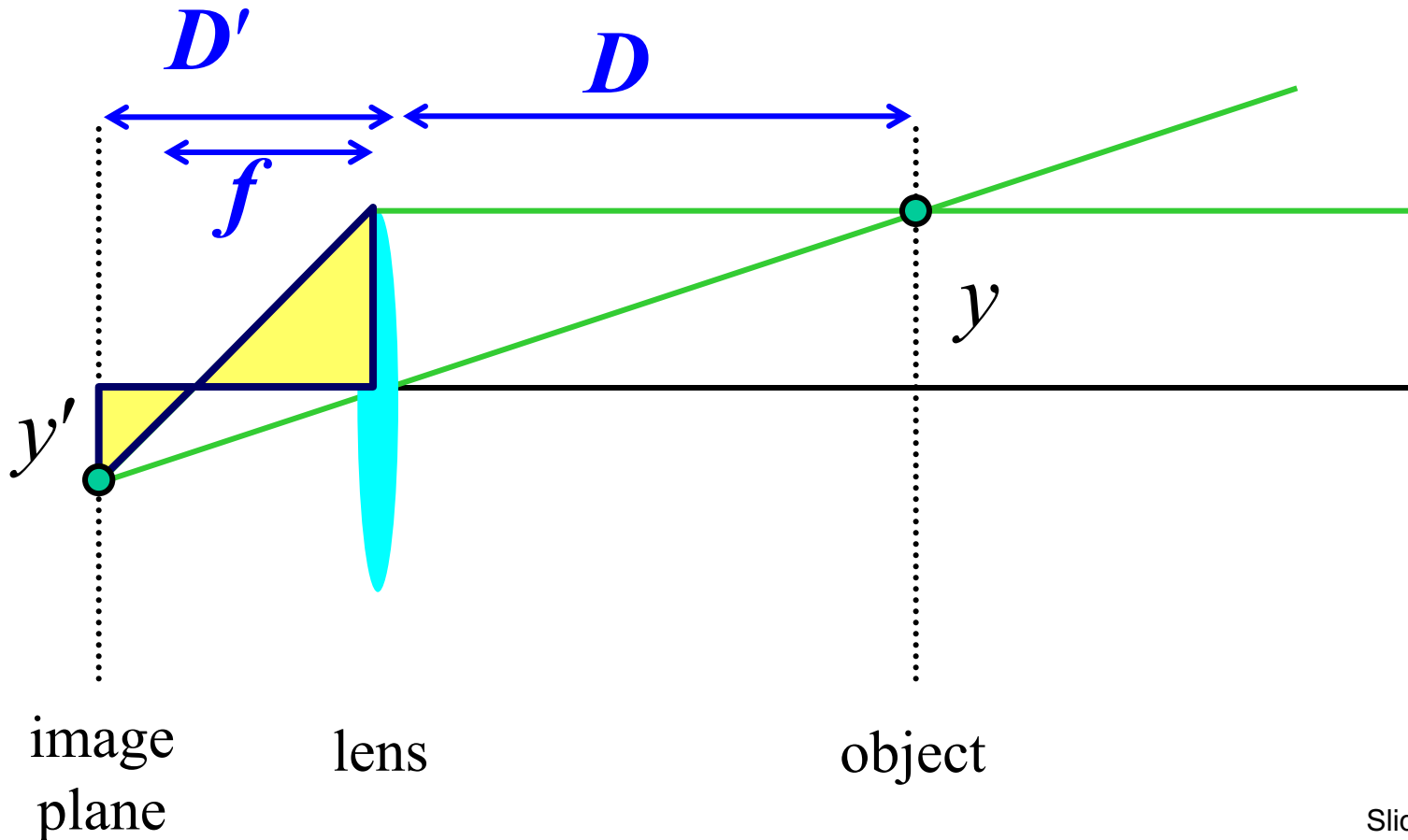


Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$

$$y'/y = (D' - f)/f$$

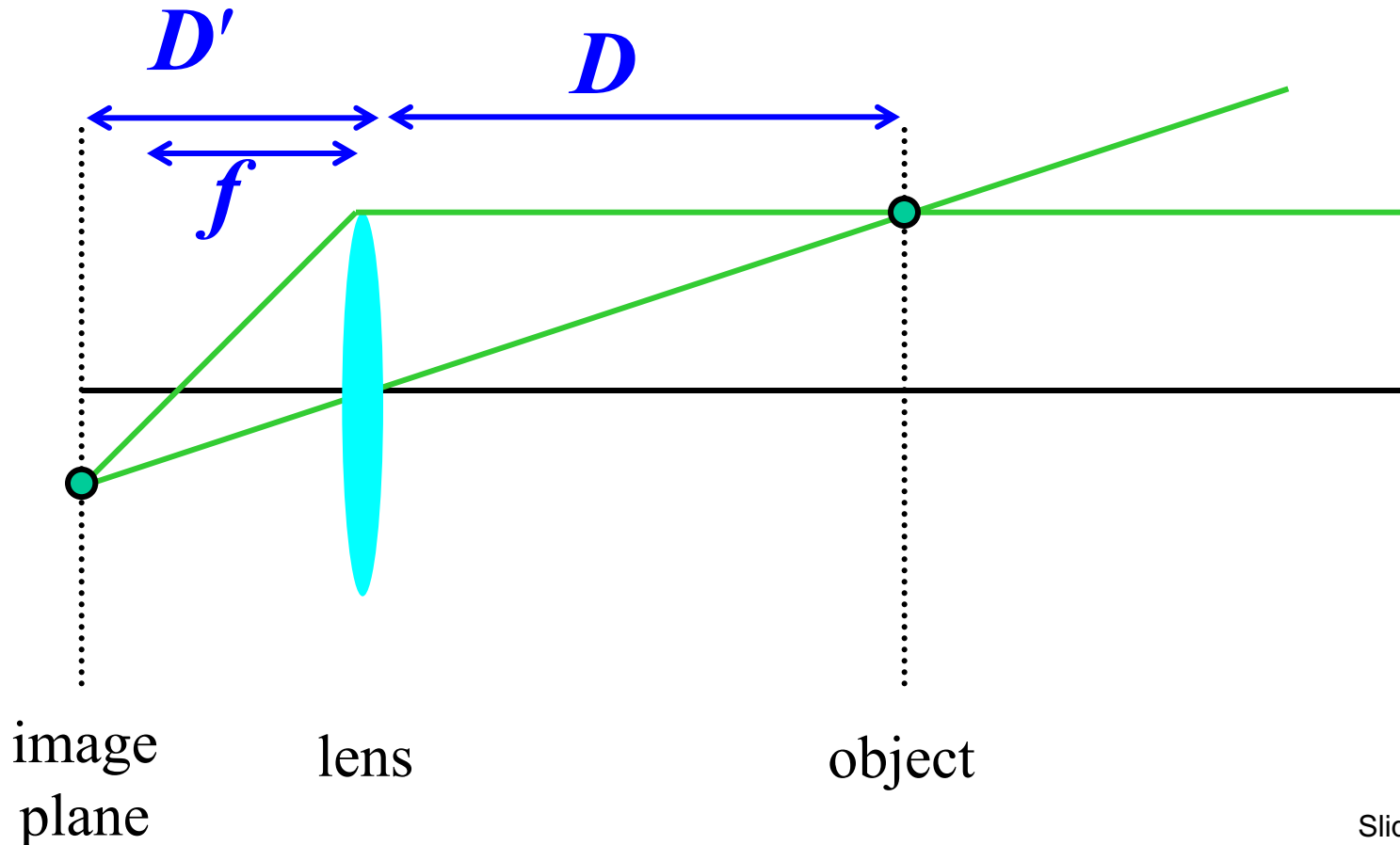


Thin lens formula

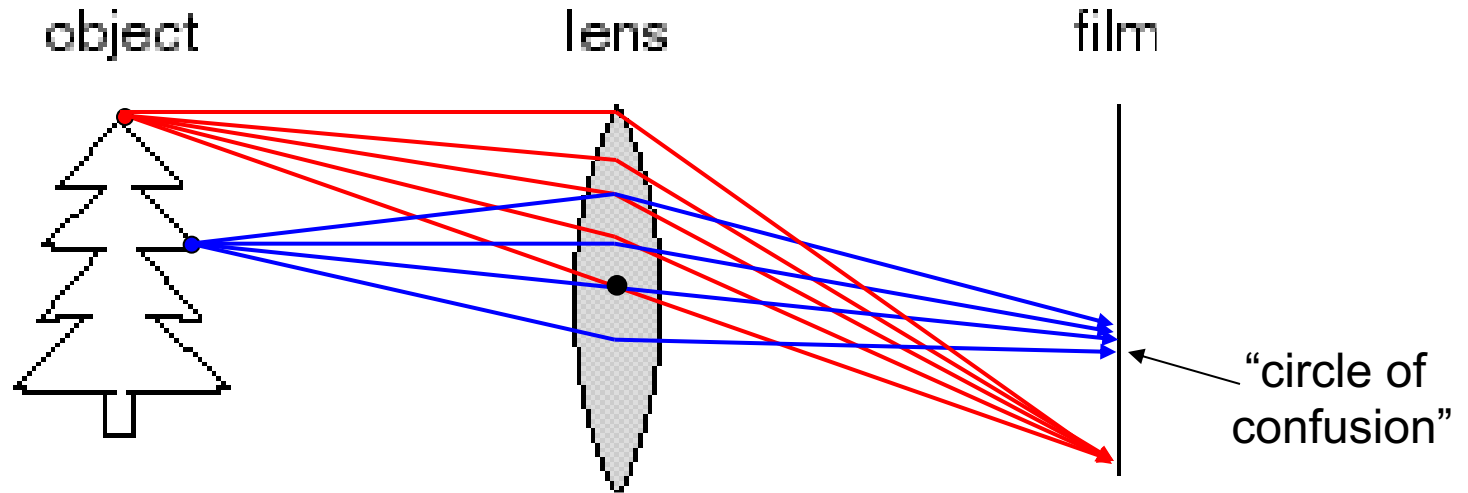
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

Any point satisfying the thin lens equation is in focus.

What happens when D is very large?



Depth of Field



For a fixed focal length, there is a specific distance at which objects are “in focus”

