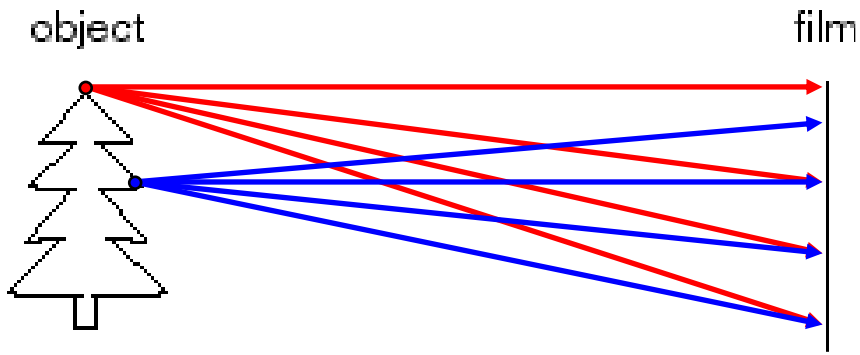
# Introduction to cameras

# Overview

- Pinhole projection model
- Cameras with lenses
  - Depth of field
  - Field of view
  - Lens aberrations
- Digital sensors

# Let’s design a camera

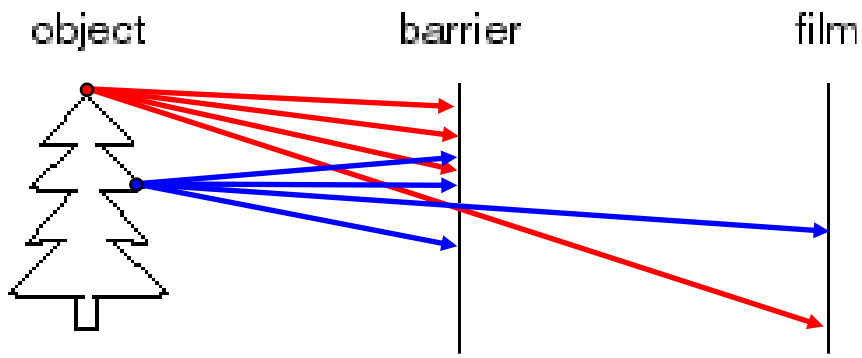



Idea 1:  put a piece of film in front of an object

Do we get a reasonable image?

Slide by Steve Seitz

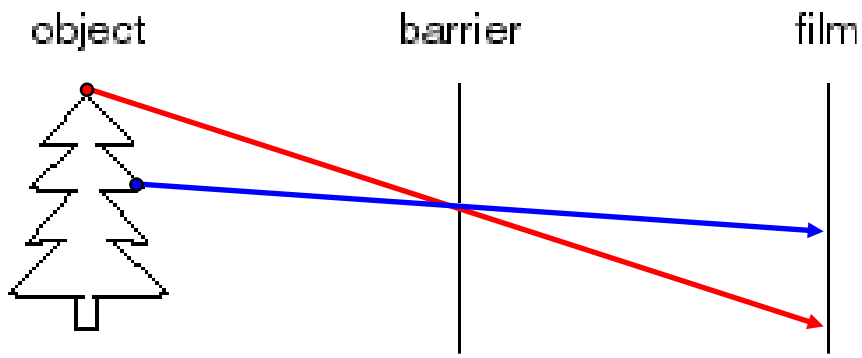
# Pinhole camera




Add a barrier to block off most of the rays

Slide by Steve Seitz

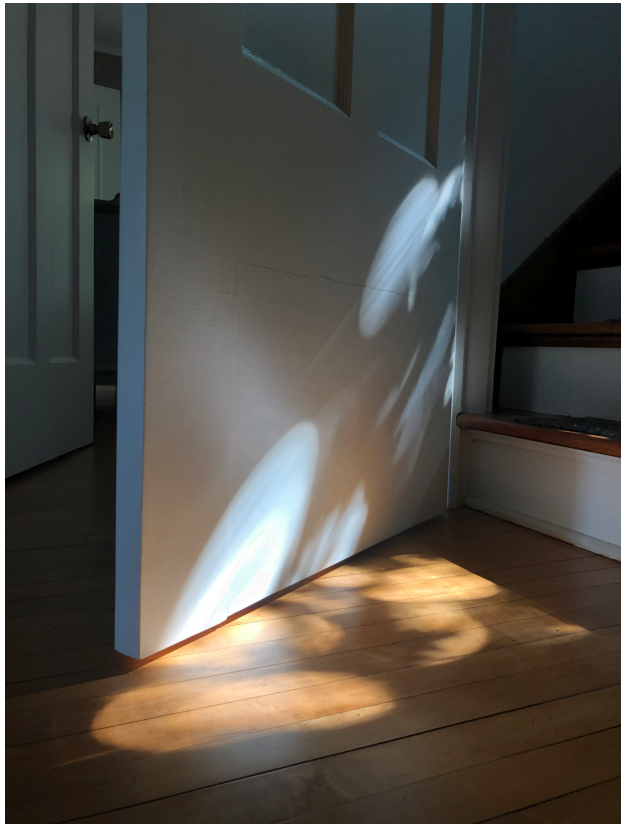
# Pinhole camera




- Captures **pencil of rays** – all rays through a single point: **aperture, center of projection, optical center, focal point, camera center**
- The image is formed on the **image plane**

Slide by Steve Seitz

# Pinhole cameras are everywhere



# Pinhole cameras are everywhere

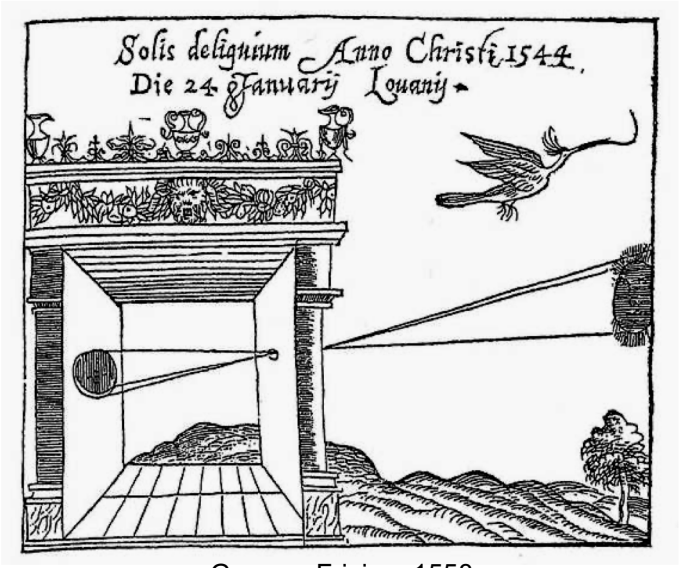
Tree shadow during a solar eclipse

photo credit: Nils van der Burg

http://www.physicstogo.org/index.cfm

Slide by Steve Seitz

# Camera obscura

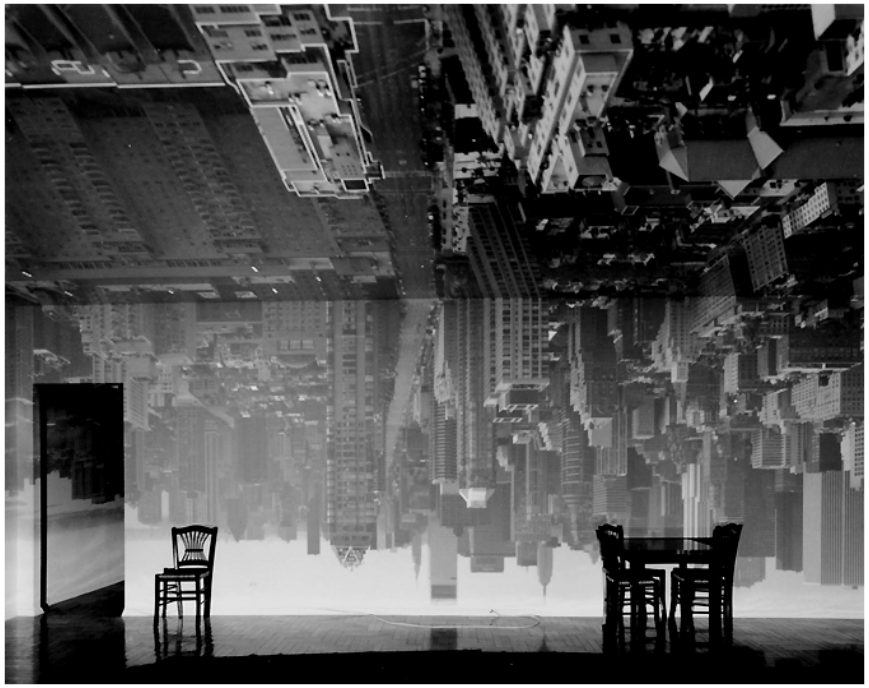



Gemma Frisius, 1558

- Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Source: A. Efros

# Turning a room into a camera obscura



Abelardo Morell, Camera Obscura Image of Manhattan View Looking South in Large Room, 1996

https://www.abelardomorell.net/camera-obscura

After scouting rooms and reserving one for at least a day, Morell masks the windows except for the aperture. He controls three elements: the size of the hole, with a smaller one yielding a sharper but dimmer image; the length of the exposure, usually eight hours; and the distance from the hole to the surface on which the outside image falls and which he will photograph. He used 4 x 5 and 8 x 10 view cameras and lenses ranging from 75 to 150 mm.

