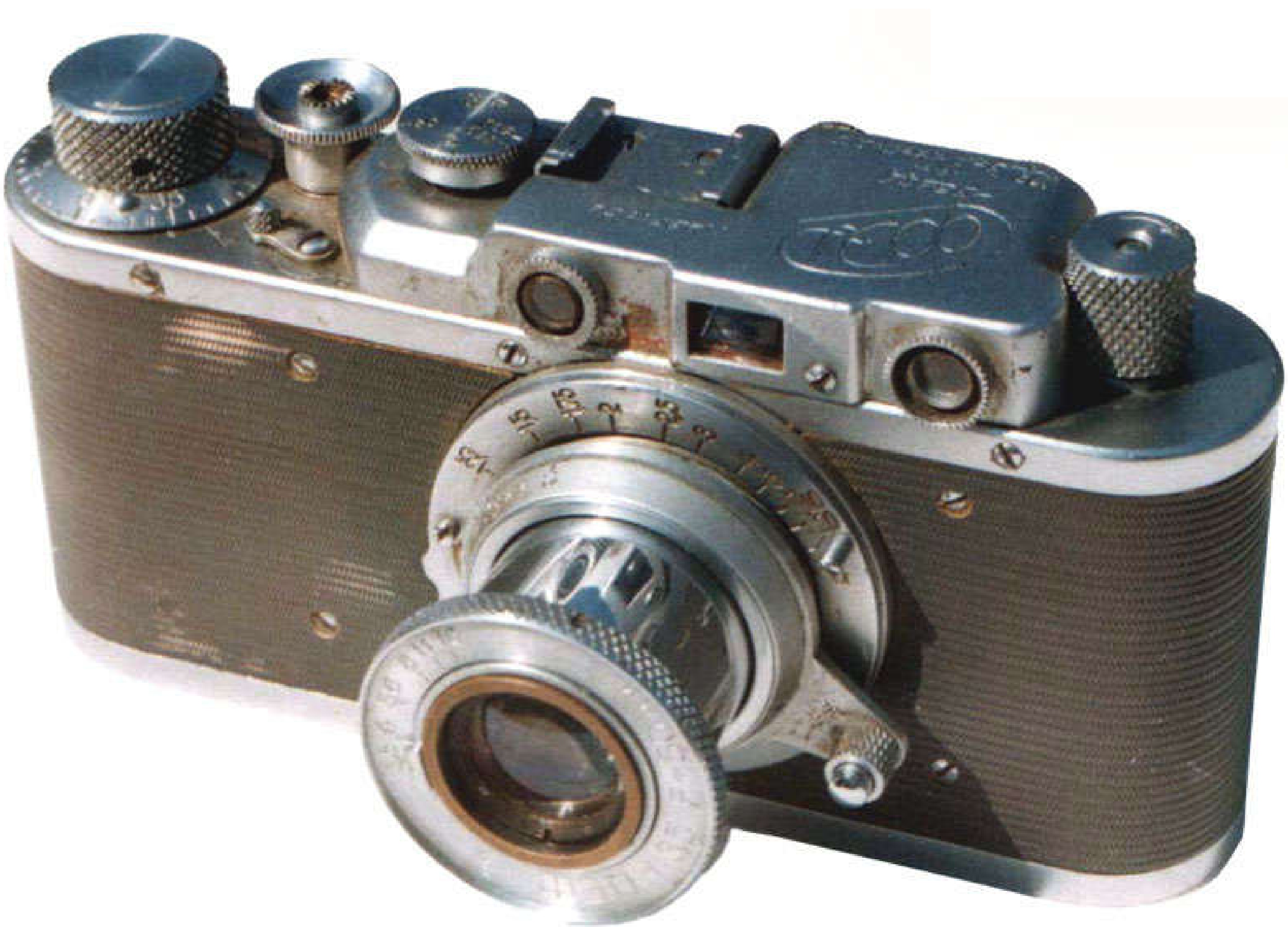
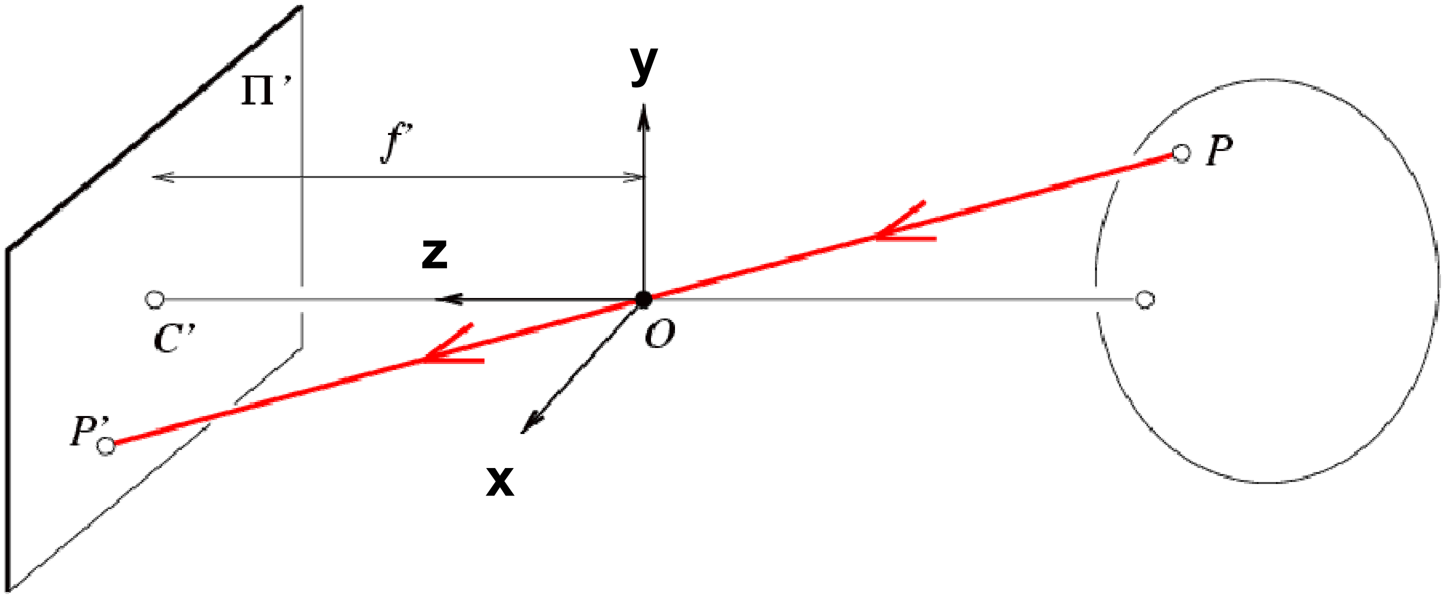
The Camera (continued)



Modeling projection

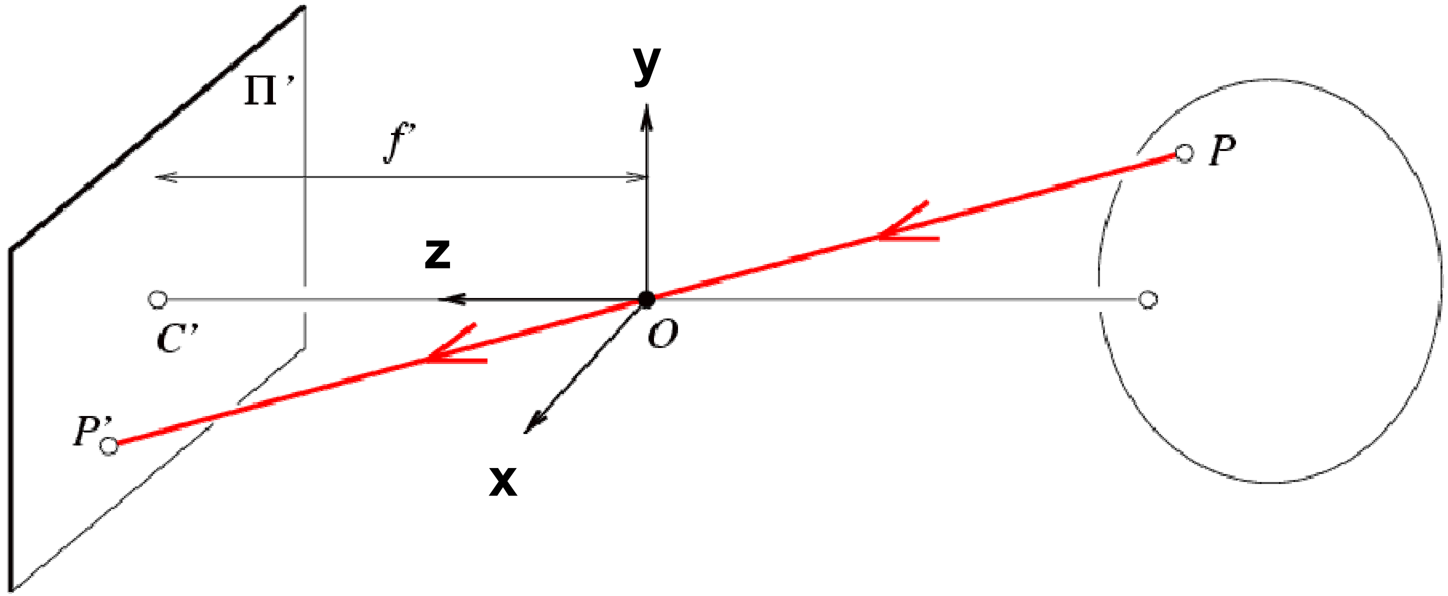


The coordinate system

- We will use the pinhole model as an approximation
- Put the optical center (***O***) at the origin
- Put the image plane (**Π'**) *in front* of ***O***

Source: J. Ponce, S. Seitz

Modeling projection

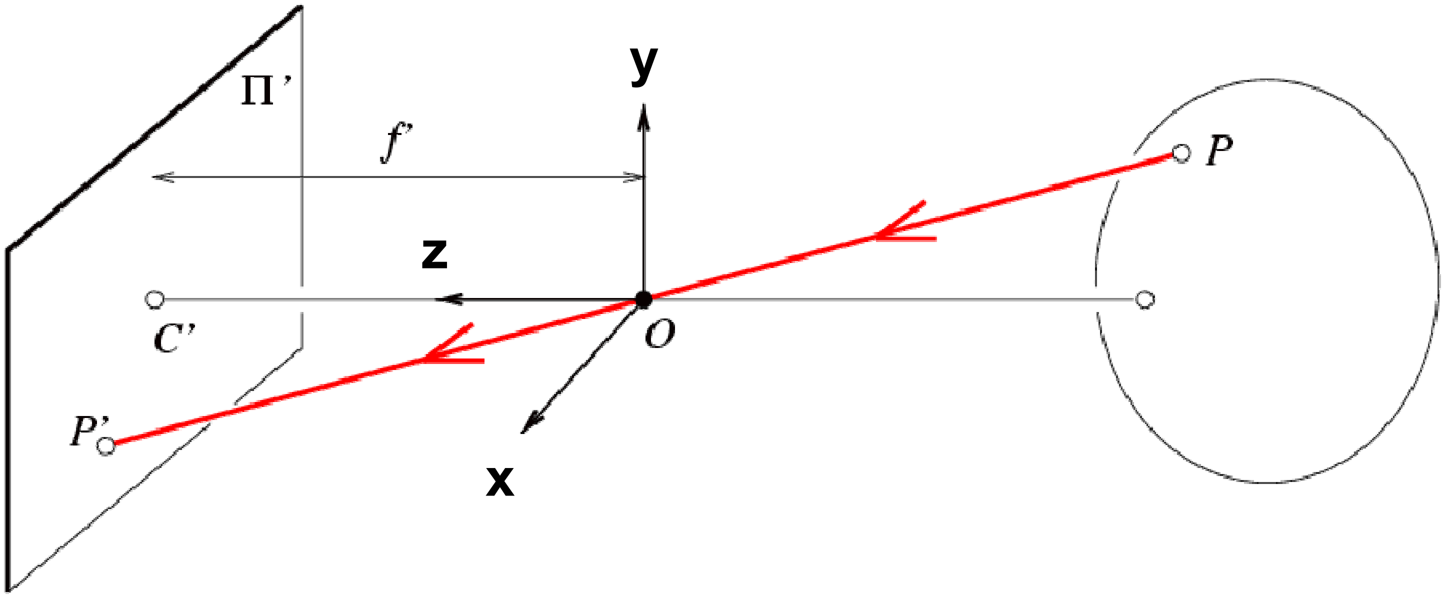


Projection equations

- Compute intersection with Π' of ray from ***P*** = (x,y,z) to ***O***
- Derived using similar triangles