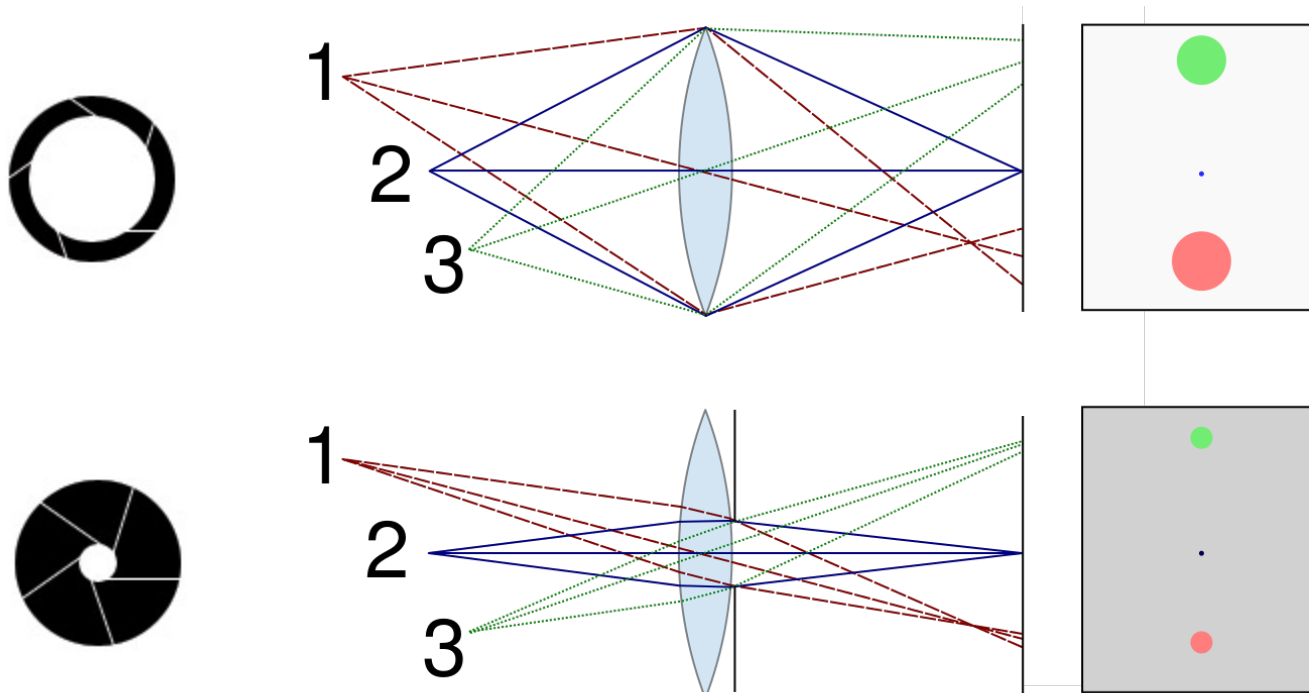
- Other points project to a “circle of confusion” in the image

Depth of Field



<http://www.cambridgeincolour.com/tutorials/depth-of-field.htm>

Controlling depth of field



Changing the aperture size affects depth of field

- A smaller *aperture* increases the range in which the object is approximately in focus
- But small aperture reduces amount of light – need to increase *exposure*