After he's done inside, it gets harder. "I leave the room and I am constantly checking the weather, I'm hoping the maid reads my note not to come in, I'm worrying that the sun will hit the plastic masking and it will fall down, or that I didn't trigger the lens."

From *Grand Images Through a Tiny Opening*, **Photo District News**, February 2005

# Turning a room into a camera obscura

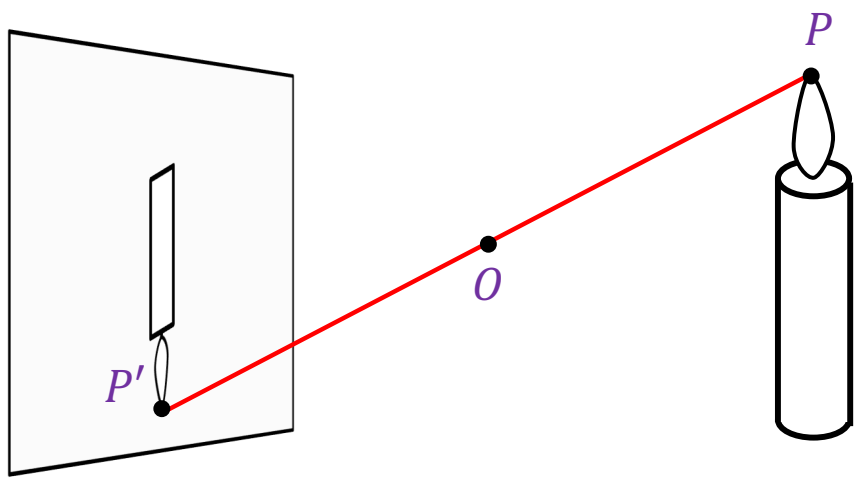
My hotel room,
contrast enhanced.

The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

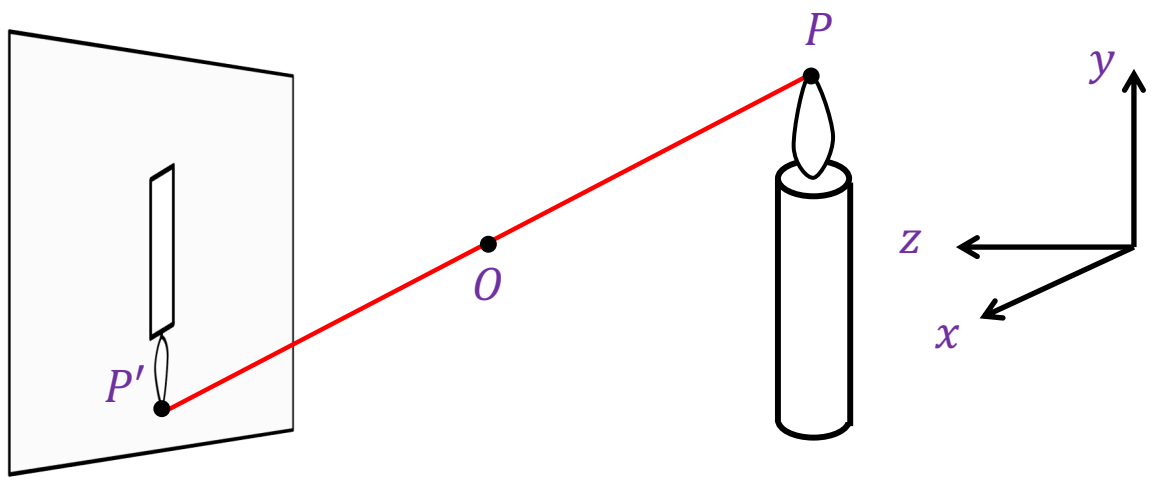
A. Torralba and W. Freeman, Accidental Pinhole and Pinspeck Cameras, CVPR 2012

# Modeling projection




- How do we find the projection $P'$ of a scene point $P$?
  - Form the **visual ray** connecting $P$ to the camera center $O$ and find where it intersects the image plane
- All scene points that lie on this visual ray have the same projection in the image
- Are there scene points for which this projection is undefined?

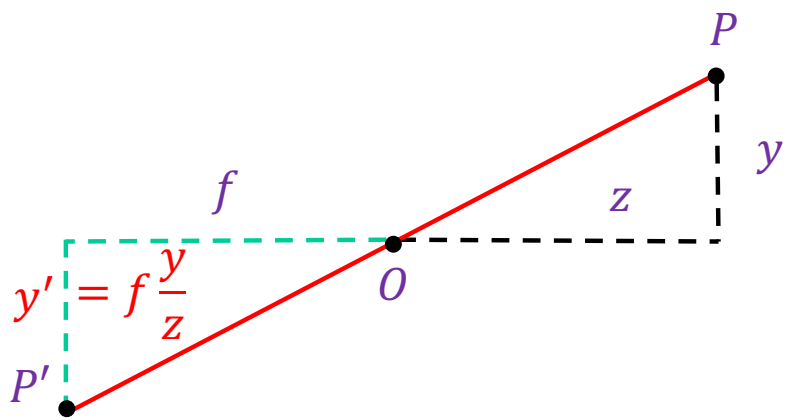
# Modeling projection




## Canonical coordinate system

- The optical center ($O$) is at the origin
- The z axis is the *optical axis* perpendicular to the image plane
- The xy plane is parallel to the image plane, x and y axes are horizontal and vertical directions of the image plane

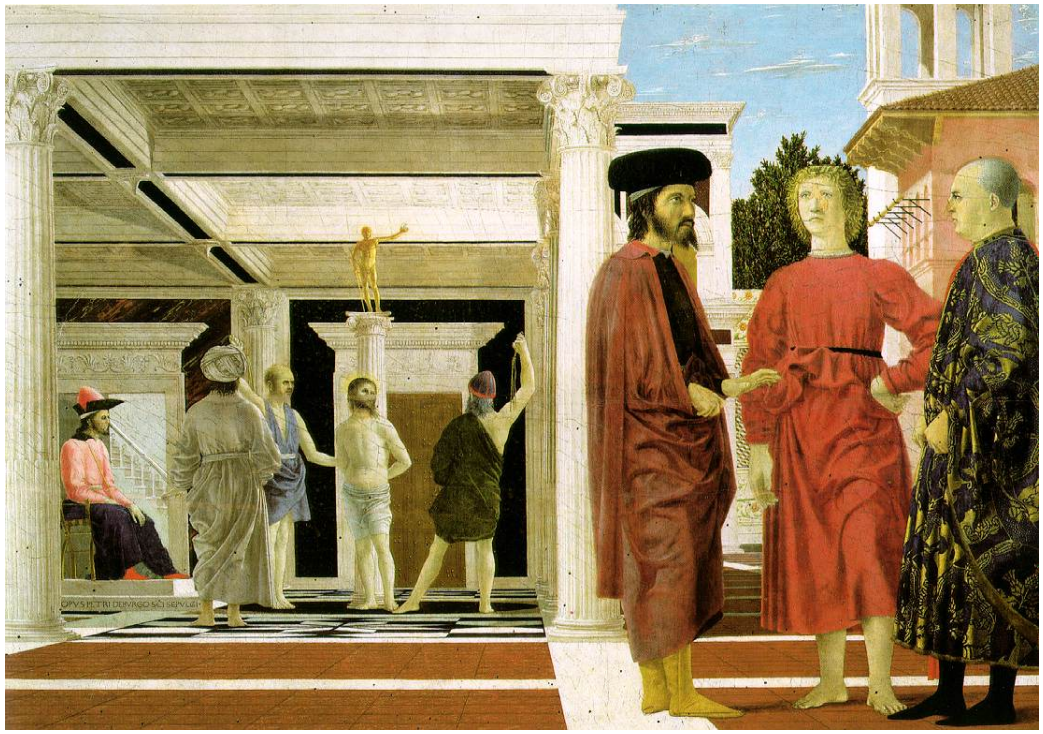
# Deriving projected coordinates




$$\boxed{(x, y, z) \rightarrow \left(f\frac{x}{z}, f\frac{y}{z}\right)}$$

# Properties of projection

- Real-world sizes (lengths) are *not* preserved in projection
  - What other properties are/are not preserved?