Source: J. Ponce, S. Seitz

Modeling projection



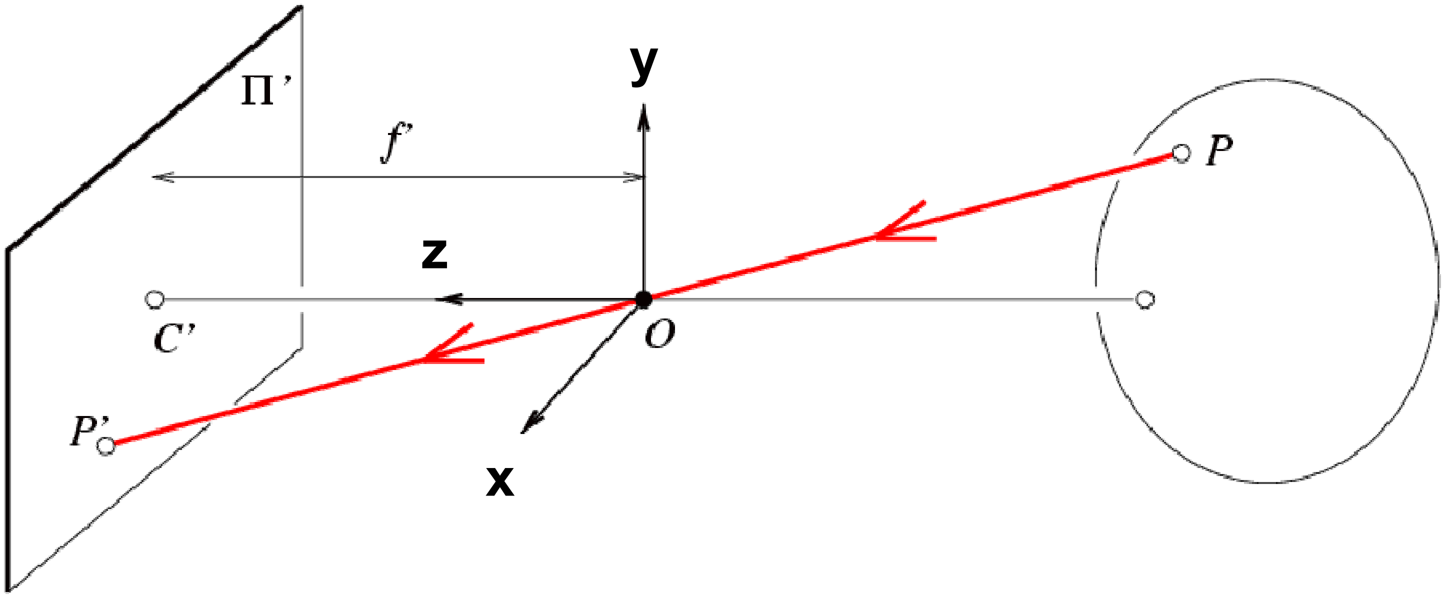
Projection equations

- Compute intersection with **Π'** of ray from ***P*** = (x,y,z) to ***O***
- Derived using similar triangles

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

Source: J. Ponce, S. Seitz

Modeling projection



Projection equations

- Compute intersection with Π' of ray from ***P*** = (x,y,z) to ***O***
- Derived using similar triangles

$$(x,y,z) \rightarrow (f'\frac{x}{z}, f'\frac{y}{z}, f')$$

- We get the projection by throwing out the last coordinate:

$$(x,y,z) \rightarrow (f'\frac{x}{z}, f'\frac{y}{z})$$

Source: J. Ponce, S. Seitz

Homogeneous coordinates

Is this a linear transformation?

- no—division by z is nonlinear

Slide by Steve Seitz

Homogeneous coordinates

Is this a linear transformation?

- no—division by z is nonlinear

Trick: add one more coordinate:

$$(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

homogeneous image coordinates

$$(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

homogeneous scene coordinates

Converting *from* homogeneous coordinates

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)$$

$$\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow (x/w, y/w, z/w)$$

Slide by Steve Seitz

Perspective Projection Matrix

Projection is a matrix multiplication using homogeneous coordinates:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/f' & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z/f' \end{bmatrix} \Rightarrow \left(f'\frac{x}{z}, f'\frac{y}{z} \right)$$

divide by the third coordinate

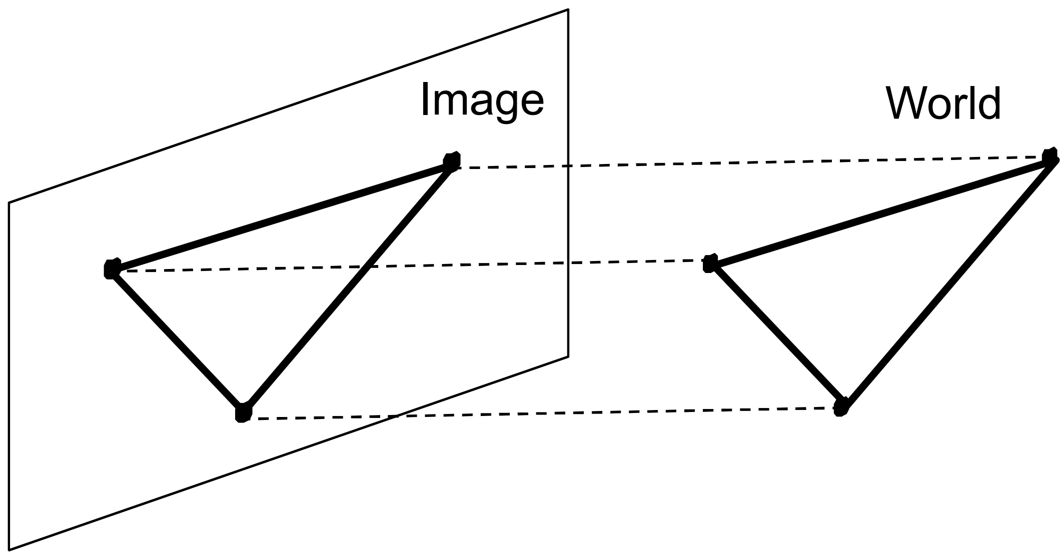
In practice: lots of coordinate transformations…

(2D point (3x1)) = (Camera to pixel coord. trans. matrix (3x3)) (Perspective projection matrix (3x4)) (World to camera coord. trans. matrix (4x4)) (3D point (4x1))

Orthographic Projection

Special case of perspective projection

- Distance from center of projection to image plane is infinite

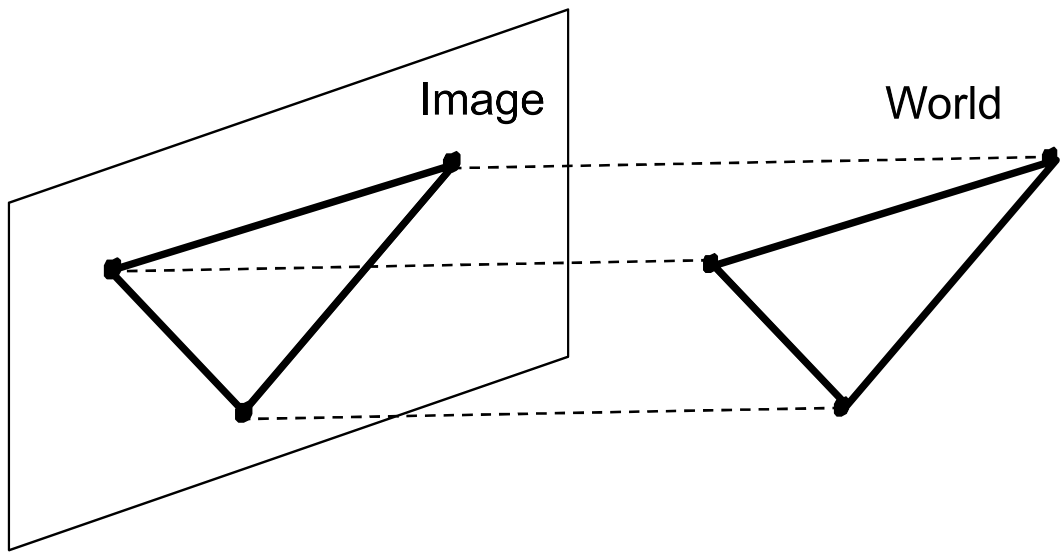


- Also called “parallel projection”
- What’s the projection matrix?

Orthographic Projection

Special case of perspective projection

- Distance from center of projection to image plane is infinite



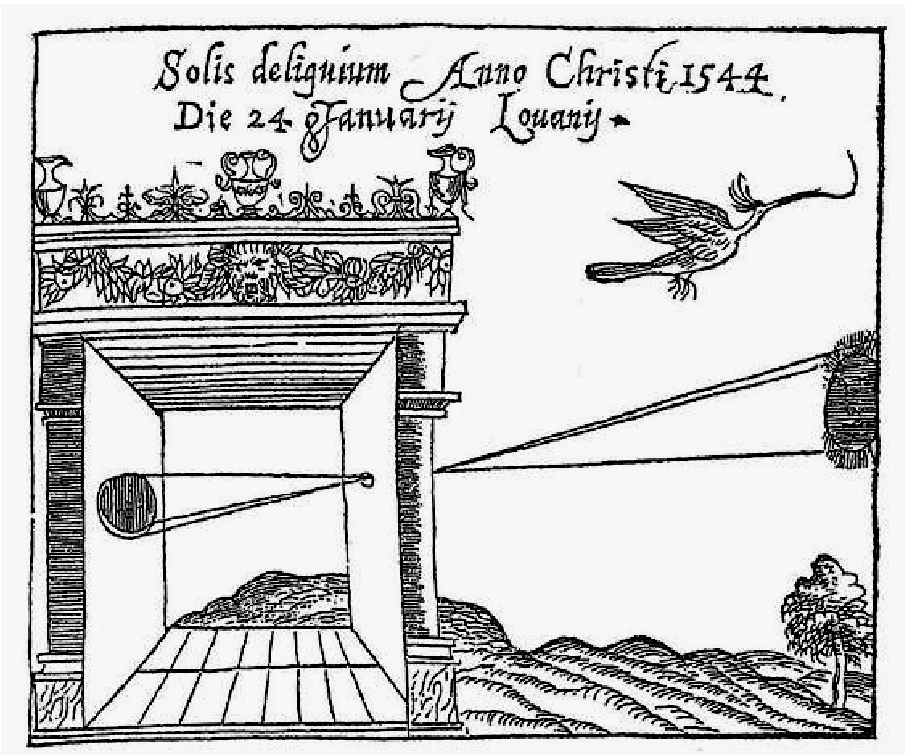
- Also called “parallel projection”
- What’s the projection matrix?