Varying the aperture

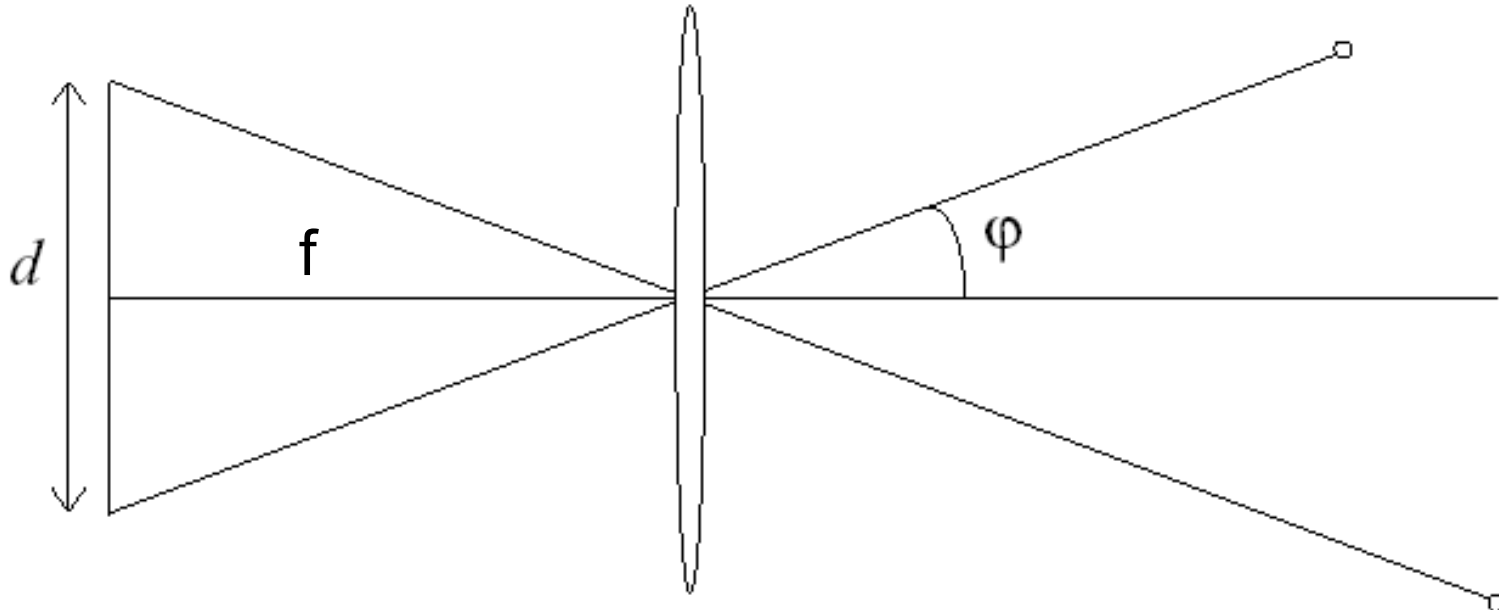


Large aperture = small DOF



Small aperture = large DOF

Field of View

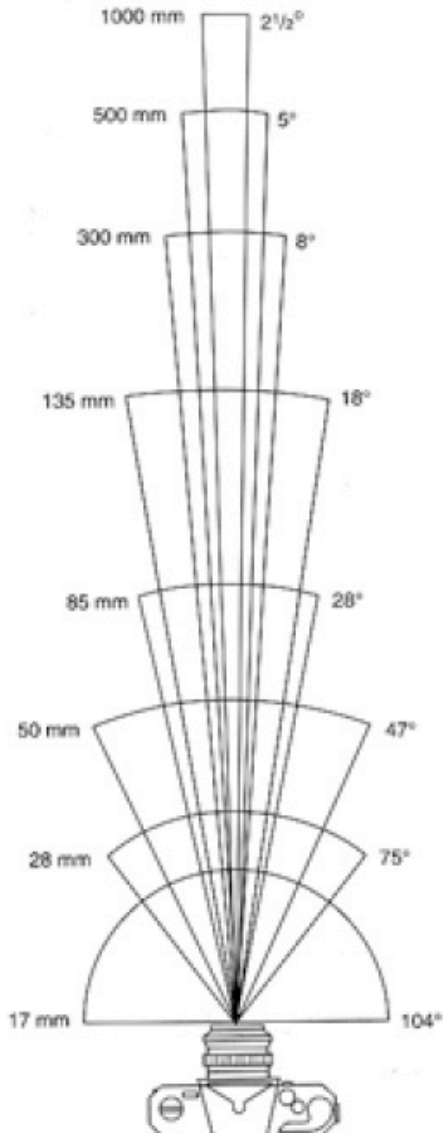


FOV depends on focal length and size of the camera retina

$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Larger focal length = smaller FOV

Field of View



17mm



28mm

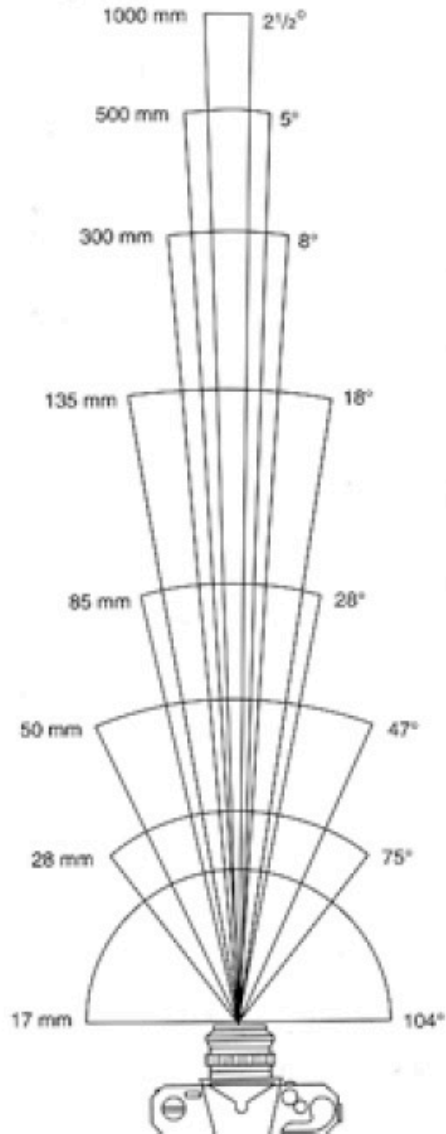


50mm

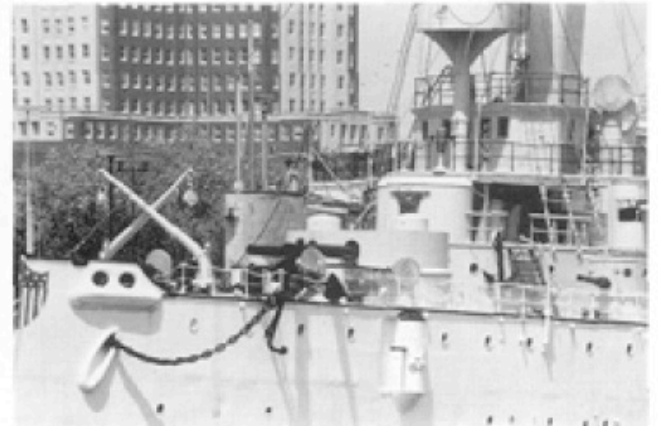


85mm

Field of View



135mm



300mm

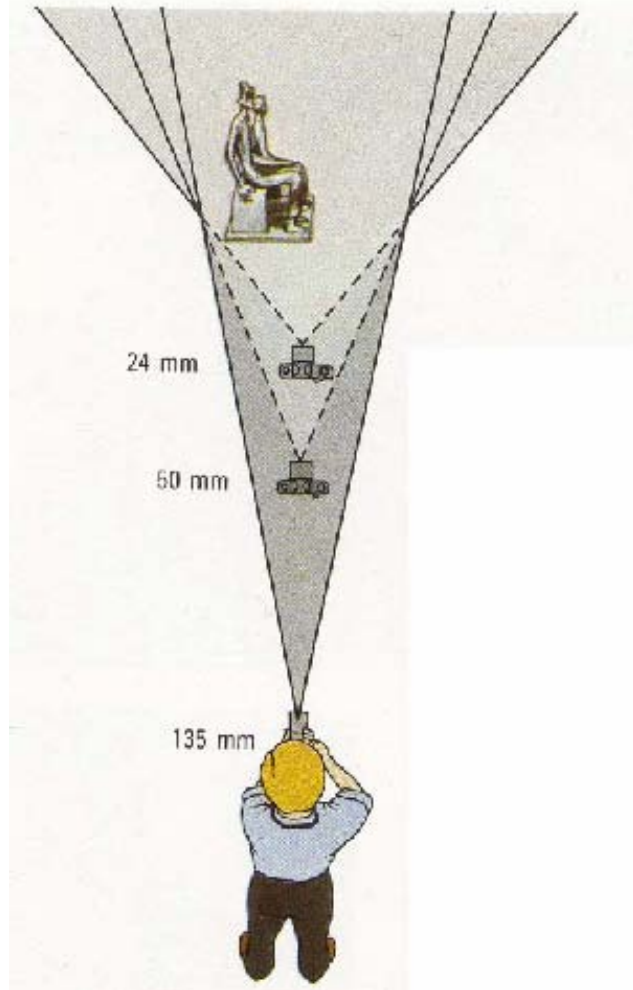


500mm



1000mm

Field of View / Focal Length



Large FOV, small f
Camera close to car



Small FOV, large f
Camera far from the car

Same effect for faces



wide-angle



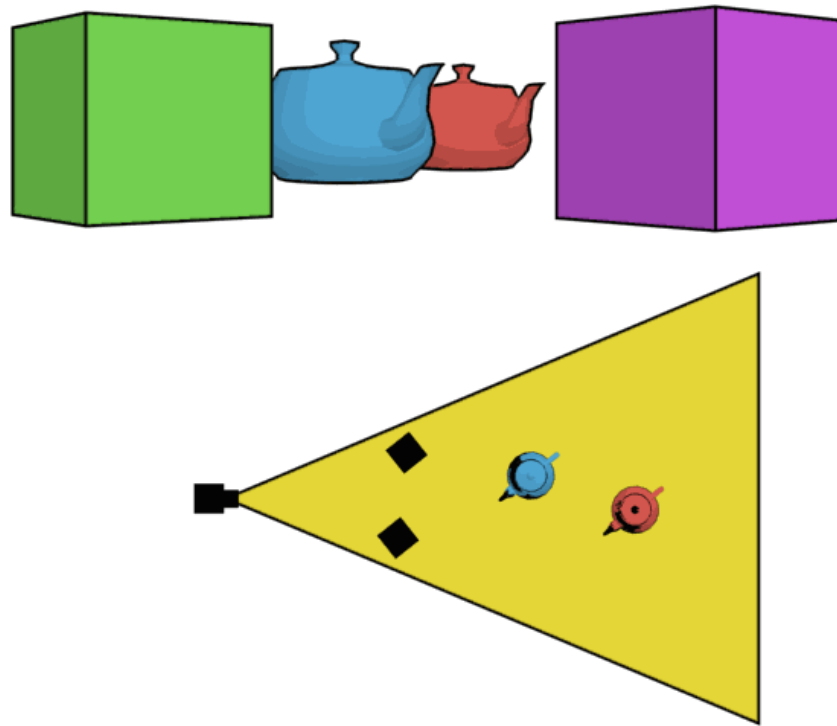
standard



telephoto

The dolly zoom

- Continuously adjusting the focal length while the camera moves away from (or towards) the subject