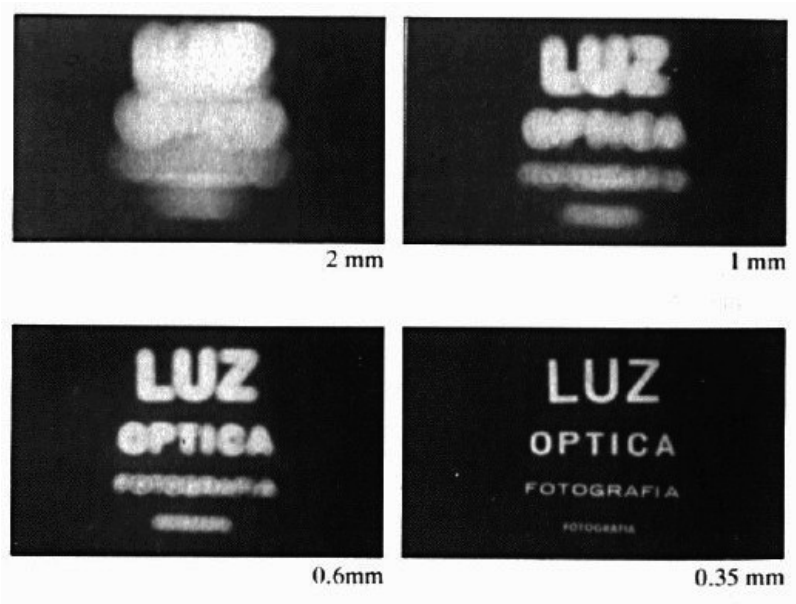
Piero della Francesca, *Flagellation of Christ*, 1455-1460

# Home-made pinhole camera


What is wrong with this image?

Source: P. Debevec via A. Efros

# Shrinking the aperture

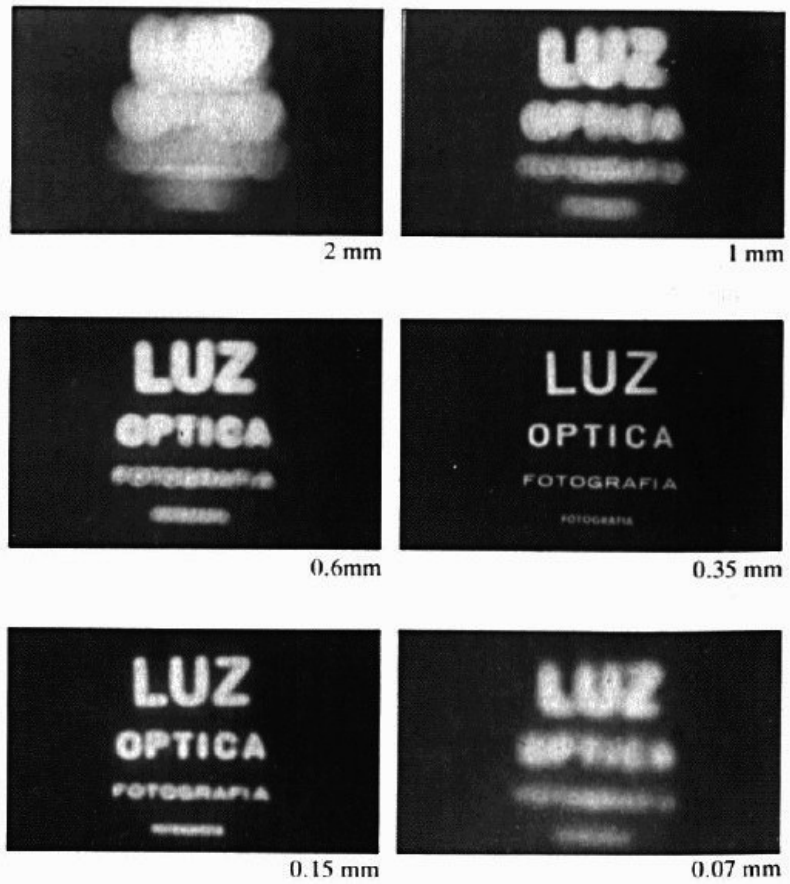



Why not make the aperture as small as possible?

- Less light gets through
- Diffraction!

Slide by Steve Seitz

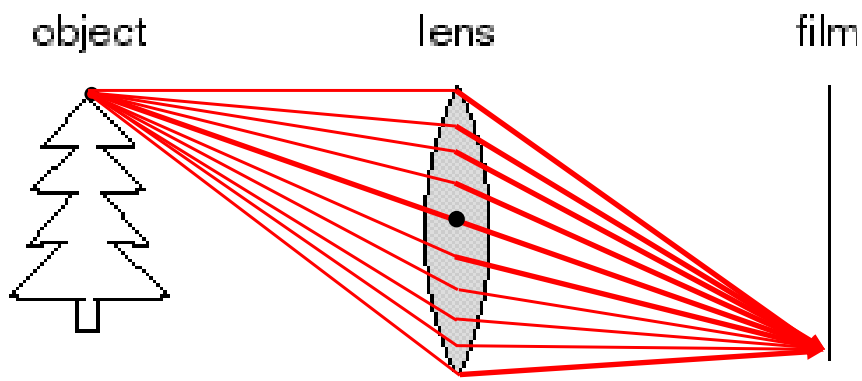
# Shrinking the aperture



# Overview

- Pinhole projection model
- Cameras with lenses

# Adding a lens

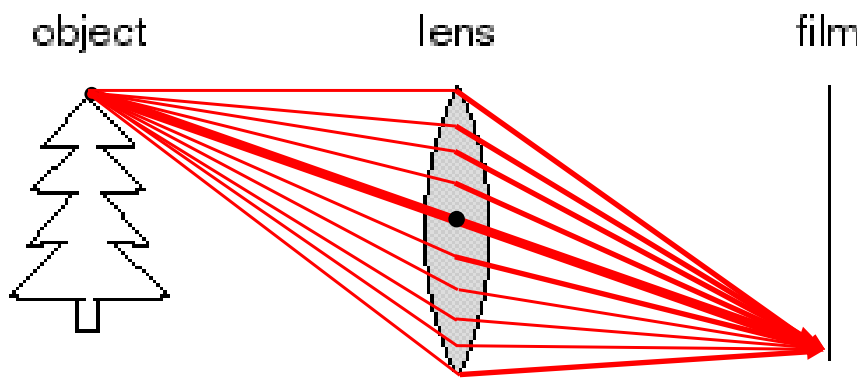



A lens focuses light onto the film

- Thin lens model:

Slide by Steve Seitz

# Adding a lens

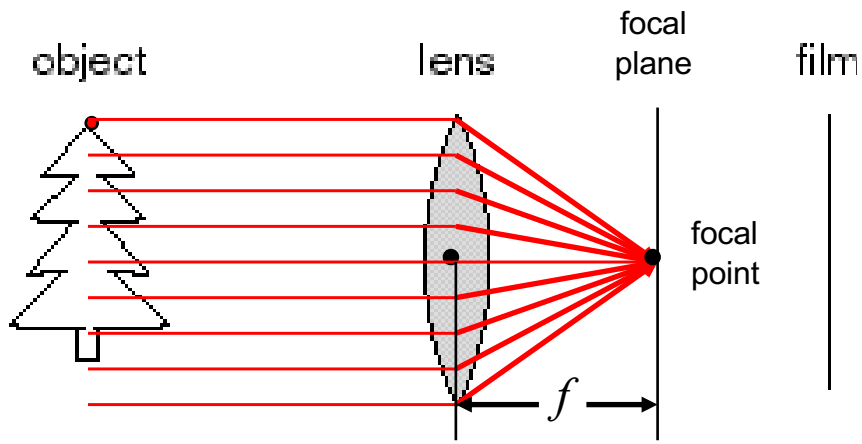



A lens focuses light onto the film

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

Slide by Steve Seitz

# Adding a lens



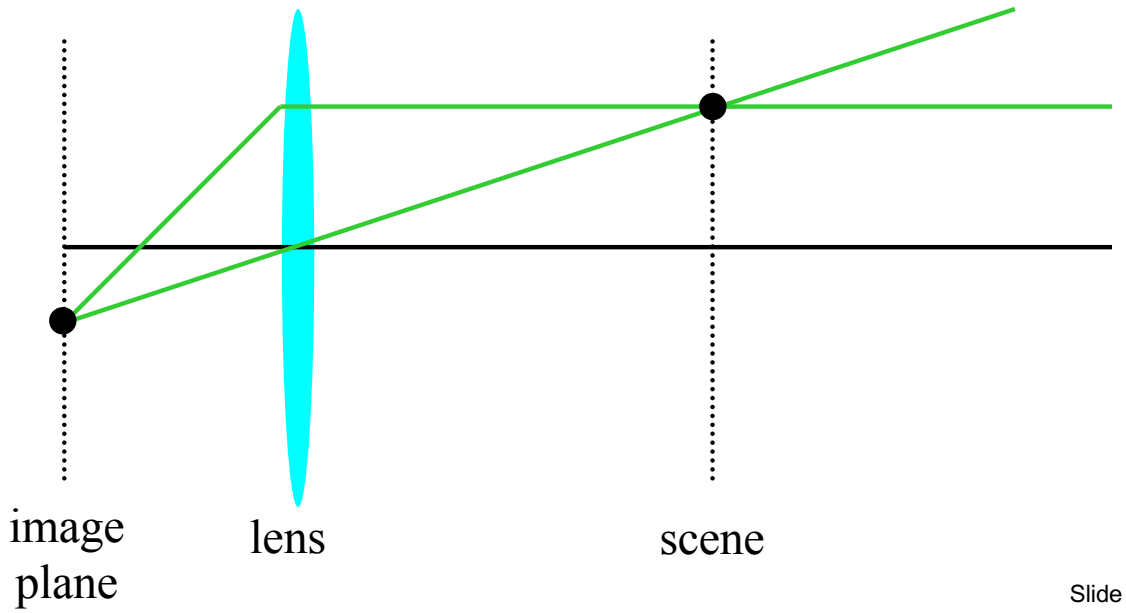

## A lens focuses light onto the film

- 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*

Slide by Steve Seitz

# Thin lens formula

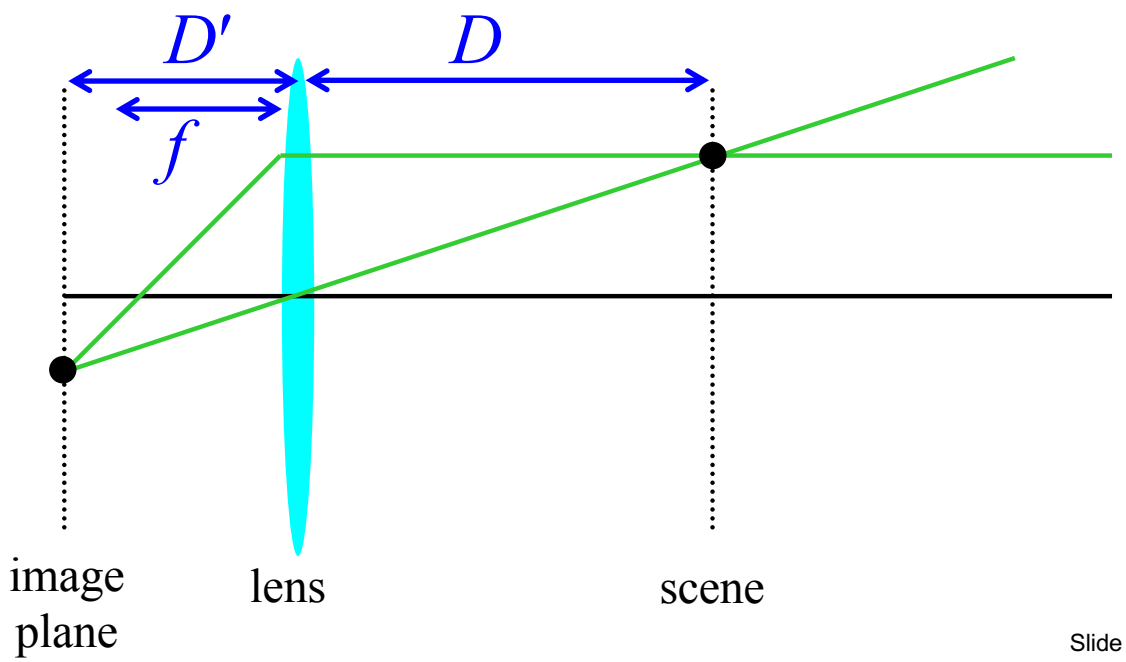
- Where does the lens focus the rays coming from a given point in the scene?




Slide by Frédo Durand

# Thin lens formula

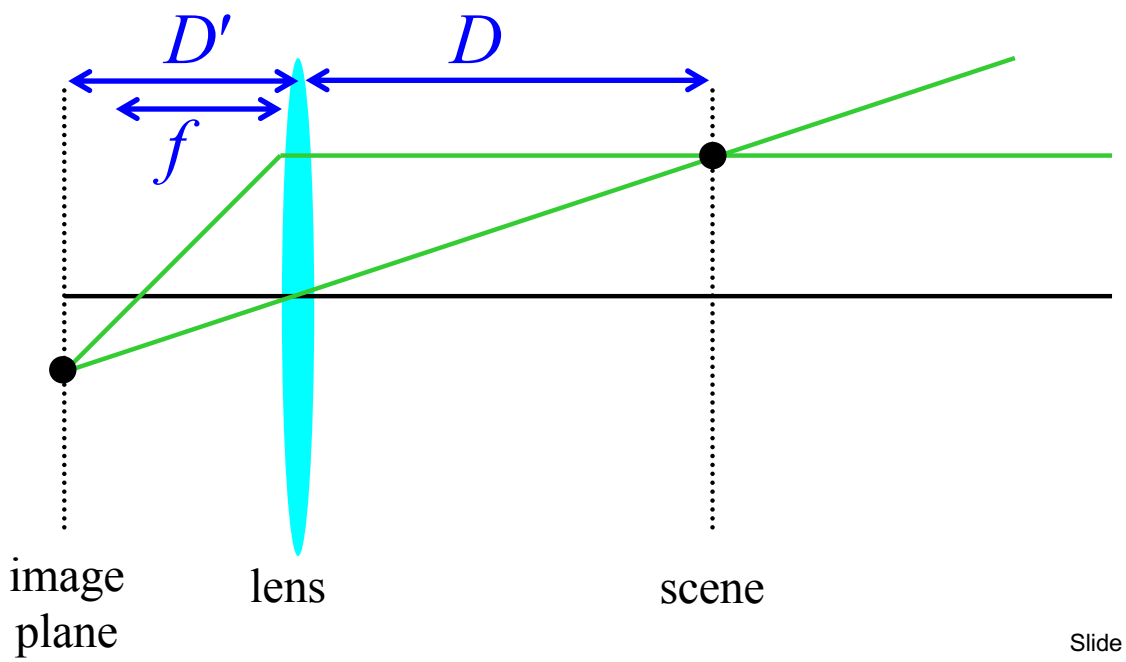
- What is the relation between the focal length ($f$),
  the distance of the object from the optical center ($D$),
  and the distance at which the object will be in focus ($D'$)?




Slide by Frédo Durand

# Thin lens formula

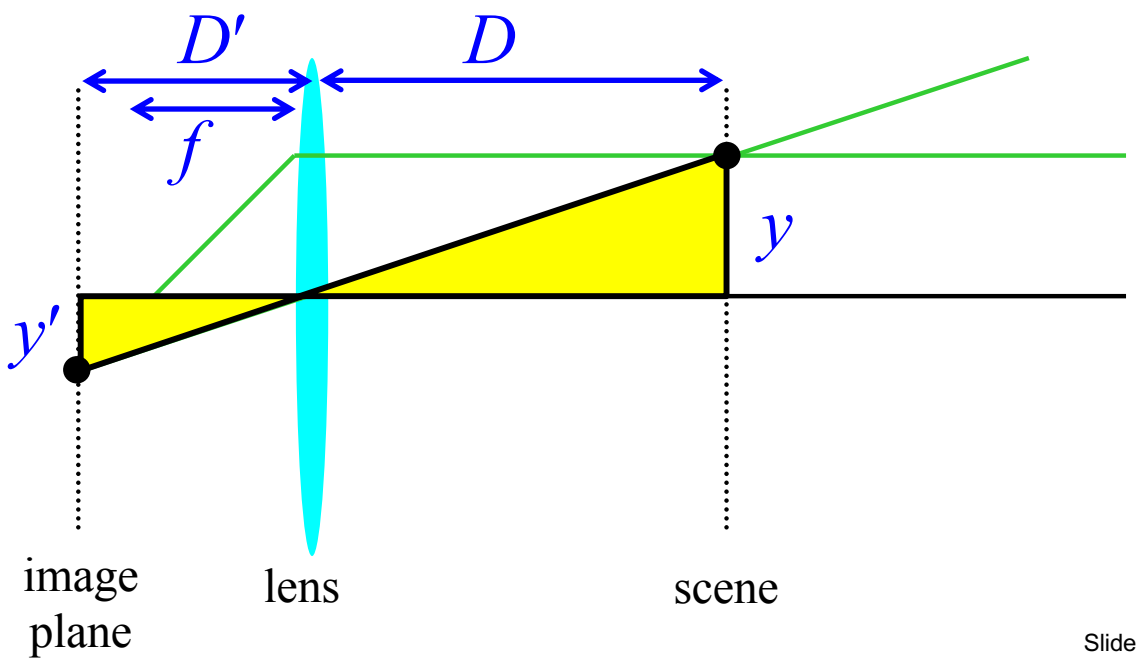
Similar triangles everywhere!