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \Rightarrow (x, y)$$

Slide by Steve Seitz

Building a real camera

Camera Obscura

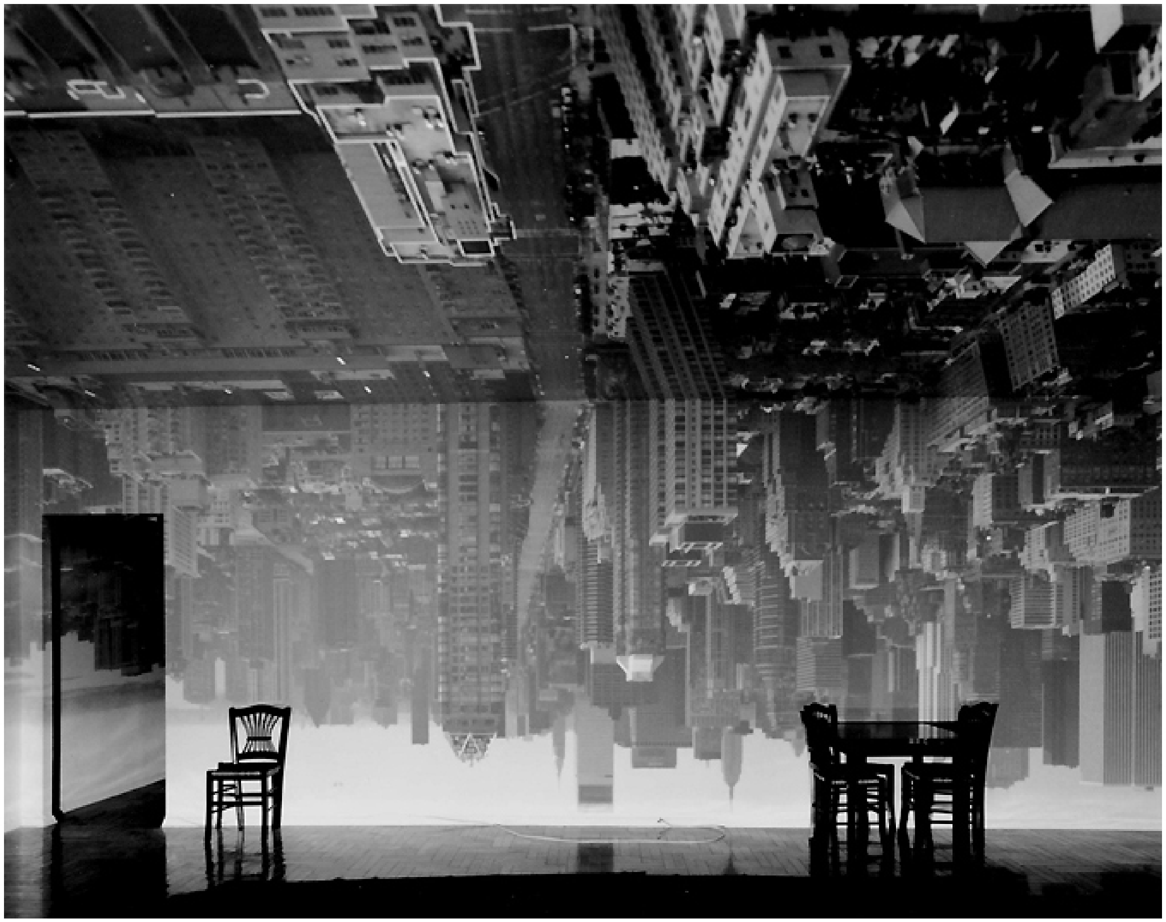


Gemma Frisius, 1558

- Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)
- Depth of the room (box) is the effective focal length

Source: A. Efros

Abelardo Morell



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

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

http://www.abelardomorell.net/camera_obscura1.html

Home-made pinhole camera

Slide by A. Efros

http://www.debevec.org/Pinhole/

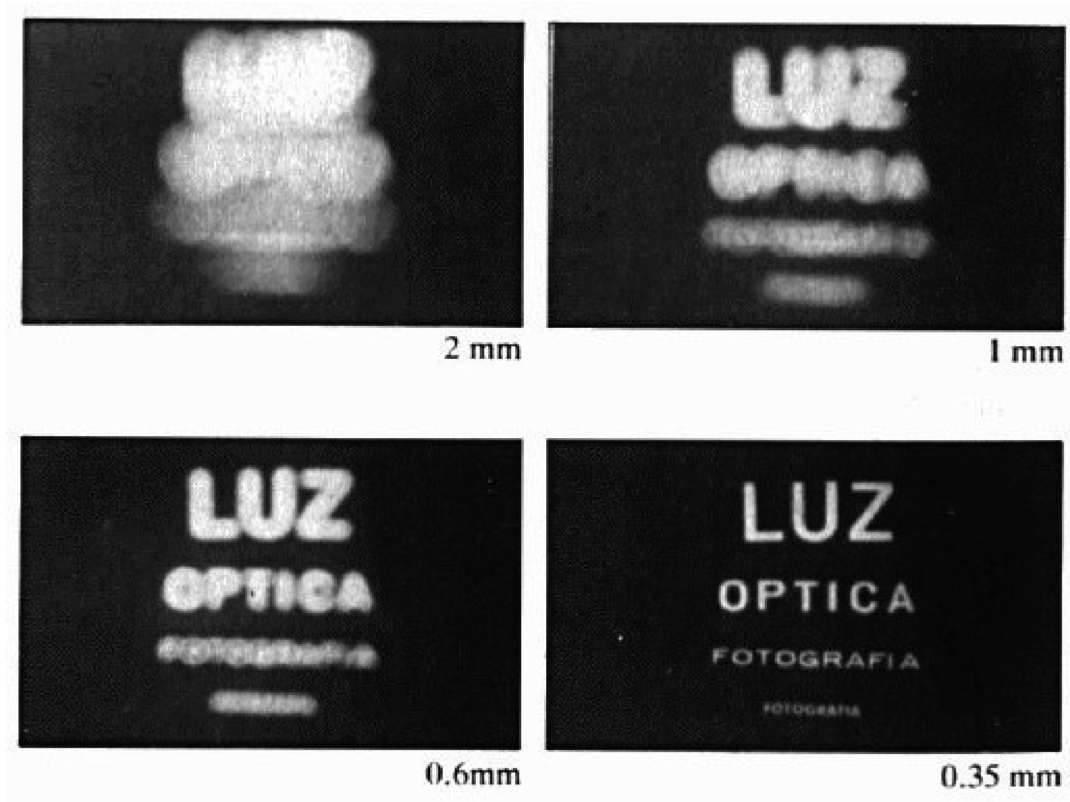
Home-made pinhole camera

Why so blurry?

Slide by A. Efros

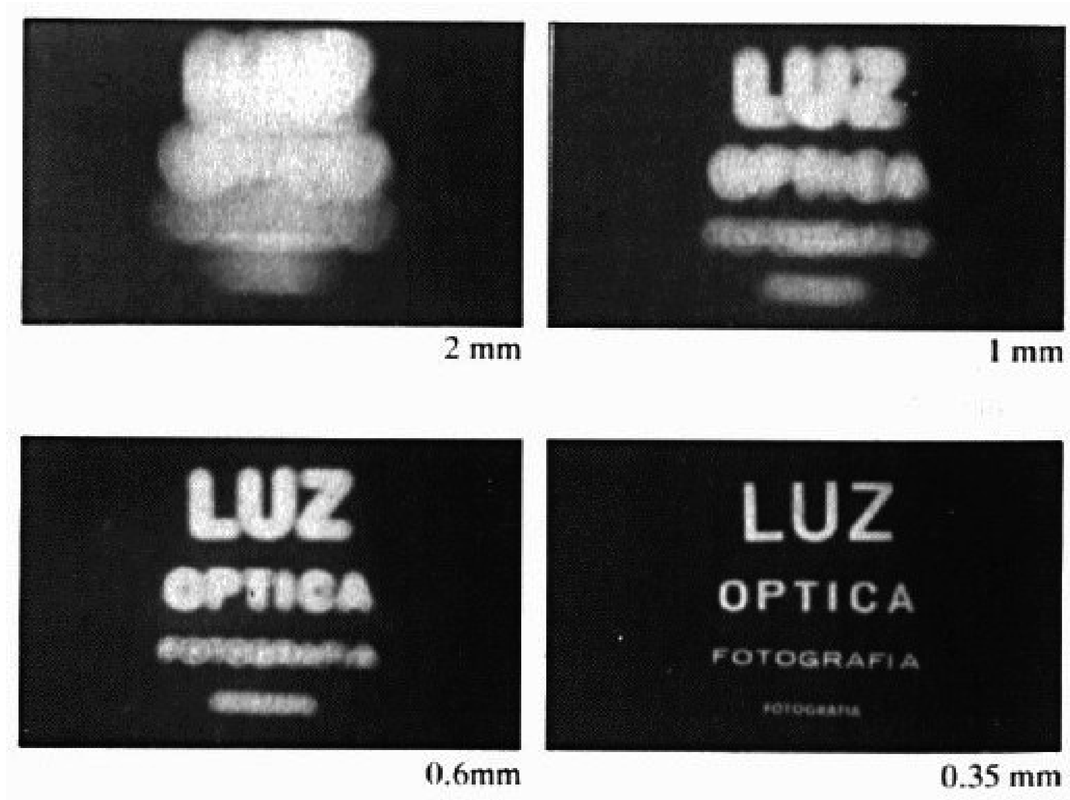
http://www.debevec.org/Pinhole/

Shrinking the aperture



Slide by Steve Seitz

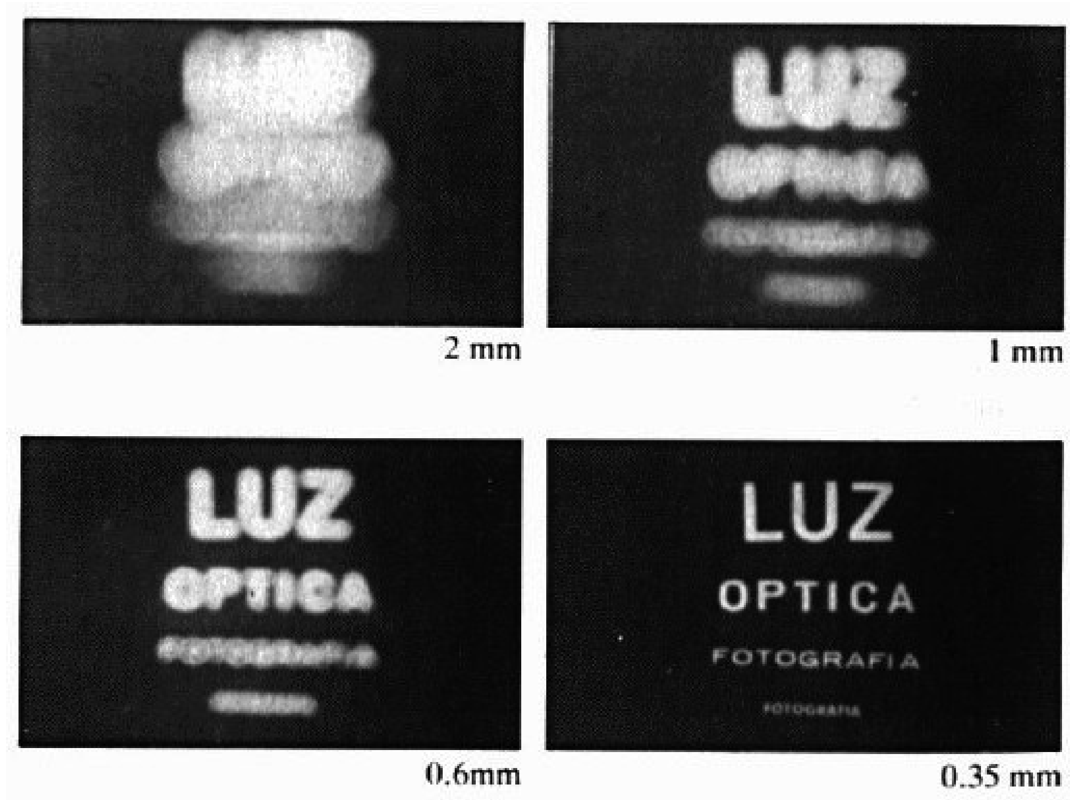
Shrinking the aperture



Why not make the aperture as small as possible?