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

The dolly zoom

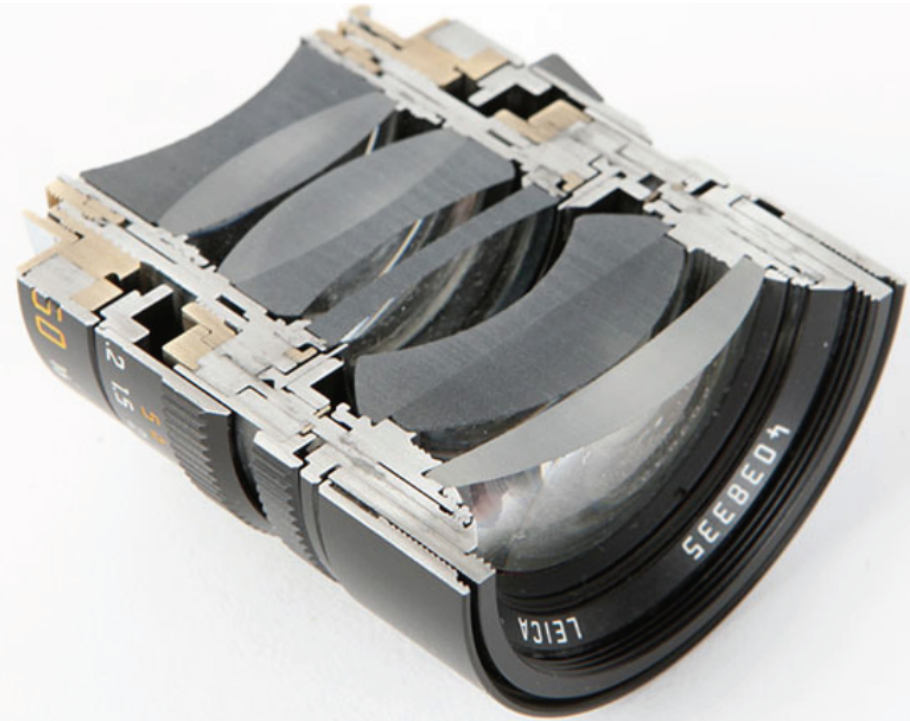
- Continuously adjusting the focal length while the camera moves away from (or towards) the subject
- “The Vertigo shot”



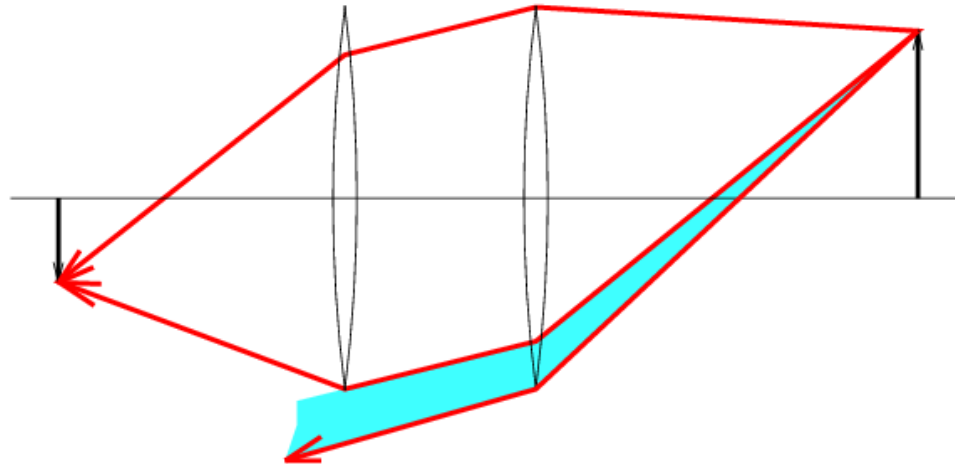
[Example of dolly zoom from *Goodfellas*](#) (YouTube)

[Example of dolly zoom from *La Haine*](#) (YouTube)

Real lenses

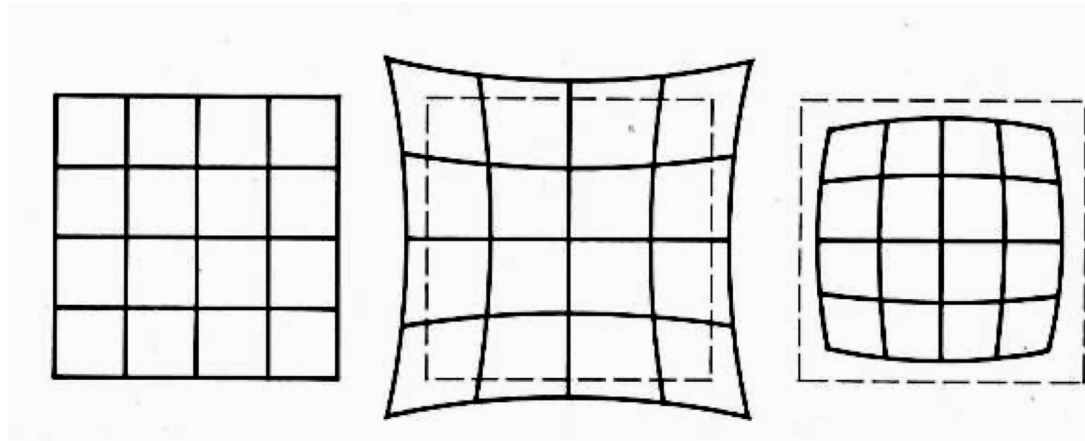


Lens flaws: Vignetting



Radial Distortion

- Caused by imperfect lenses
- Deviations are most noticeable near the edge of the lens



No distortion

Pin cushion

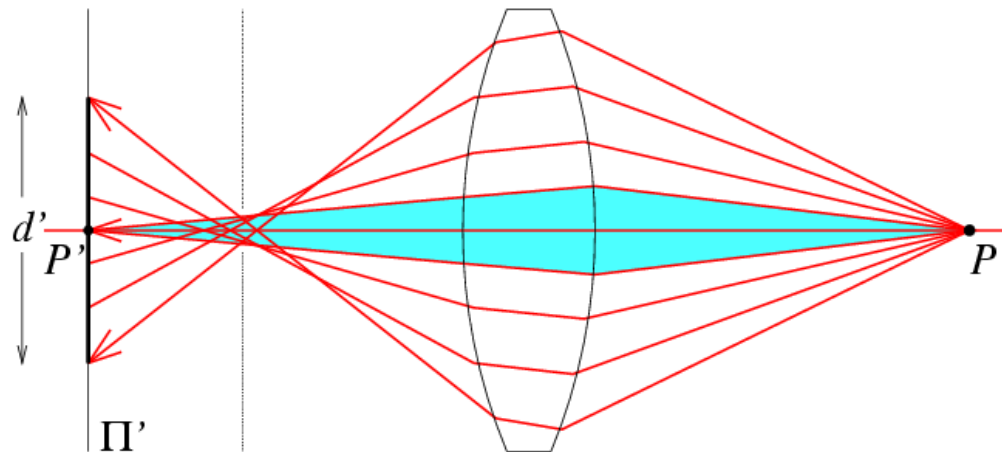
Barrel



Lens flaws: Spherical aberration

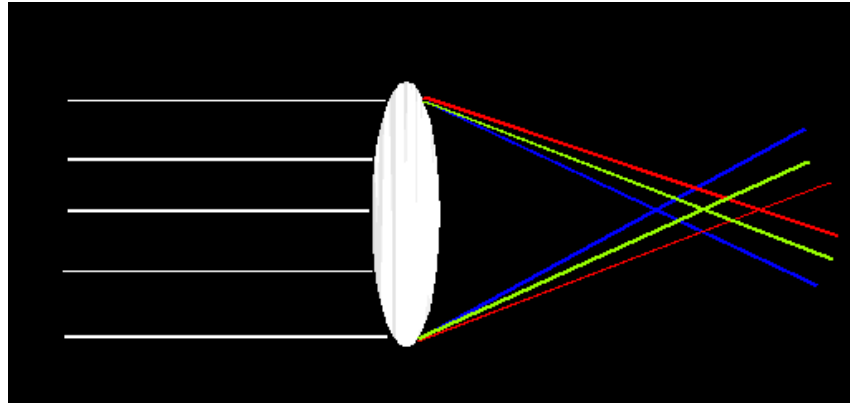
Spherical lenses don't focus light perfectly

Rays farther from the optical axis focus closer



Lens Flaws: Chromatic Aberration

Lens has different refractive indices for different wavelengths: causes color fringing