Slide by Frédo Durand

# Thin lens formula

Similar triangles everywhere! $y'/y = D'/D$



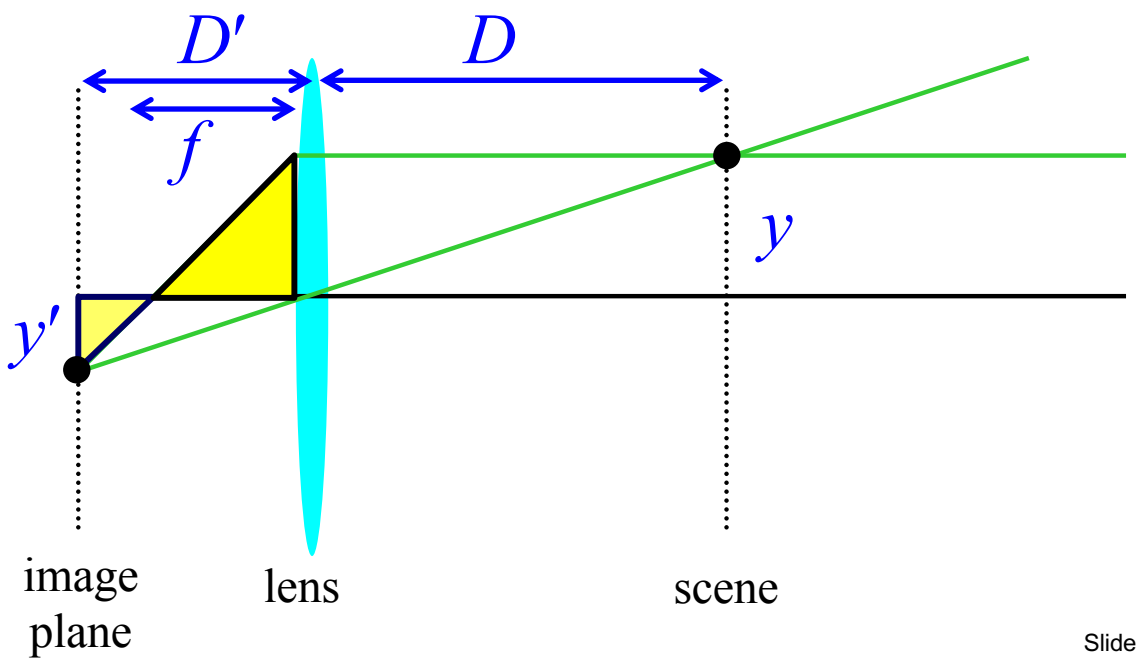

Slide by Frédo Durand

# Thin lens formula

Similar triangles everywhere!

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

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



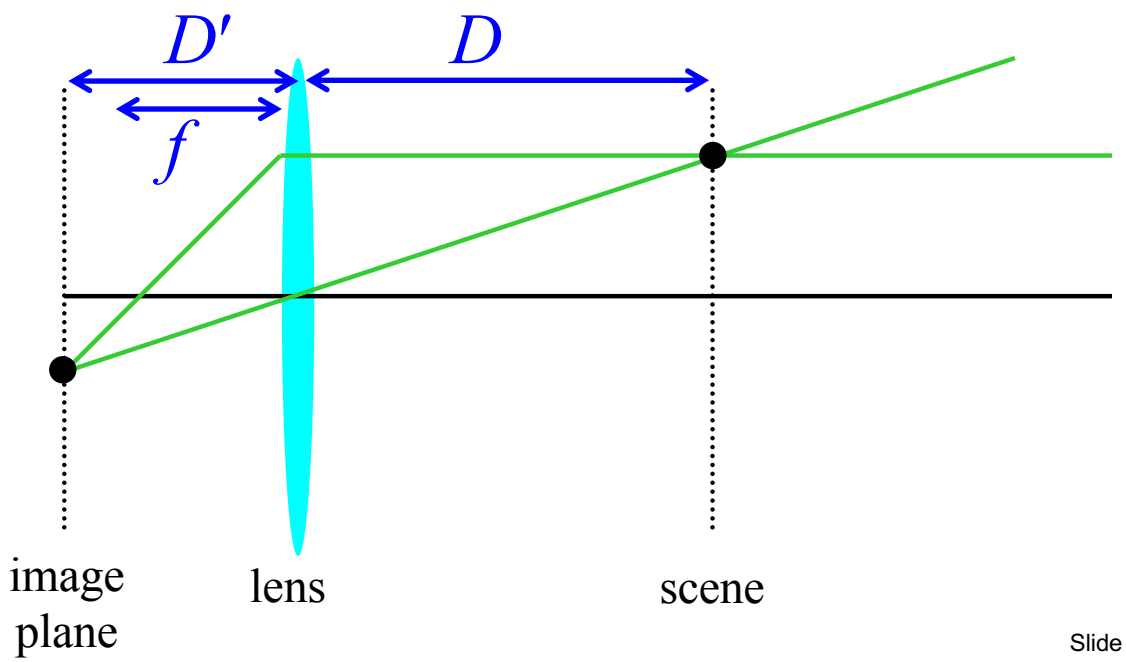

Slide by Frédo Durand

# 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?




Slide by Frédo Durand

# Overview

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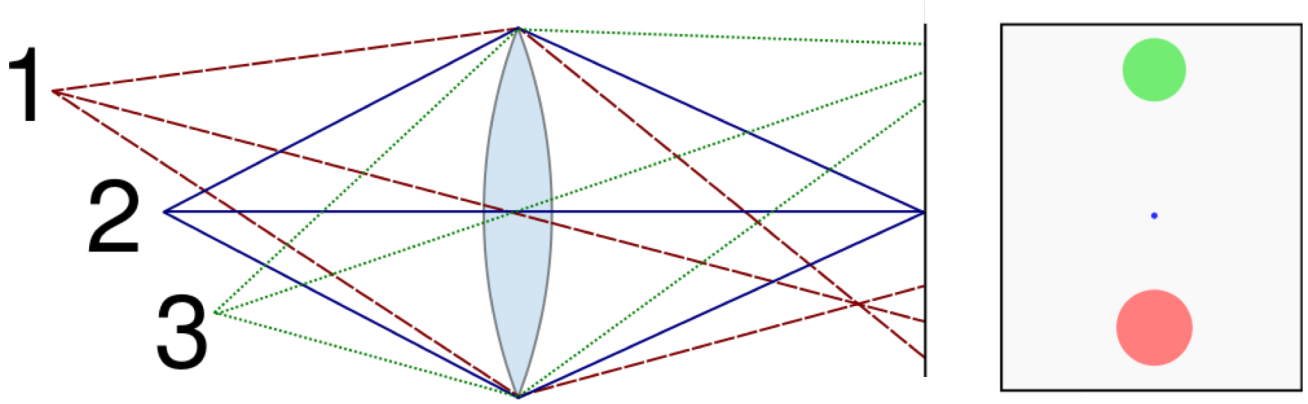
- Cameras with lenses
  - Depth of field
  - Field of view

# Depth of field




- For a fixed focal length and image plane, 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

- Depth of field is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image (Wikipedia)



Image source
(via A. Efros)

# Controlling depth of field

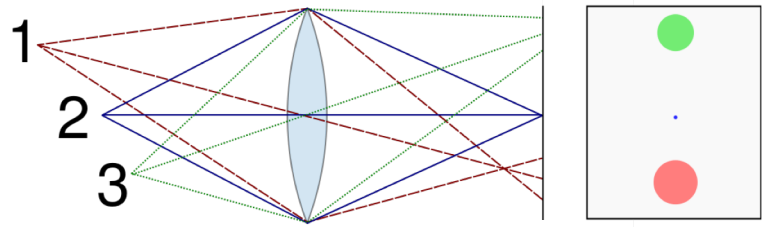
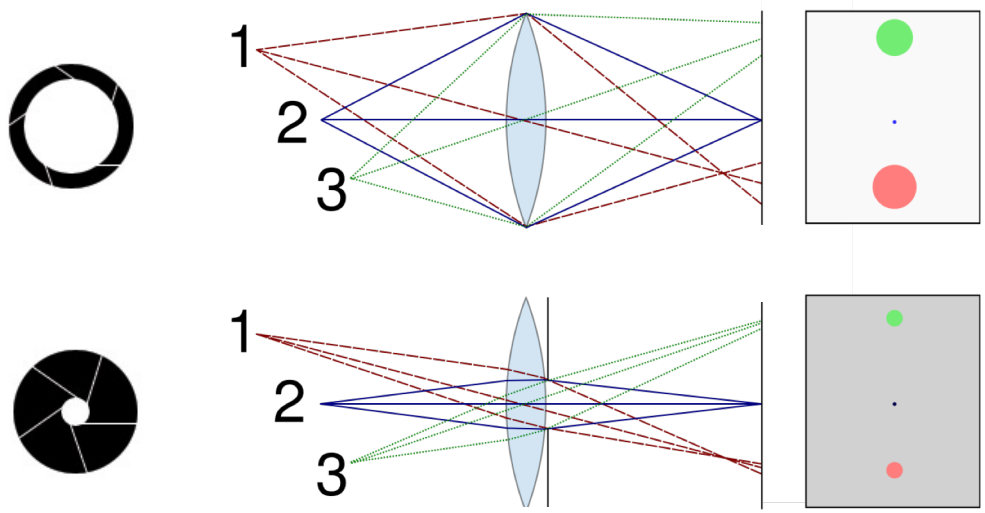