Slide by Steve Seitz

Shrinking the aperture

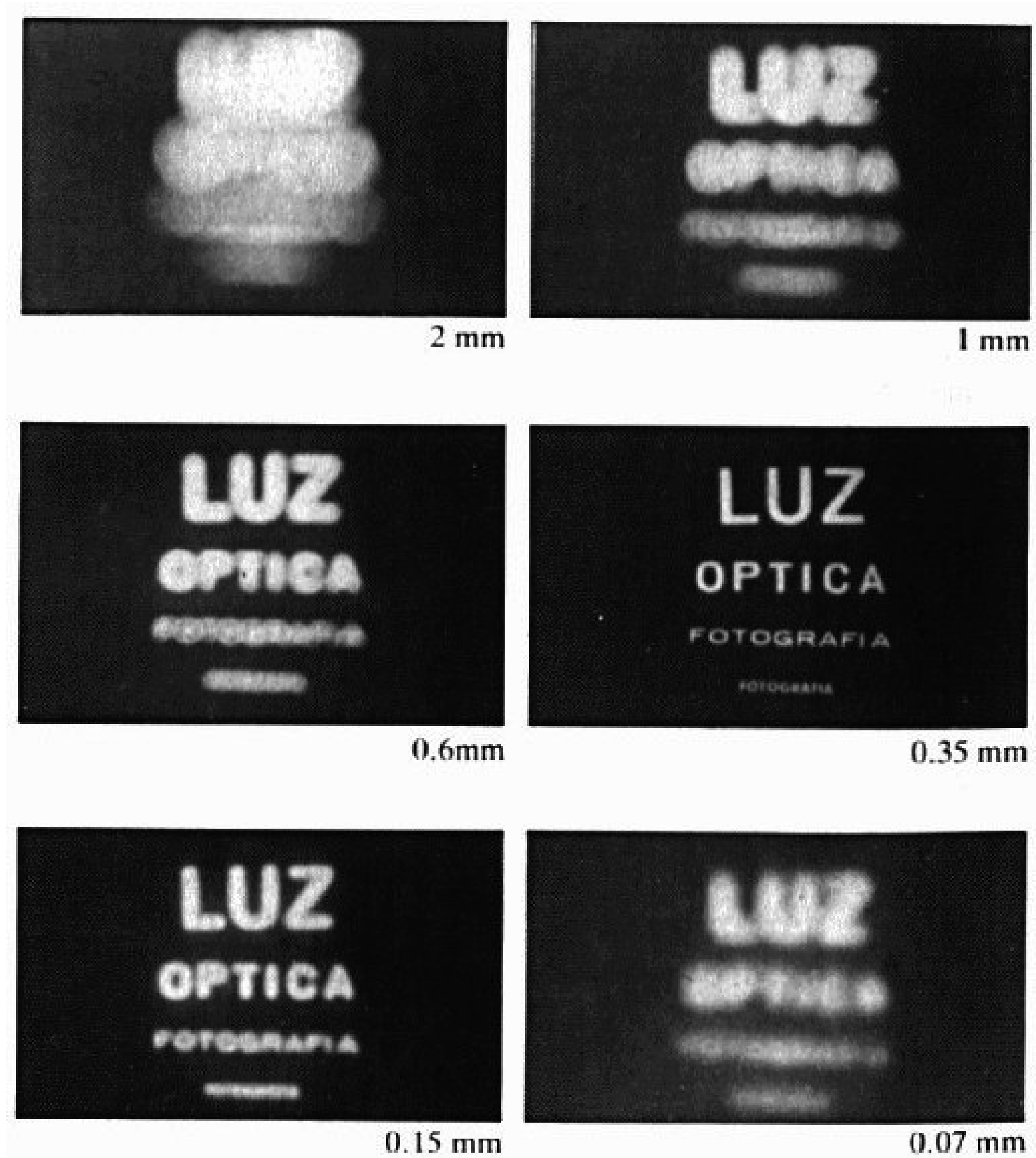


Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects…

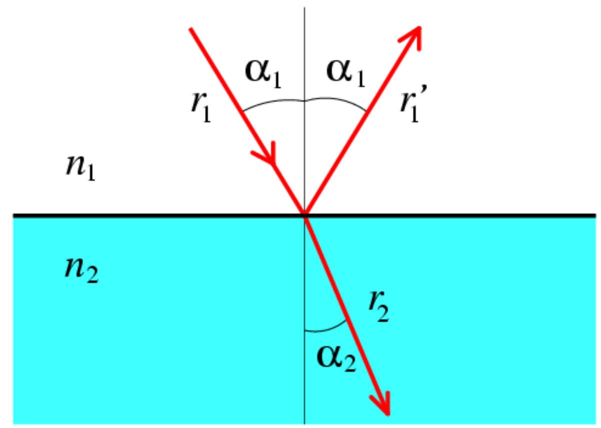
Slide by Steve Seitz

Shrinking the aperture



Solution: Refraction

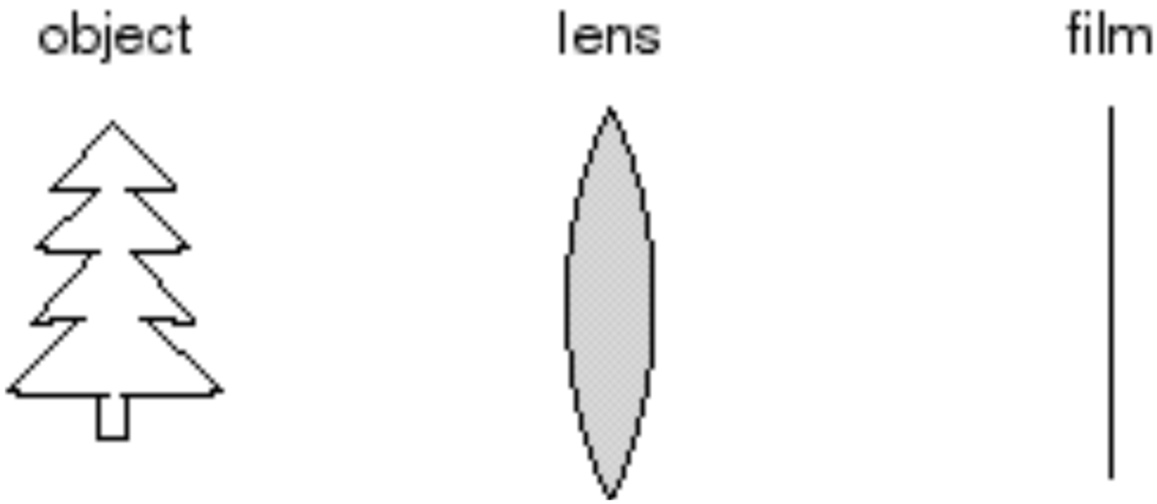
Image source: F. Durand



Snell's law:

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

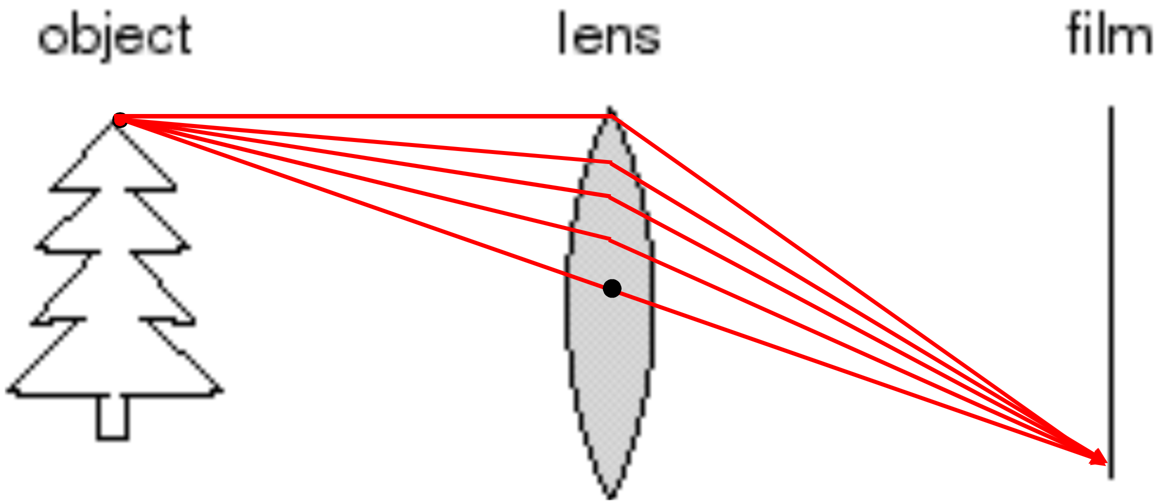
Adding a lens



A lens focuses light onto the film

- Rays passing through the center are not deviated

Adding a lens

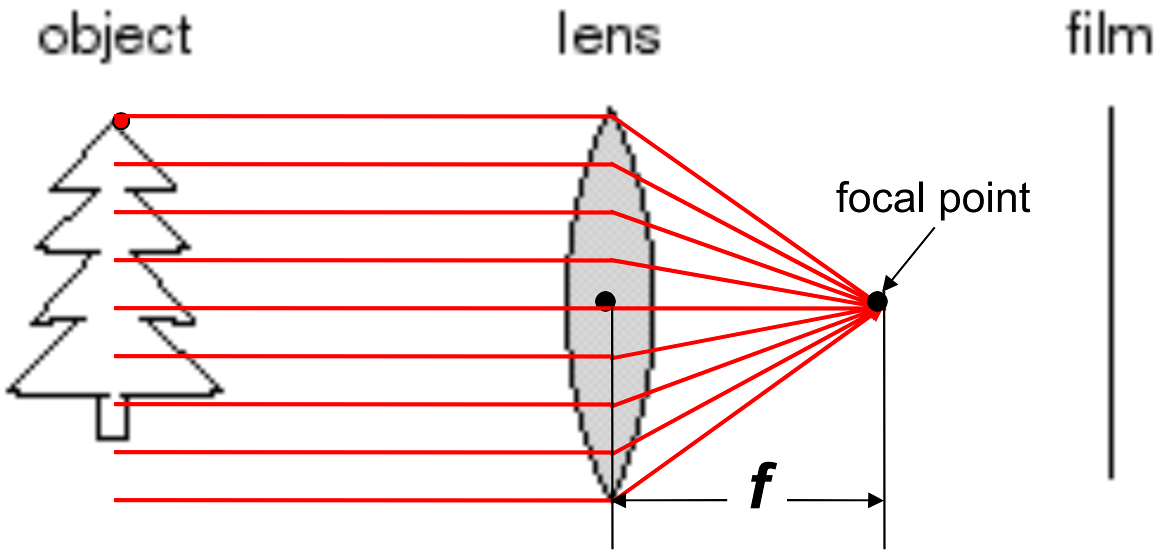


A lens focuses light onto the film

- Rays passing through the center are not deviated

Slide by Steve Seitz

Adding a lens

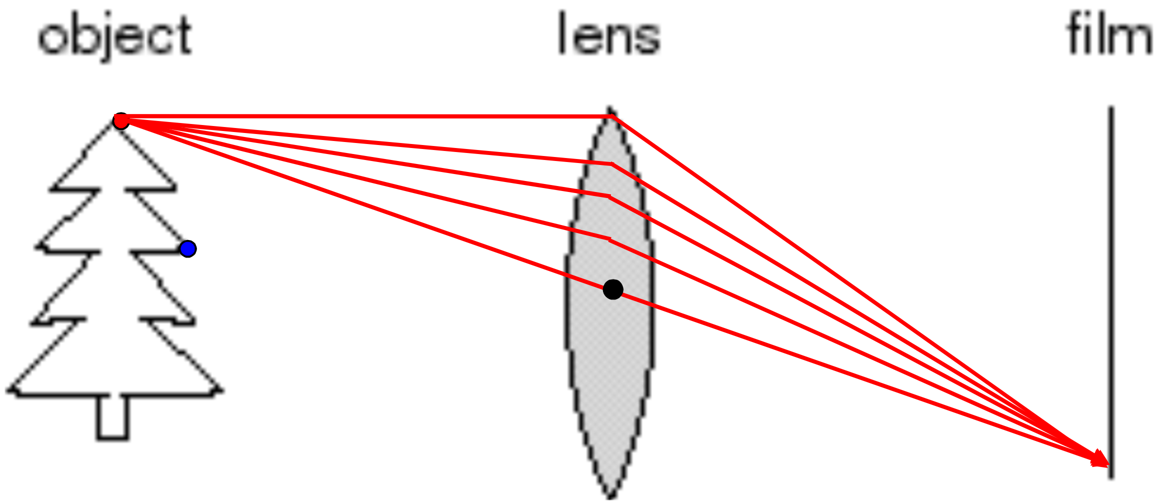


A lens focuses light onto the film

- Rays passing through the center are not deviated
- All parallel rays converge to one point on a plane located at the *focal length f*

Slide by Steve Seitz

Adding a lens

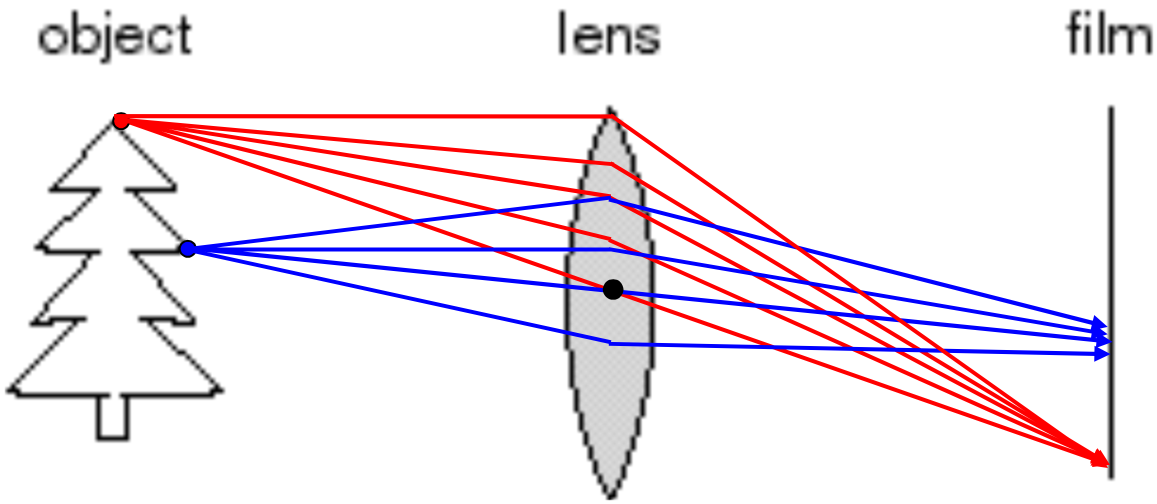


A lens focuses light onto the film

- There is a specific distance at which objects are "in focus"
  - other points project to a "circle of confusion" in the image

Slide by Steve Seitz

Adding a lens

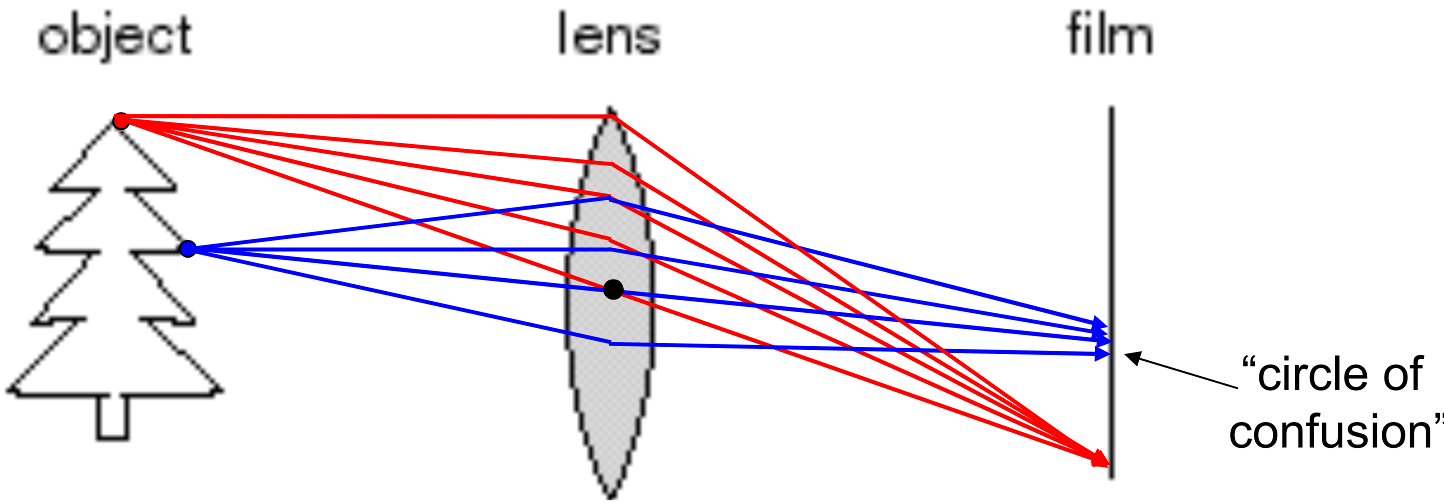


A lens focuses light onto the film

- There is a specific distance at which objects are “in focus”
  - other points project to a “circle of confusion” in the image

Slide by Steve Seitz

Adding a lens

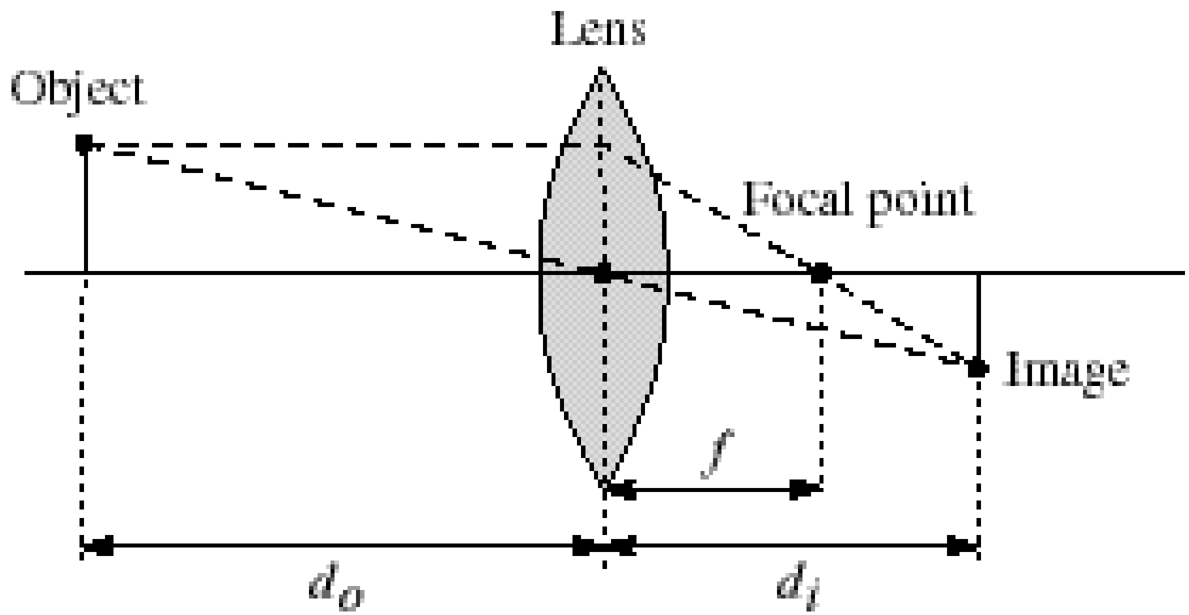


A lens focuses light onto the film

- There is a specific distance at which objects are "in focus"
  - other points project to a "circle of confusion" in the image

Slide by Steve Seitz

Thin lenses

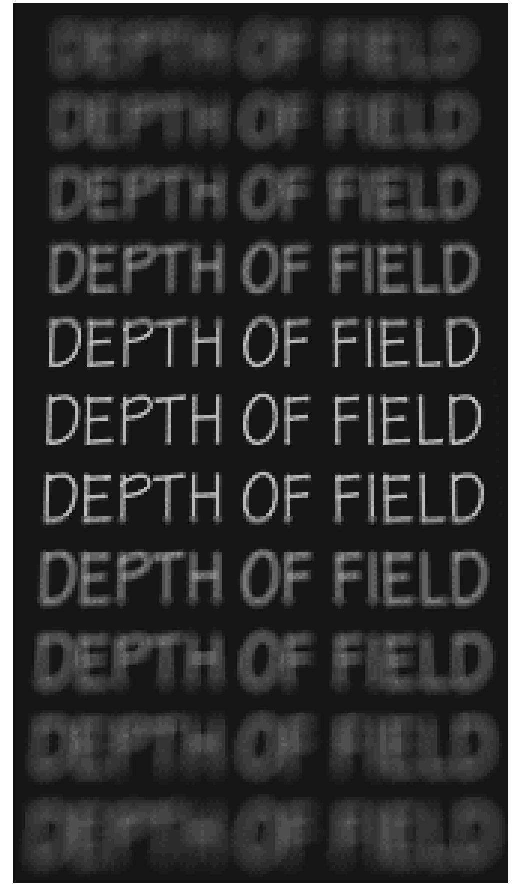


Thin lens equation: $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

- Any object point satisfying this equation is in focus
- What is the shape of the focus region?
- How can we change the focus region?