Near Lens Center

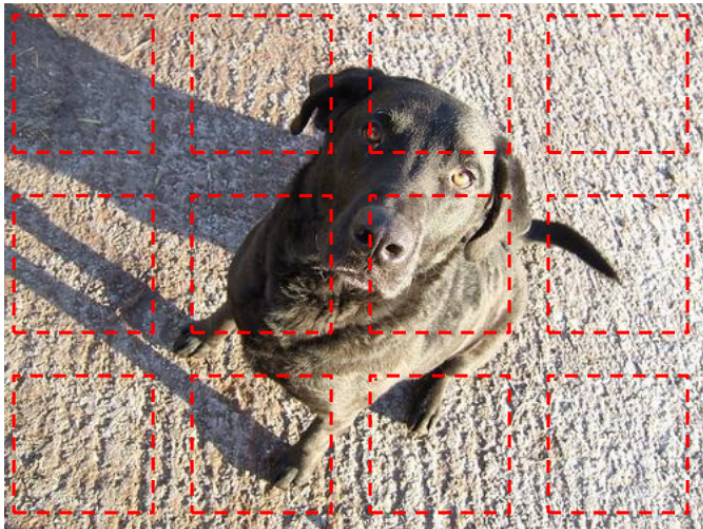


Near Lens Outer Edge



Lens Flaws: Chromatic Aberration

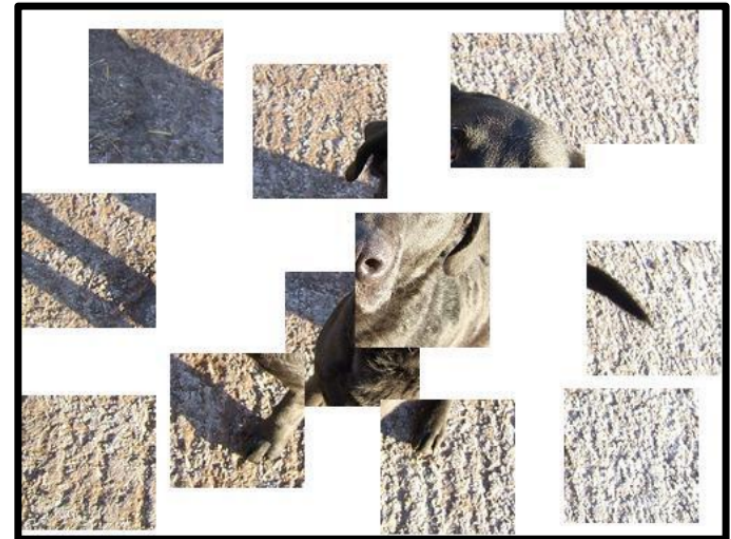
Researchers tried teaching a network about objects by forcing it to assemble jigsaws.



Initial layout, with sampled patches in red

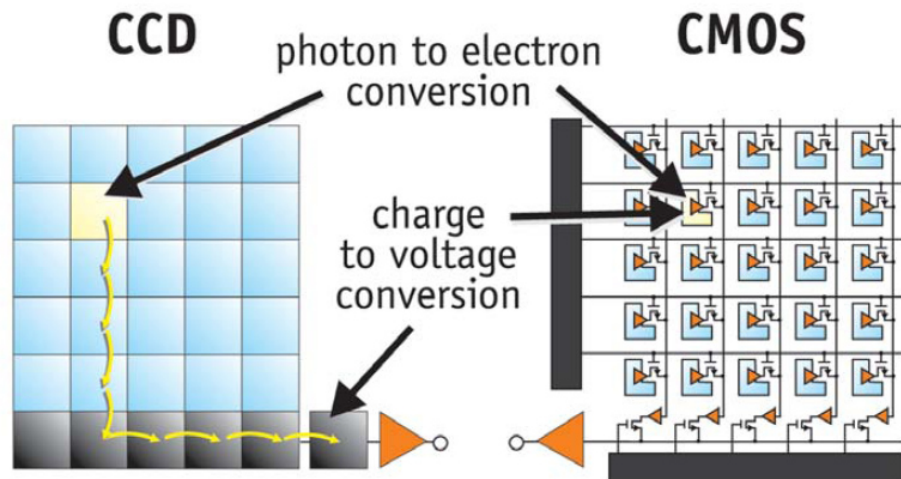


Image layout



We can recover image layout automatically

Digital camera sensors



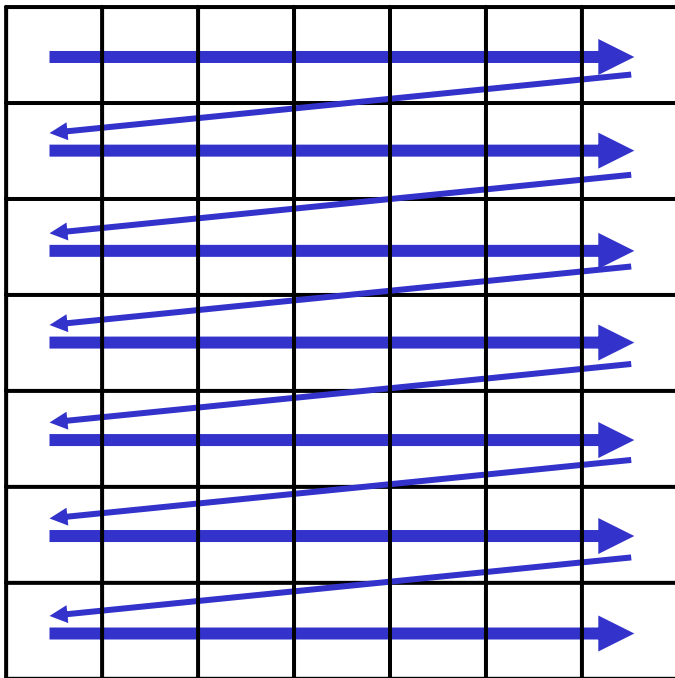
CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

- Each cell in a sensor array is a light-sensitive diode that converts photons to electrons
 - Dominant in the past: **Charge Coupled Device (CCD)**
 - Dominant now: **Complementary Metal Oxide Semiconductor (CMOS)**

<http://electronics360.globalspec.com/article/9464/ccd-vs-cmos-the-shift-in-image-sensor-technology>