Figure source

# 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*

Figure source

# Varying the aperture

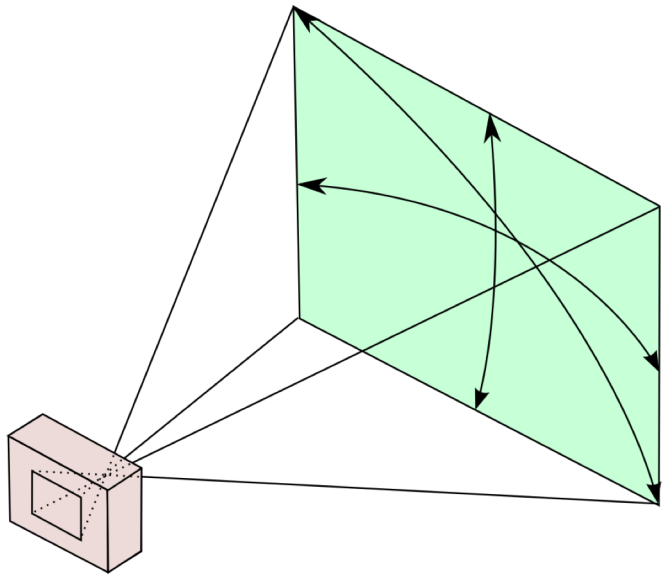

Large aperture = small DOF


Small aperture = large DOF

Slide by A. Efros

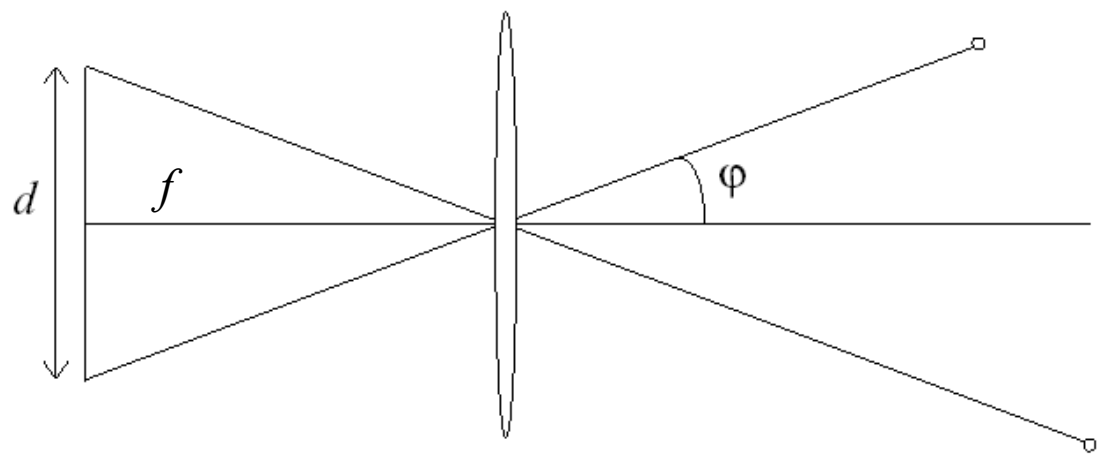
# Field of view

- The field of view is the angular extent of the world observed by the camera (Wikipedia)
- What determines the FOV?



# Field of view

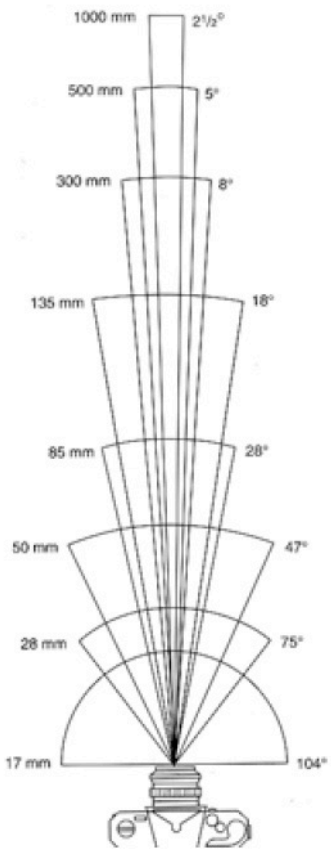
- The field of view is the angular extent of the world observed by the camera (Wikipedia)
- What determines the FOV?
  - Focal length ($f$), length of the sensor ($d$):