Slide by Steve Seitz

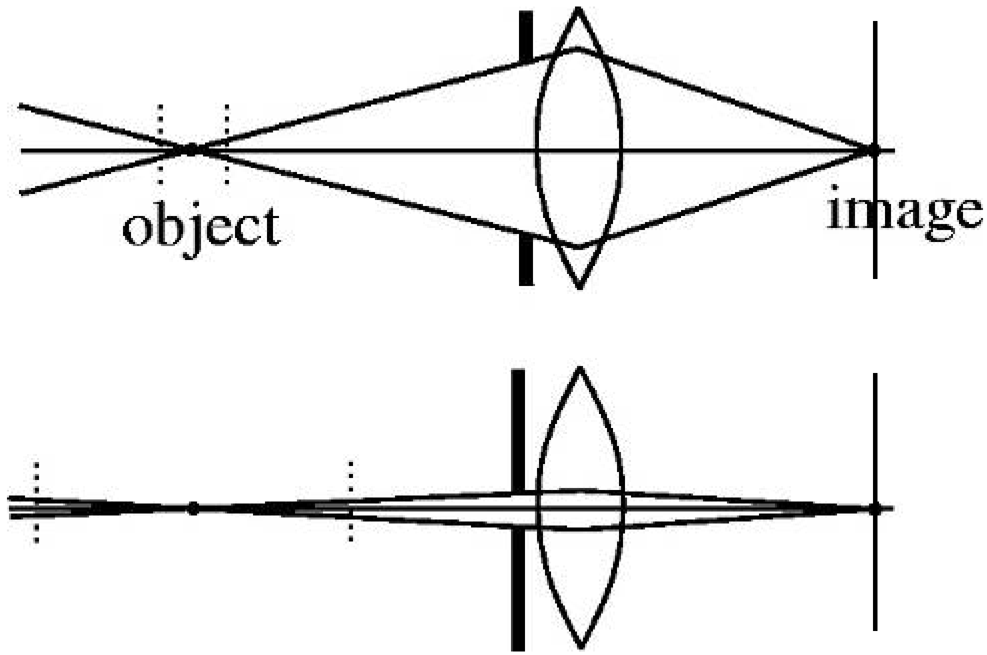
Depth of Field



Slide by A. Efros

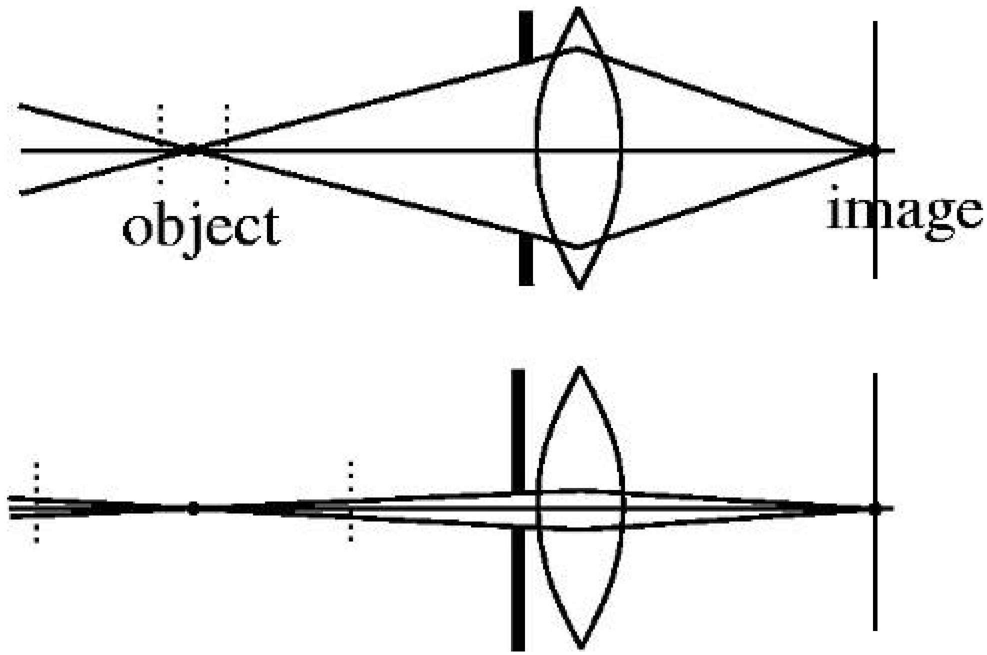
http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

How can we control the depth of field?