From Photon to Photo

Rolling Shutter: pixels read in sequence
Can get global reading, but \$\$\$

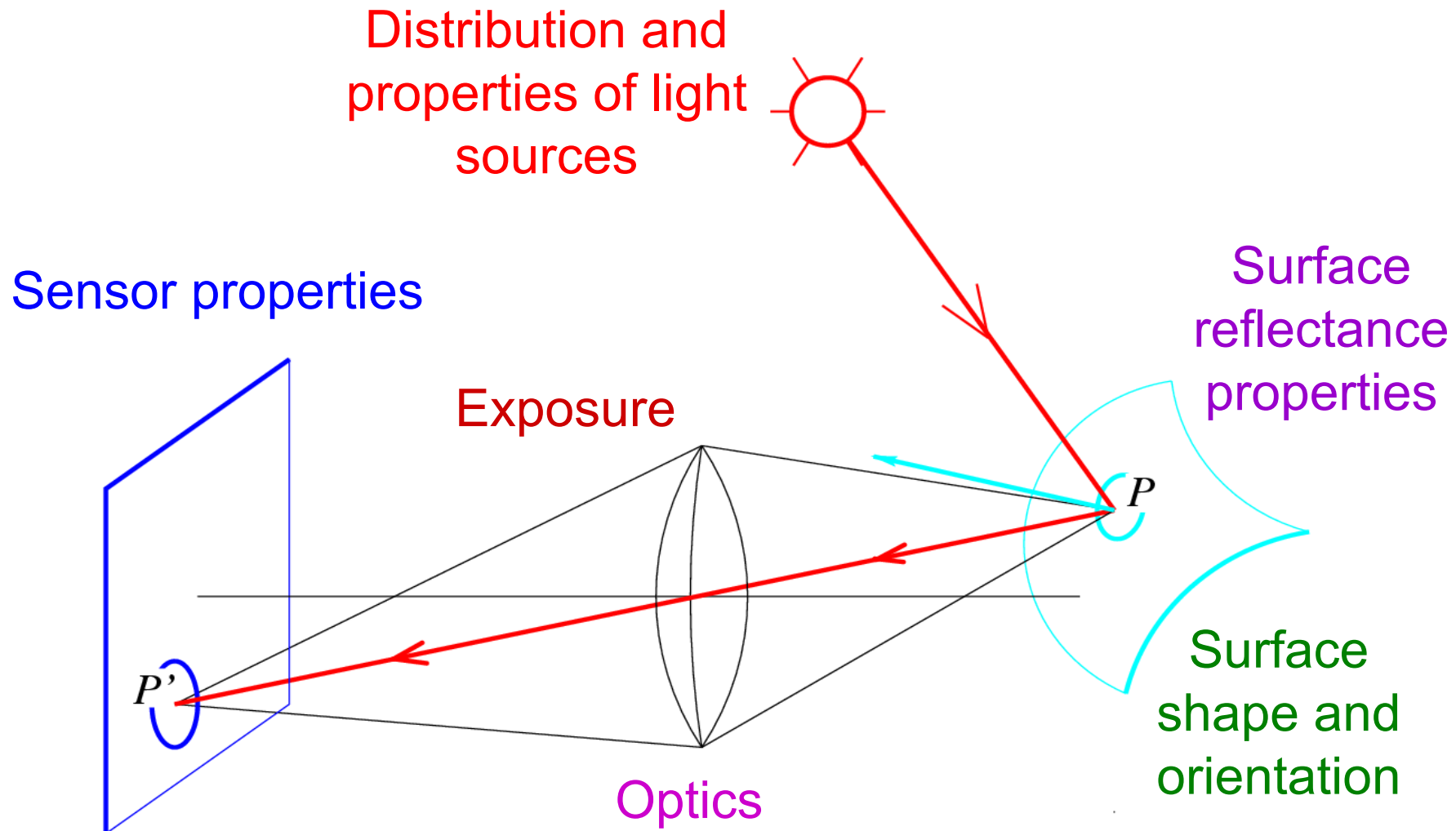


Overview

- Cameras with lenses
 - Depth of field
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 - Lens aberrations
- Brightness of a pixel
 - Small taste of radiometry
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 - Lambertian reflection model
 - Shape from shading

Image formation

What determines the brightness of an image pixel?



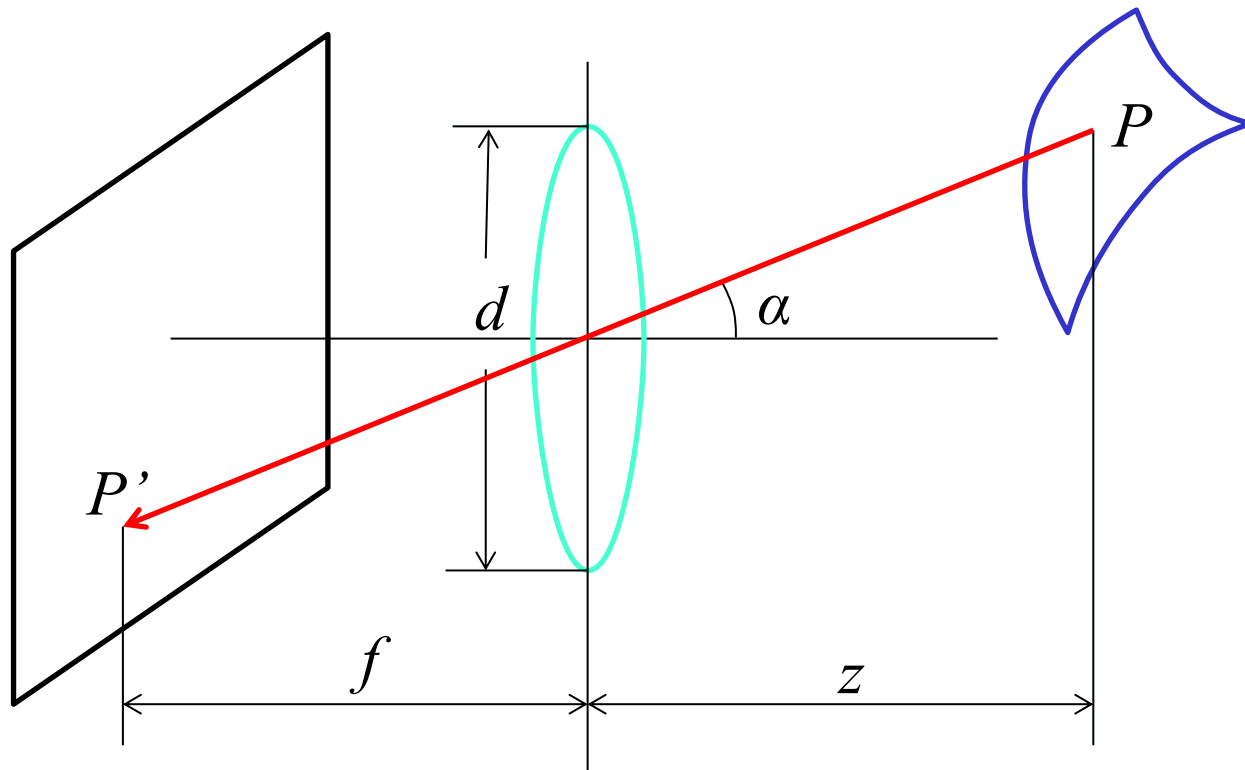
Fundamental radiometric relation

L: Radiance emitted from P toward P'

- Energy carried by a ray (Watts per sq. meter per steradian)

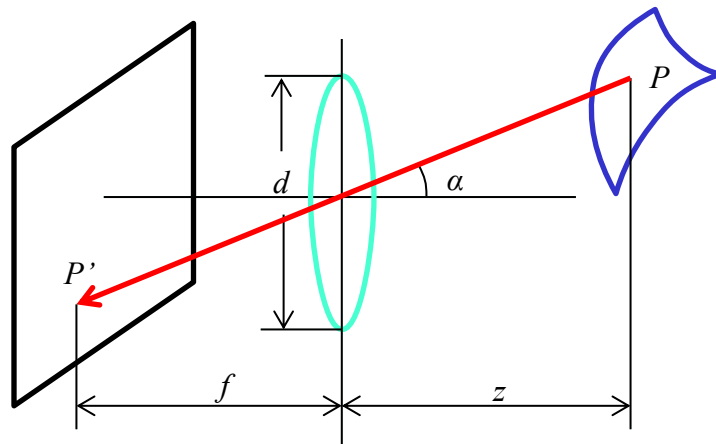
E: Irradiance falling on P' from the lens

- Energy arriving at a surface (Watts per sq. meter)



What is the relationship between *E* and *L*?

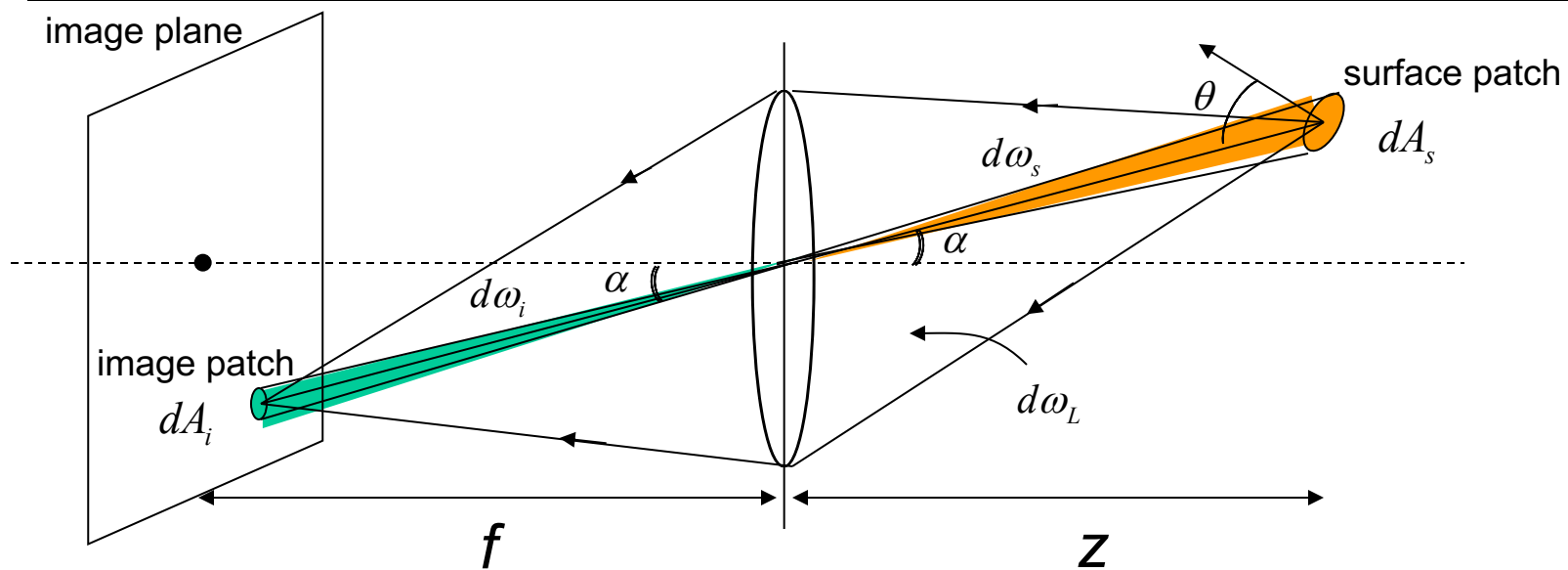
Fundamental radiometric relation



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

- Image irradiance is linearly related to scene radiance
- Irradiance is proportional to the area of the lens and inversely proportional to the squared distance between the lens and the image plane
- The irradiance falls off as the angle between the viewing ray and the optical axis increases