$$\varphi = \tan^{-1}\frac{d}{2f}$$

  - Larger focal length = smaller FOV

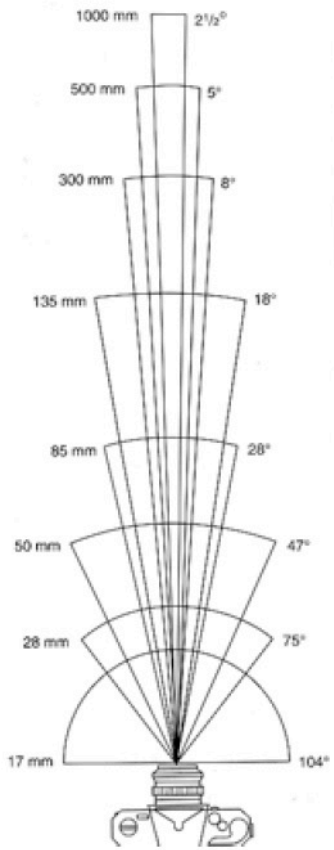
# Field of view

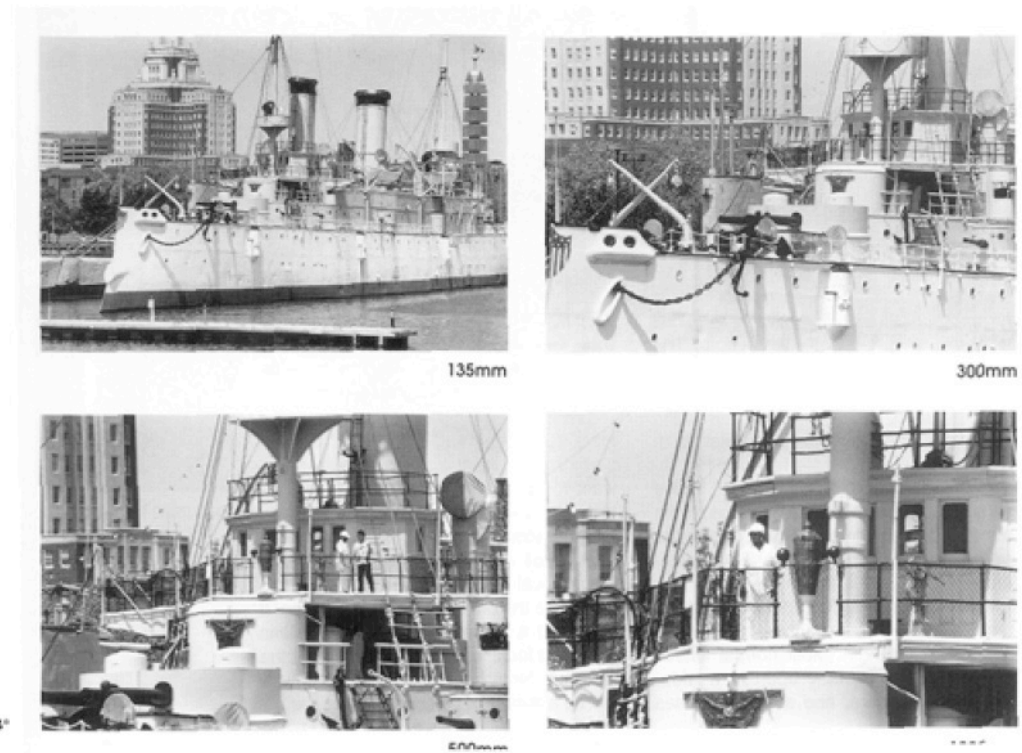




Slide by A. Efros

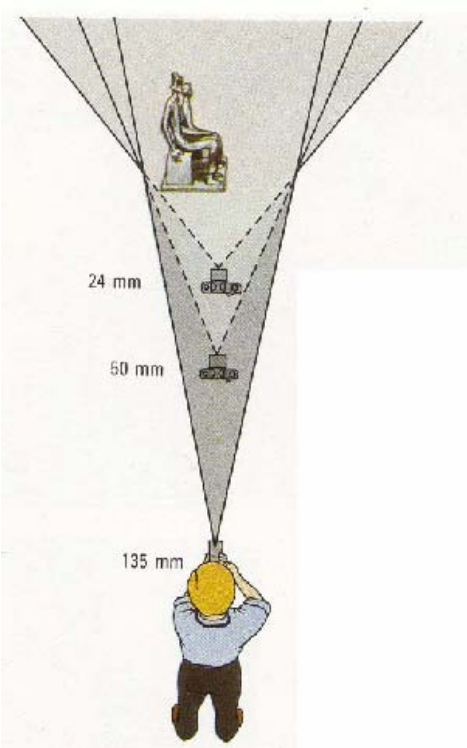
# Field of view




Slide by A. Efros

# Field of view / focal length




Large FOV, small *f*
Camera close to car

Small FOV, large *f*
Camera far from the car

Sources: A. Efros, F. Durand

# Same effect for faces

wide-angle

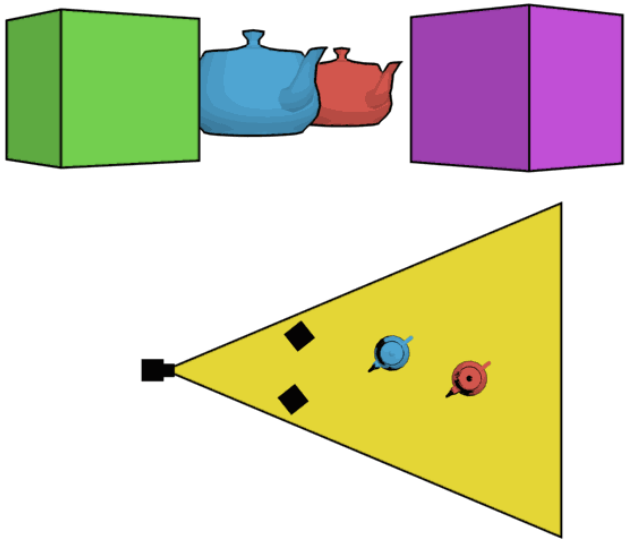
standard

telephoto

Source: F. Durand

# 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)

# My “dolly zoom”

# My “dolly zoom”

# Choice of lens and viewpoint: A COVID-era illustration


Source

# Overview

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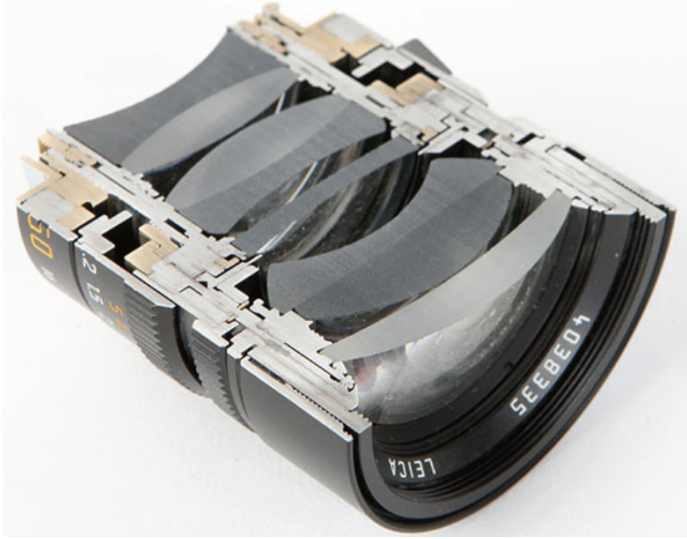
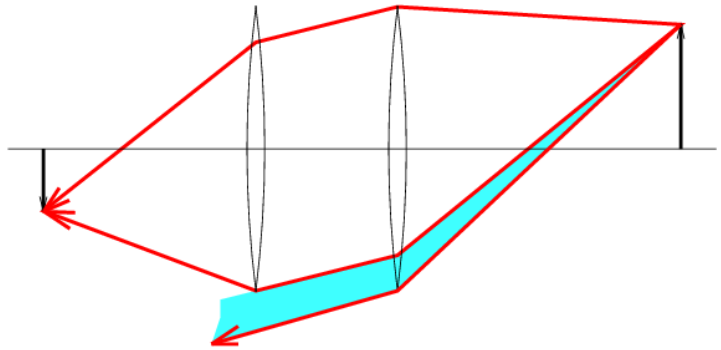
# Real lenses

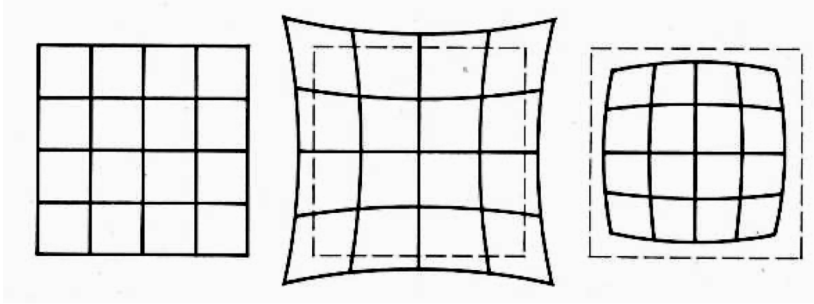



# Lens flaws: Vignetting



# Lens flaws: Radial distortion

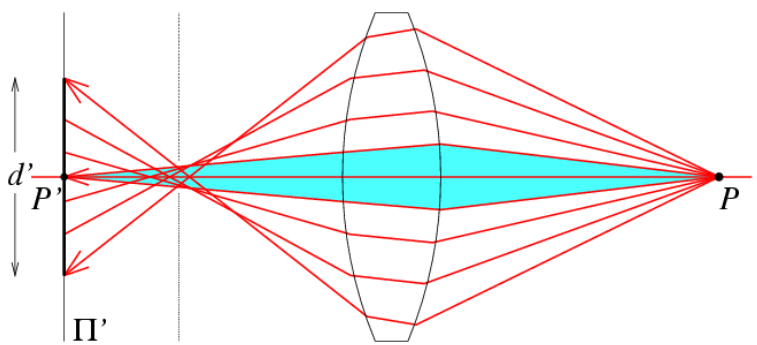
- Caused by imperfect lenses
- Distortion is stronger towards the edges of the photo



No distortion Pin cushion Barrel

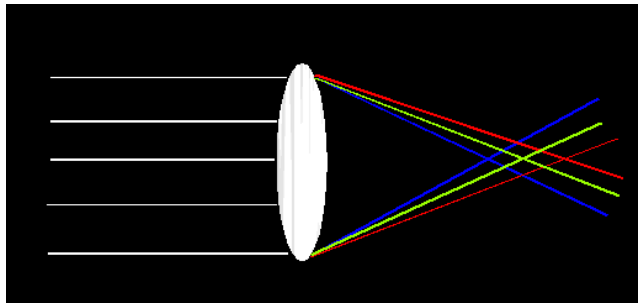
# Lens flaws: Spherical aberration

- Spherical lenses don’t focus light perfectly
- Rays farther from the optical axis focus closer



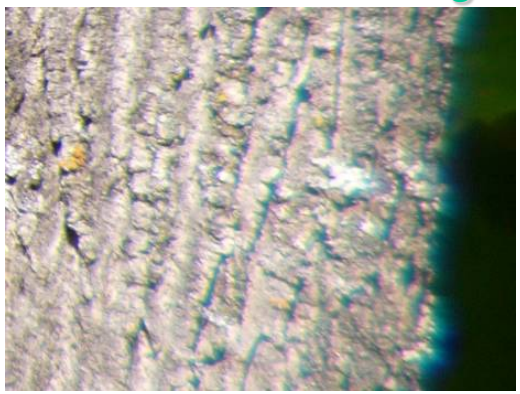
# Lens flaws: Chromatic aberration

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



Near Lens Center

Near Lens Outer Edge



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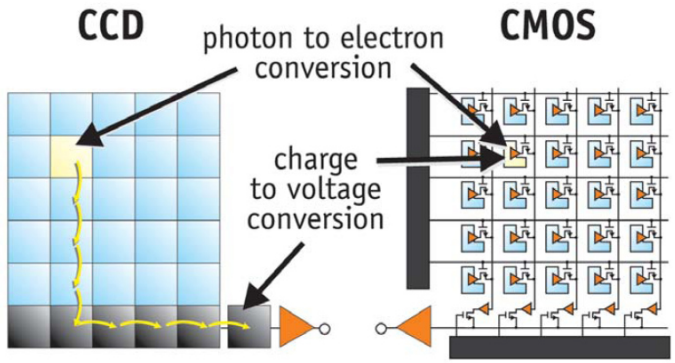
# Digital camera sensors