Slide by A. Efros

How can we control the 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

Slide by A. Efros

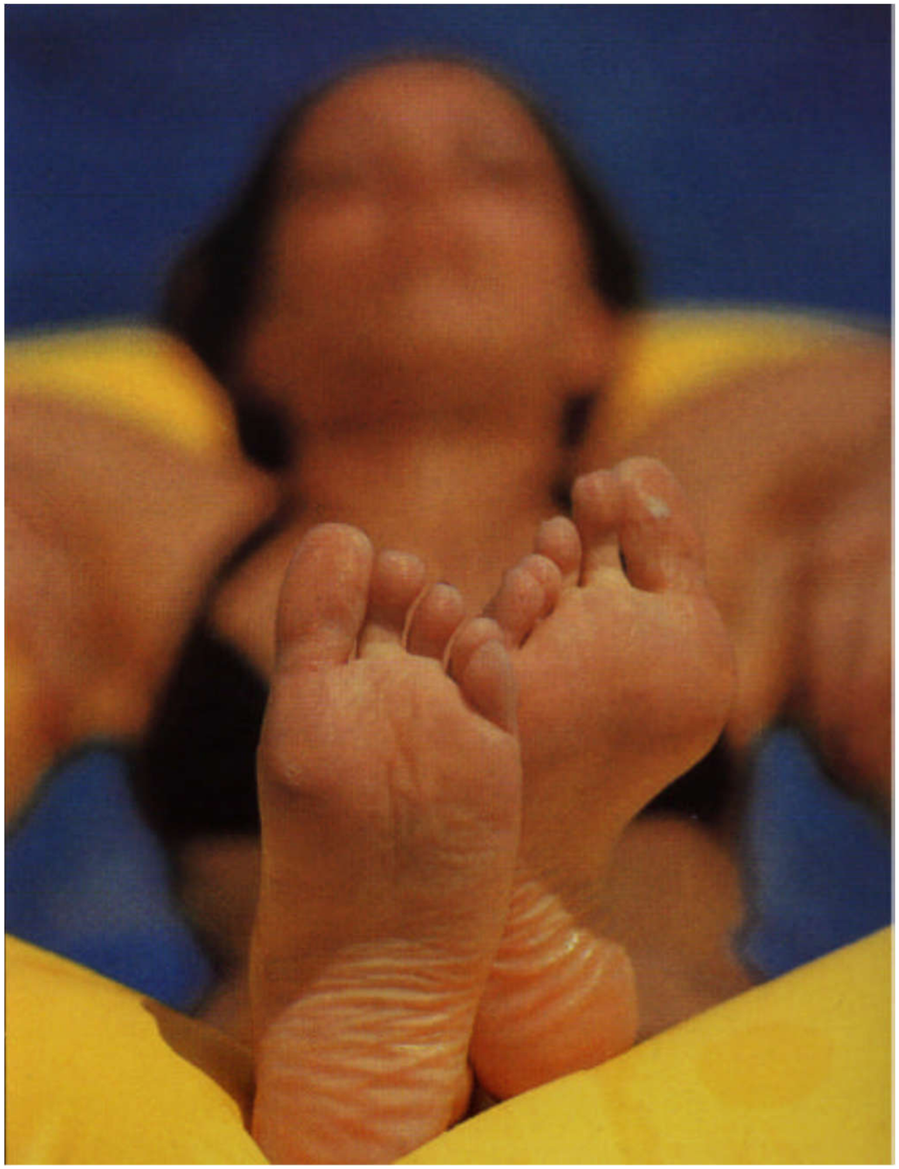
Varying the aperture

Large apeture = small DOF

Small apeture = large DOF

Slide by A. Efros

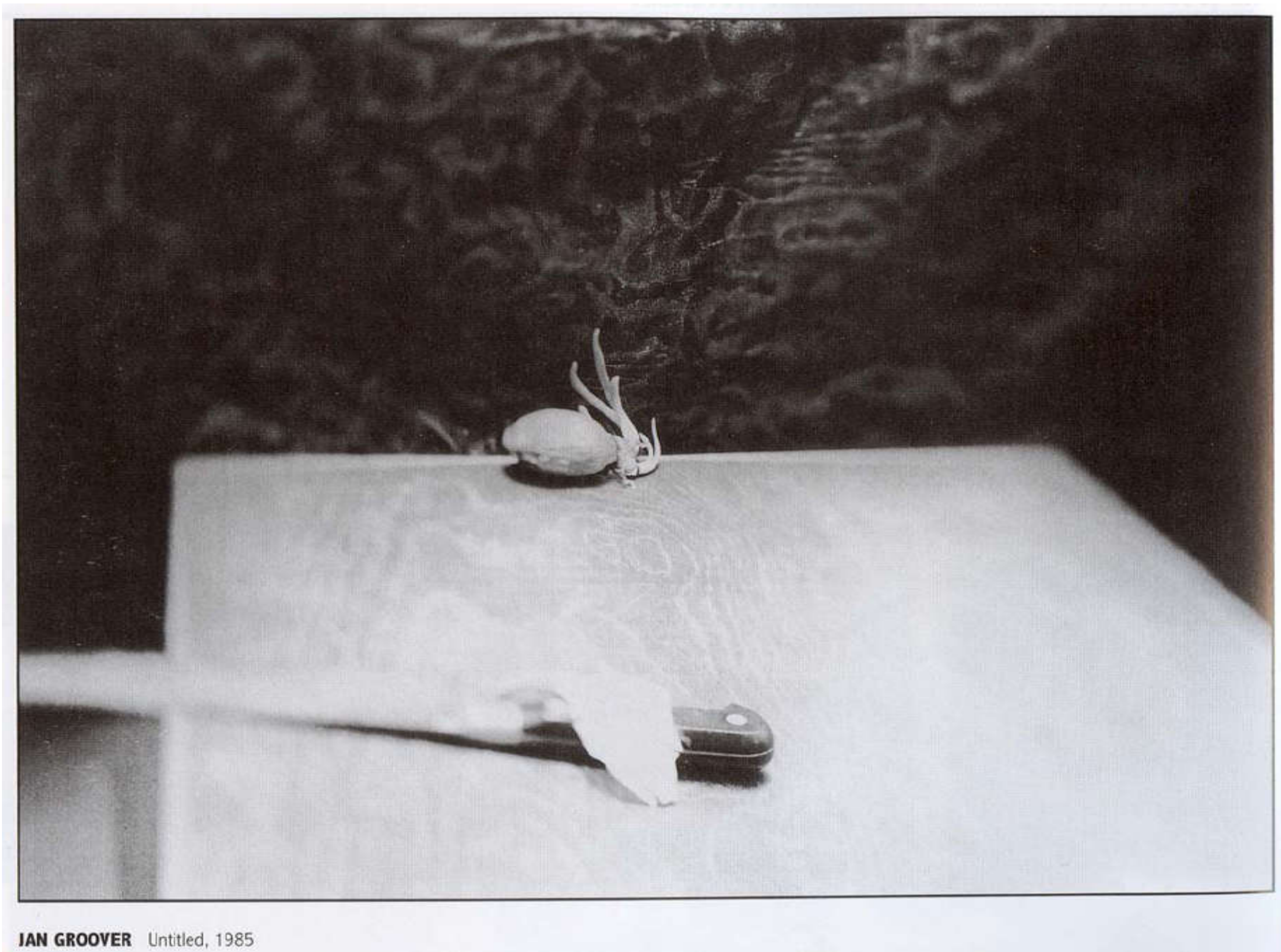
Nice Depth of Field effect



Source: F. Durand

Manipulating the plane of focus

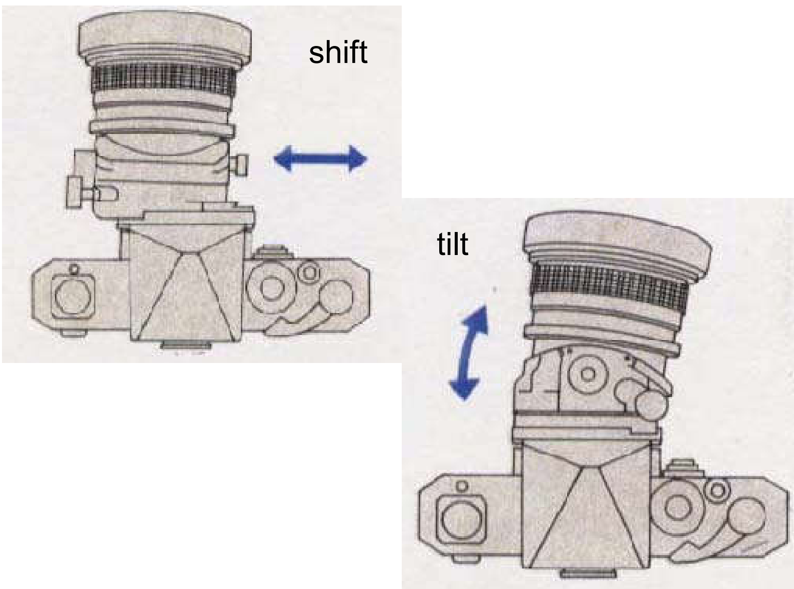
In this image, the plane of focus is almost at a right angle to the image plane

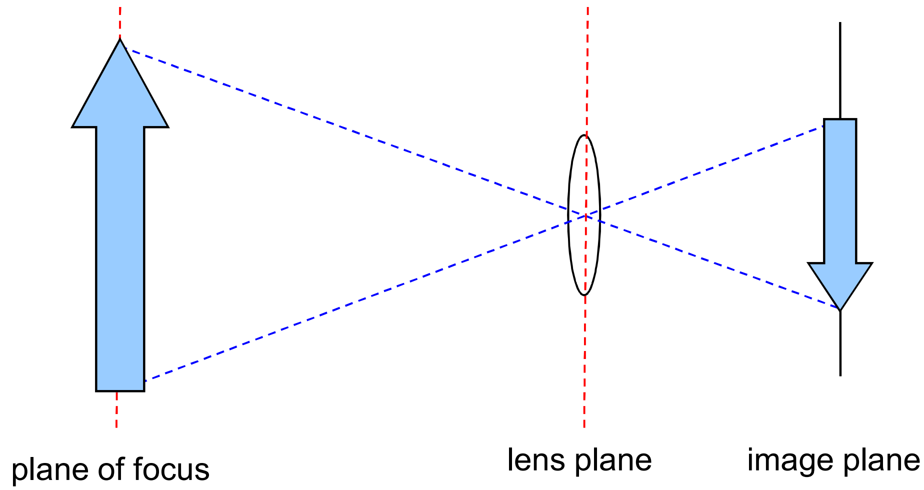


Source: F. Durand

Tilt-shift lenses

- Tilting the lens with respect to the image plane allows to choose an arbitrary plane of focus

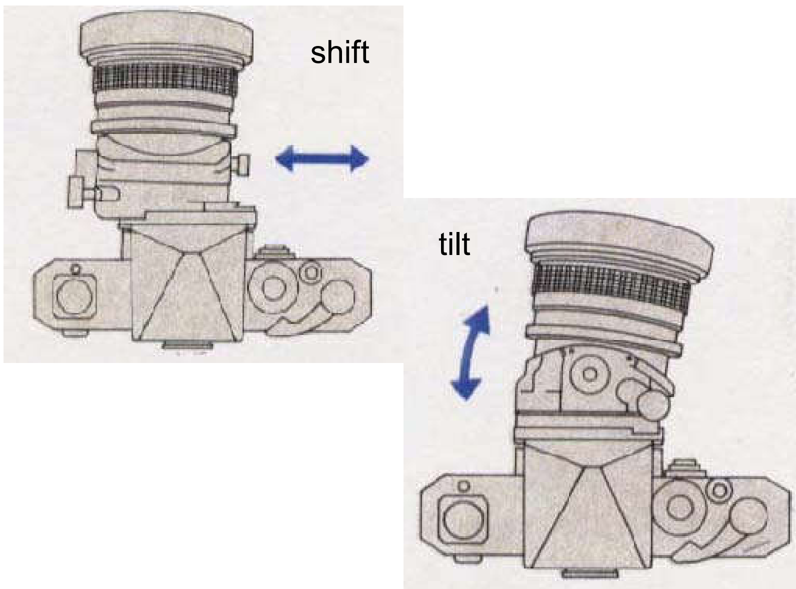


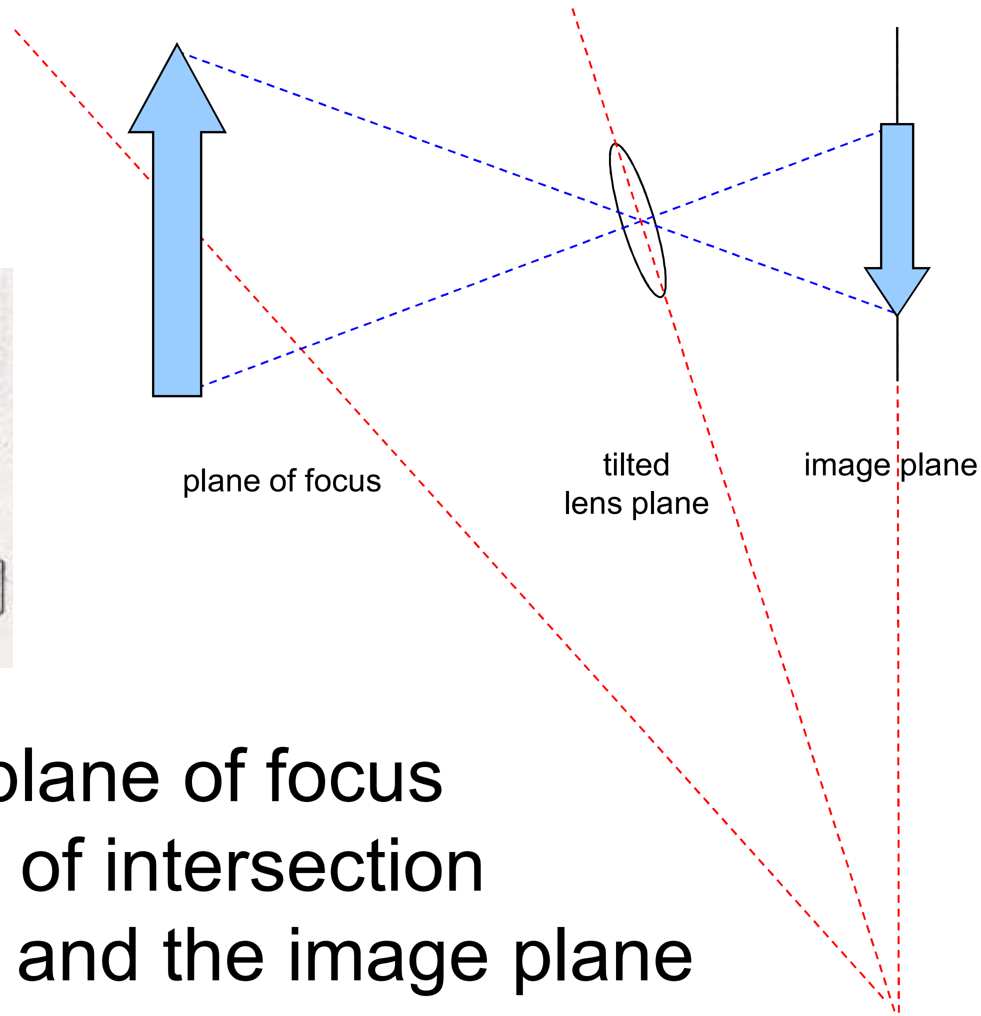


- Standard setup: plane of focus is parallel to image plane and lens plane

Tilt-shift lenses

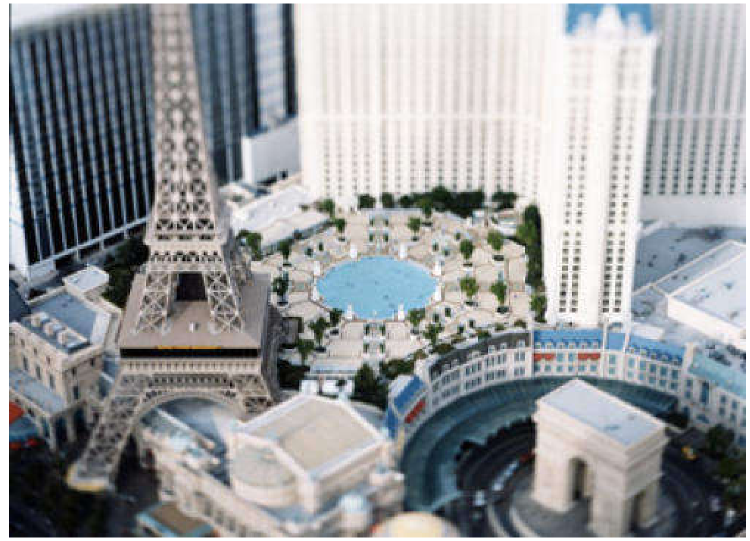
- Tilting the lens with respect to the image plane allows to choose an arbitrary plane of focus