Relation between Image Irradiance E and Scene Radiance L



- Solid angles of the double cone (orange and green):

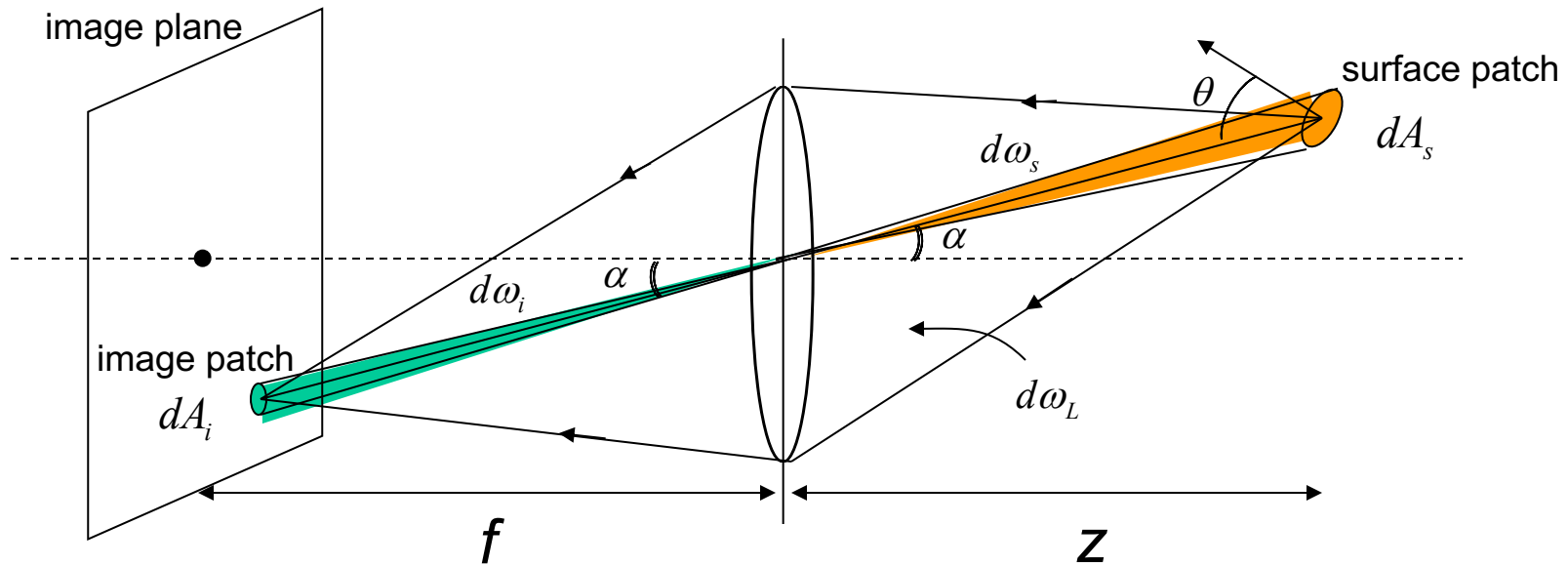
$$d\omega_i = d\omega_s \quad \frac{dA_i \cos \alpha}{(f / \cos \alpha)^2} = \frac{dA_s \cos \theta}{(z / \cos \alpha)^2} \quad \boxed{\frac{dA_s}{dA_i} = \frac{\cos \alpha}{\cos \theta} \left(\frac{z}{f} \right)^2}$$

- Solid angle subtended by lens:

$$\boxed{d\omega_L = \frac{\pi d^2}{4} \frac{\cos \alpha}{(z / \cos \alpha)^2}} \quad \longrightarrow \quad (2)$$

(1)

Relation between Image Irradiance E and Scene Radiance L



- Flux received by lens from dA_s = Flux projected onto image dA_i

$$L (dA_s \cos \theta) d\omega_L = E dA_i \quad \rightarrow (3)$$

- From (1), (2), and (3):

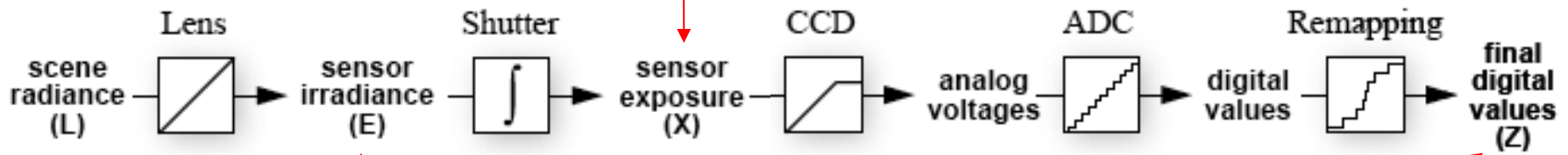
$$E = L \frac{\pi}{4} \left(\frac{d}{f} \right)^2 \cos^4 \alpha$$

- Image irradiance is proportional to Scene Radiance!

- Small field of view \rightarrow Effects of 4th power of cosine are small.

From light rays to pixel values

$$X = E \cdot \Delta t$$



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

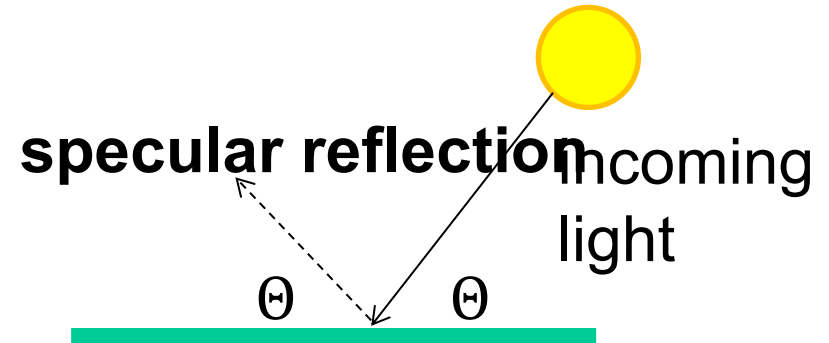
$$Z = f(E \cdot \Delta t)$$

- Camera response function: the mapping f from irradiance to pixel values
 - Useful if we want to estimate material properties
 - Enables us to create *high dynamic range (HDR) images*
 - Classic reference: P. E. Debevec and J. Malik, [Recovering High Dynamic Range Radiance Maps from Photographs](#), SIGGRAPH 97

Basic models of reflection

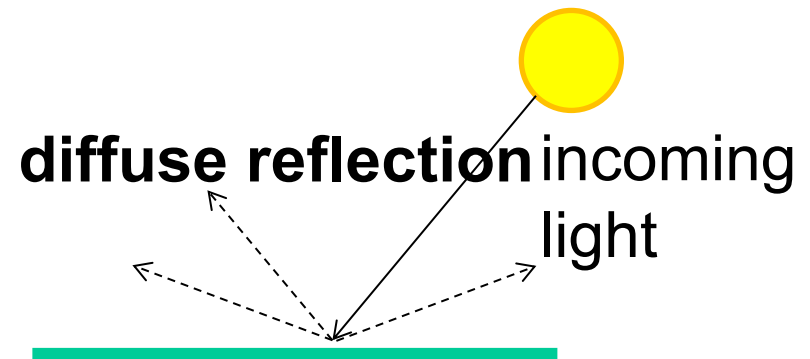
Specular: light bounces off at the incident angle