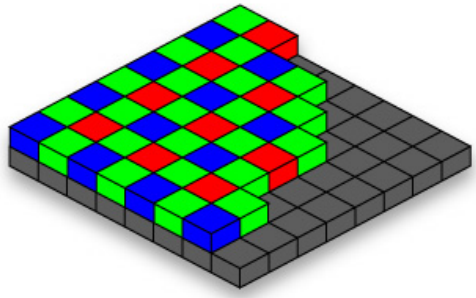

*CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.*

- 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)**

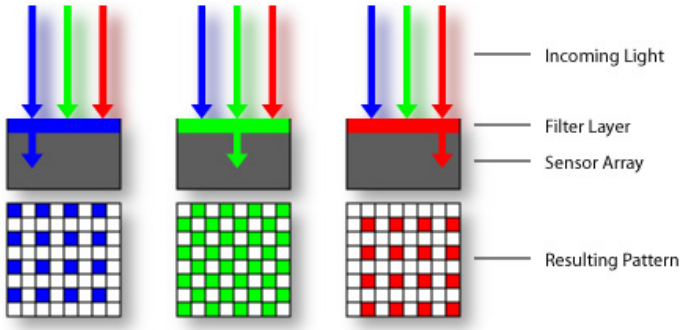
http://electronics360.globalspec.com/article/9464/ccd-vs-cmos-the-shift-in-image-sensor-technology

# Color filter arrays

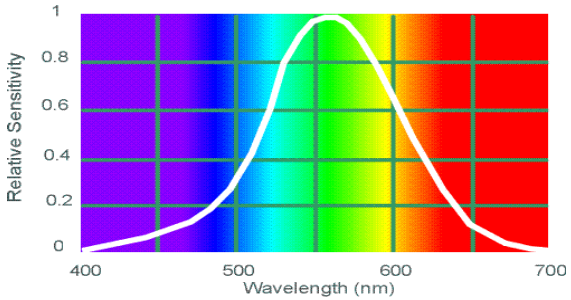
Bayer grid (1976)



**Demosaicing**:
Estimation of missing components from neighboring values




Why more green?

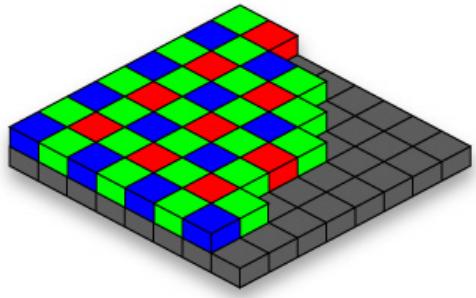


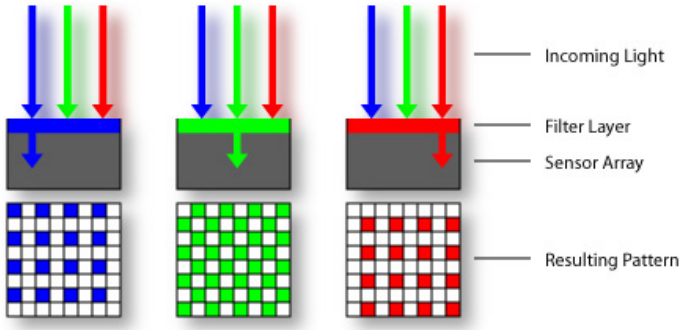

Human Luminance Sensitivity Function

Source: Steve Seitz

# Color filter arrays

Bayer grid (1976)



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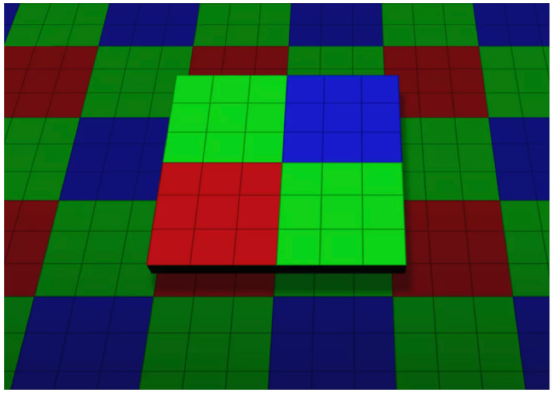


Recent cameraphone technology: pixel binning

# Misc. digital camera artifacts

## Noise

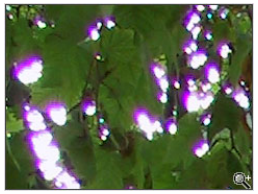
- low light is where you most notice noise
- light sensitivity (ISO) / noise tradeoff
- stuck pixels

## In-camera processing

- oversharpening can produce halos

## Compression

- JPEG artifacts, blocking

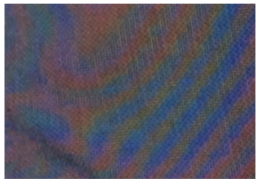


## Blooming

- CCD charge overflowing into neighboring pixels

## Color artifacts

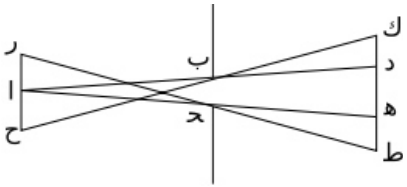
- Color moire
- Purple fringing from microlenses



# Historic milestones

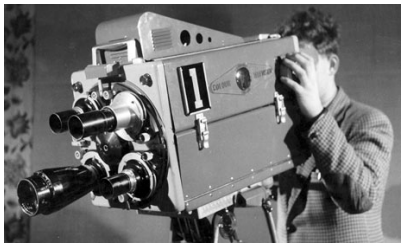
- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic film** (Eastman, 1889)
- **Cinema** (Lumière Brothers, 1895)
- **Color Photography** (Lumière Brothers, 1908)
- **Television** (Baird, Farnsworth, Zworykin, 1920s)
- **First consumer camera with CCD** Sony Mavica (1981)
- **First fully digital camera:** Kodak DCS100 (1990)

https://en.wikipedia.org/wiki/History_of_photography



Alhacen's notes

Niepce, "La Table Servie," 1822



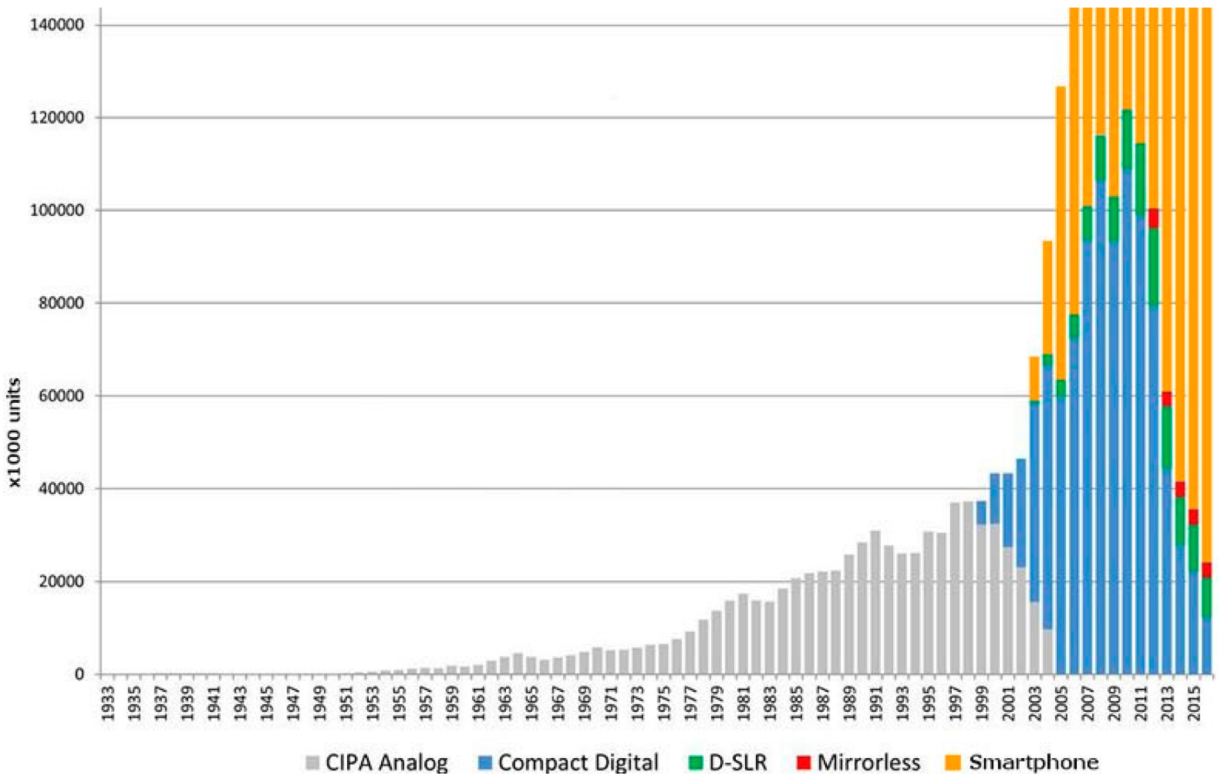
Old television camera

# First digitally scanned photograph

- NIST (1957), 176x176 pixels

http://listverse.com/history/top-10-incredible-early-firsts-in-photography/

# Camera sales over time




Source

# Camera sales over time

The full chart…


Source