- E.g., mirror



Diffuse: light scatters in all directions

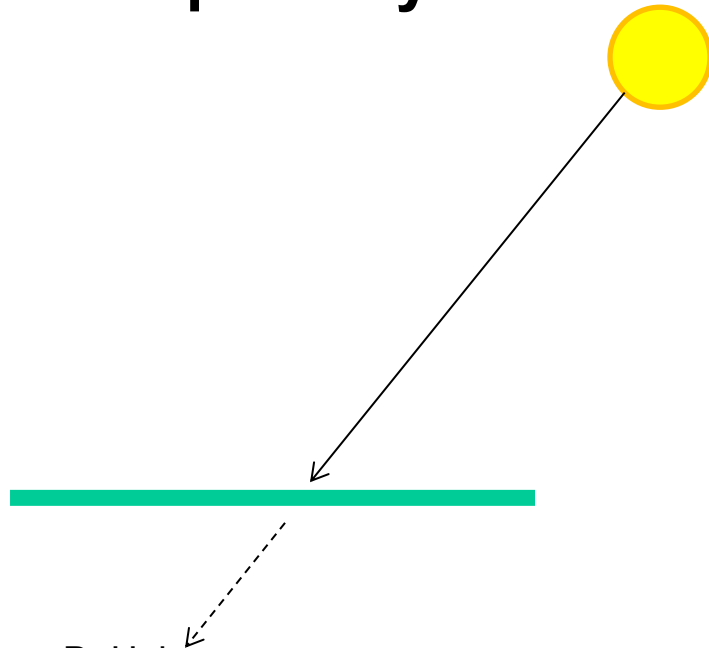
- E.g., brick, cloth, rough wood



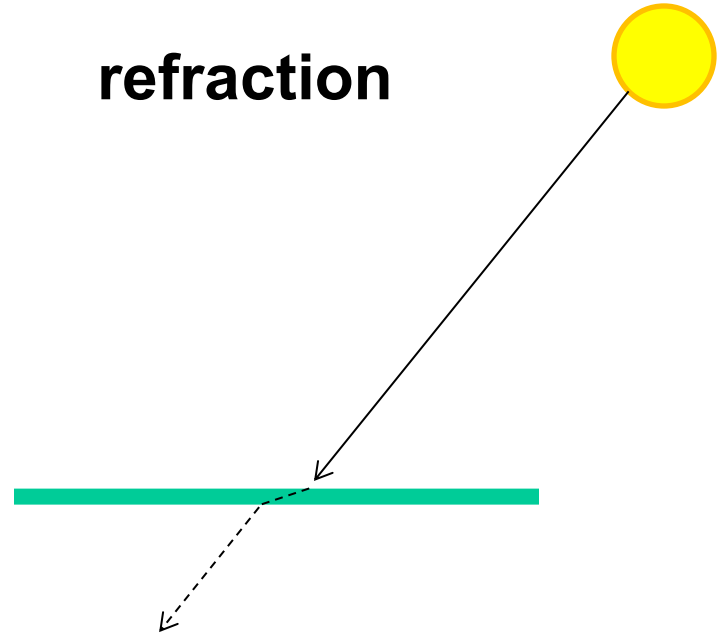
Other possible effects



transparency light source



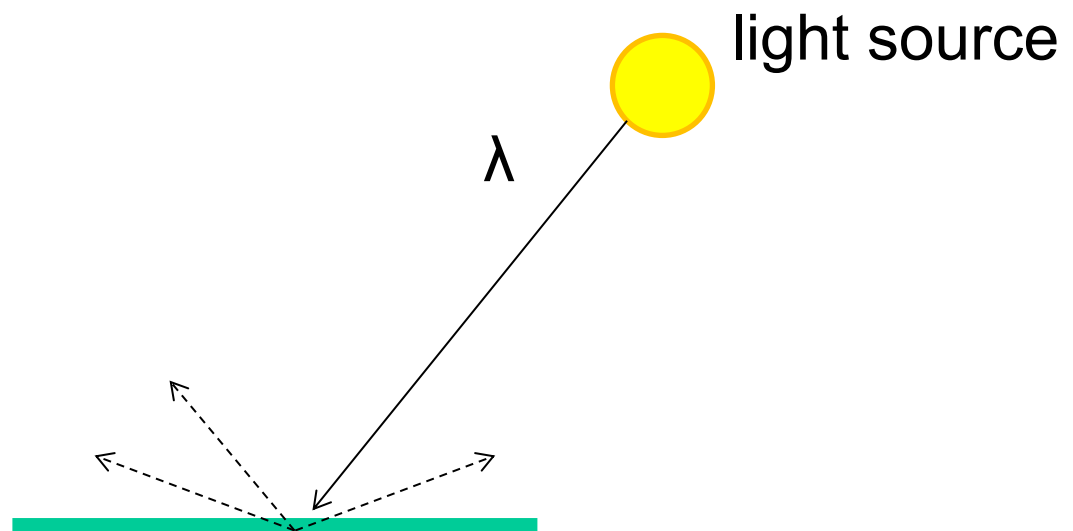
refraction light source



Other possible effects



**subsurface
scattering**

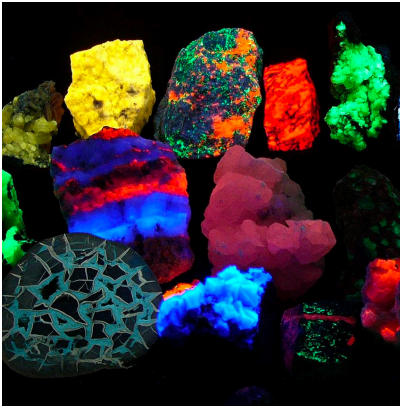


Slide from D. Hoiem

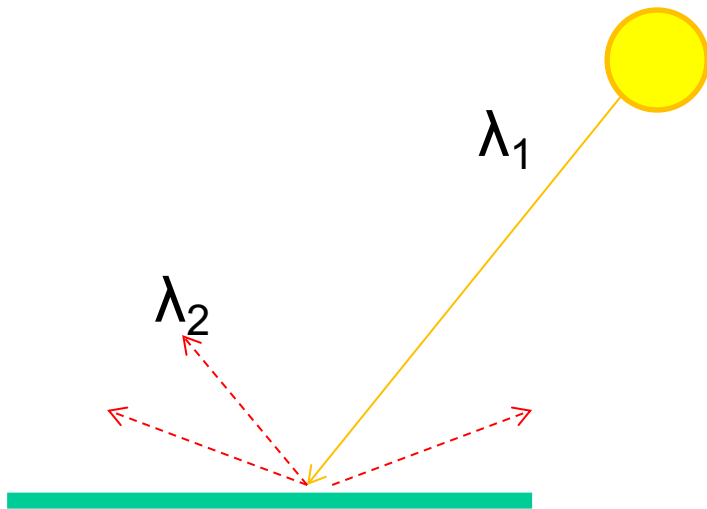
https://en.wikipedia.org/wiki/Subsurface_scattering#/media/File:Skin_Subsurface_Scattering.jpg

Other possible effects

fluorescence



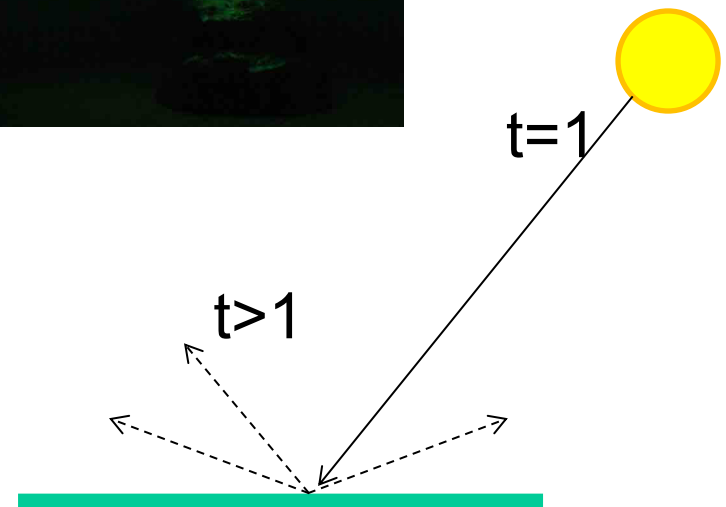
light source



phosphorescence



light source



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More next class ...