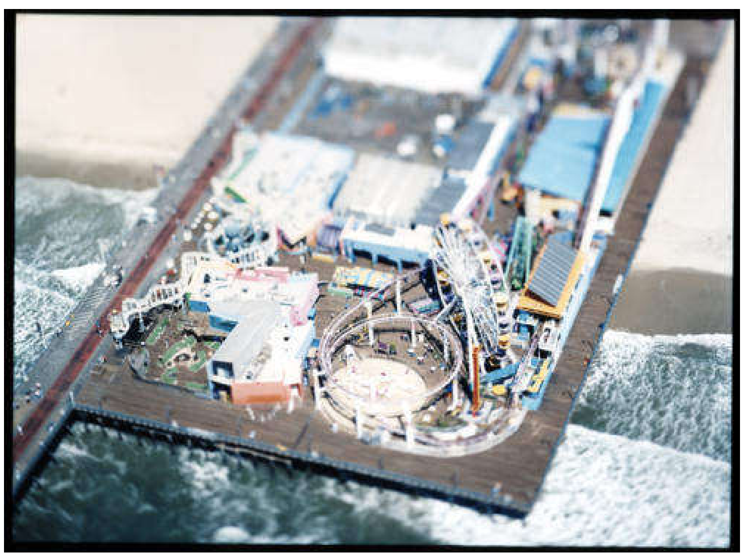


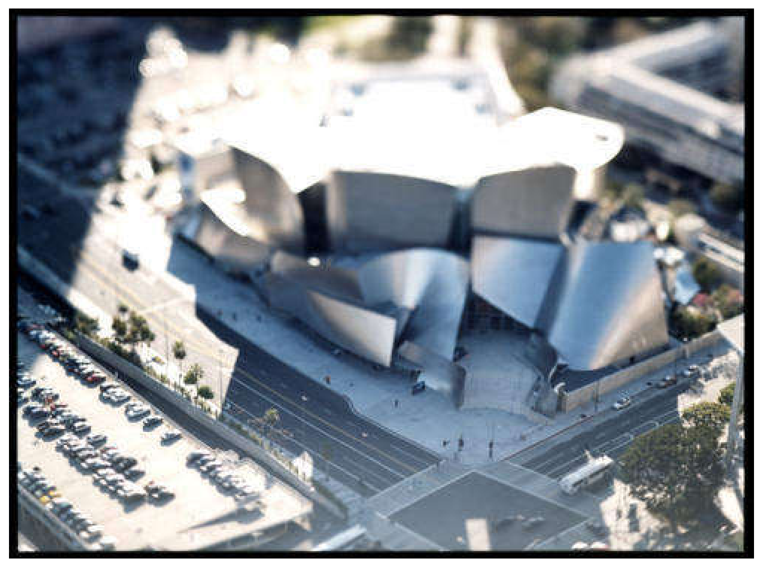


- Scheimpflug principle: plane of focus passes through the line of intersection between the lens plane and the image plane

"Fake miniatures"

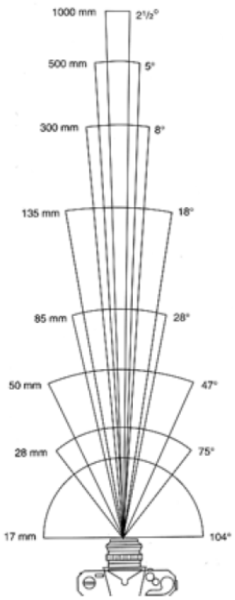






Olivo Barbieri: http://www.metropolismag.com/cda/story.php?artid=1760

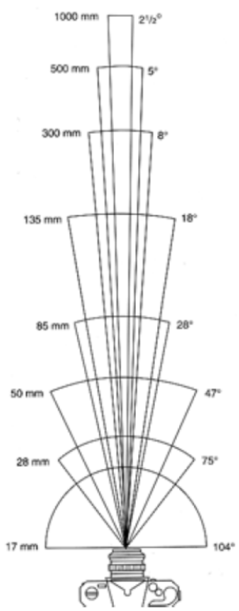
Field of View (Zoom)

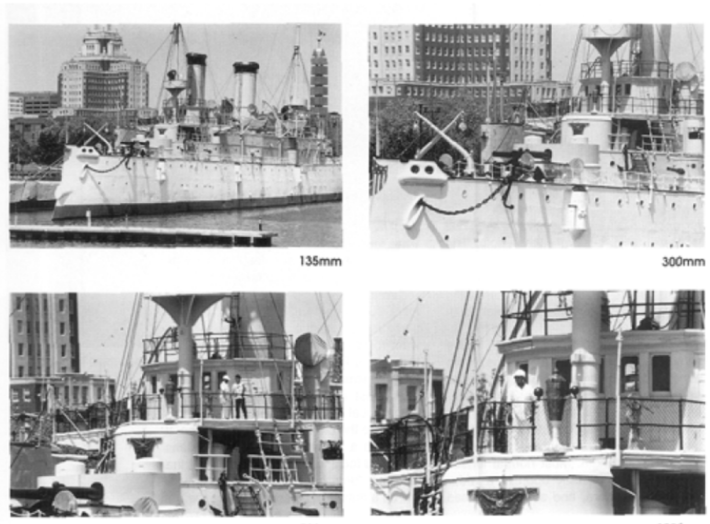


From London and Upton

Slide by A. Efros

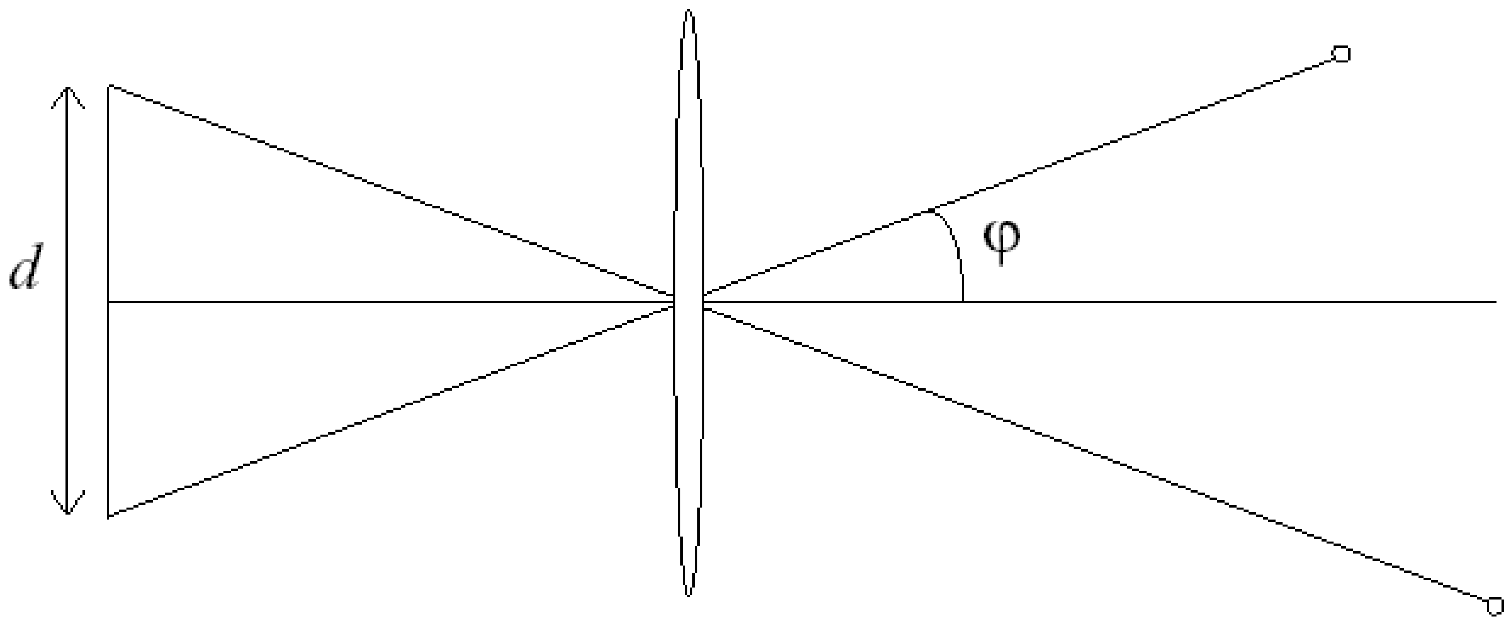
Field of View (Zoom)





From London and Upton

FOV depends of Focal Length



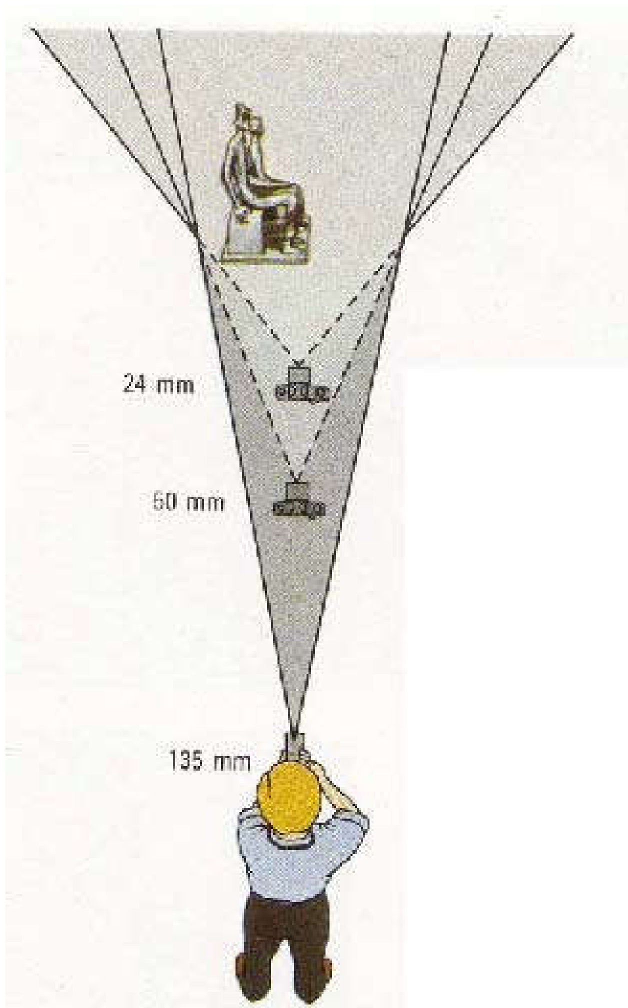
Size of field of view governed by size of the camera retina:

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

Smaller FOV = larger Focal Length

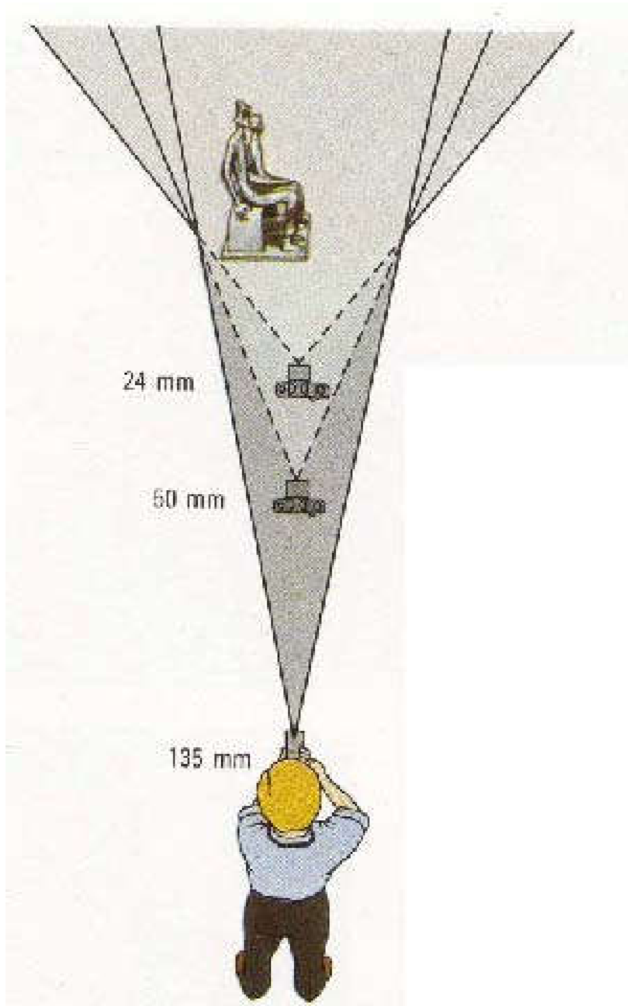
Slide by A. Efros

Field of View / Focal Length



Sources: A. Efros, F. Durand

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

Source: F. Durand

Same effect for faces

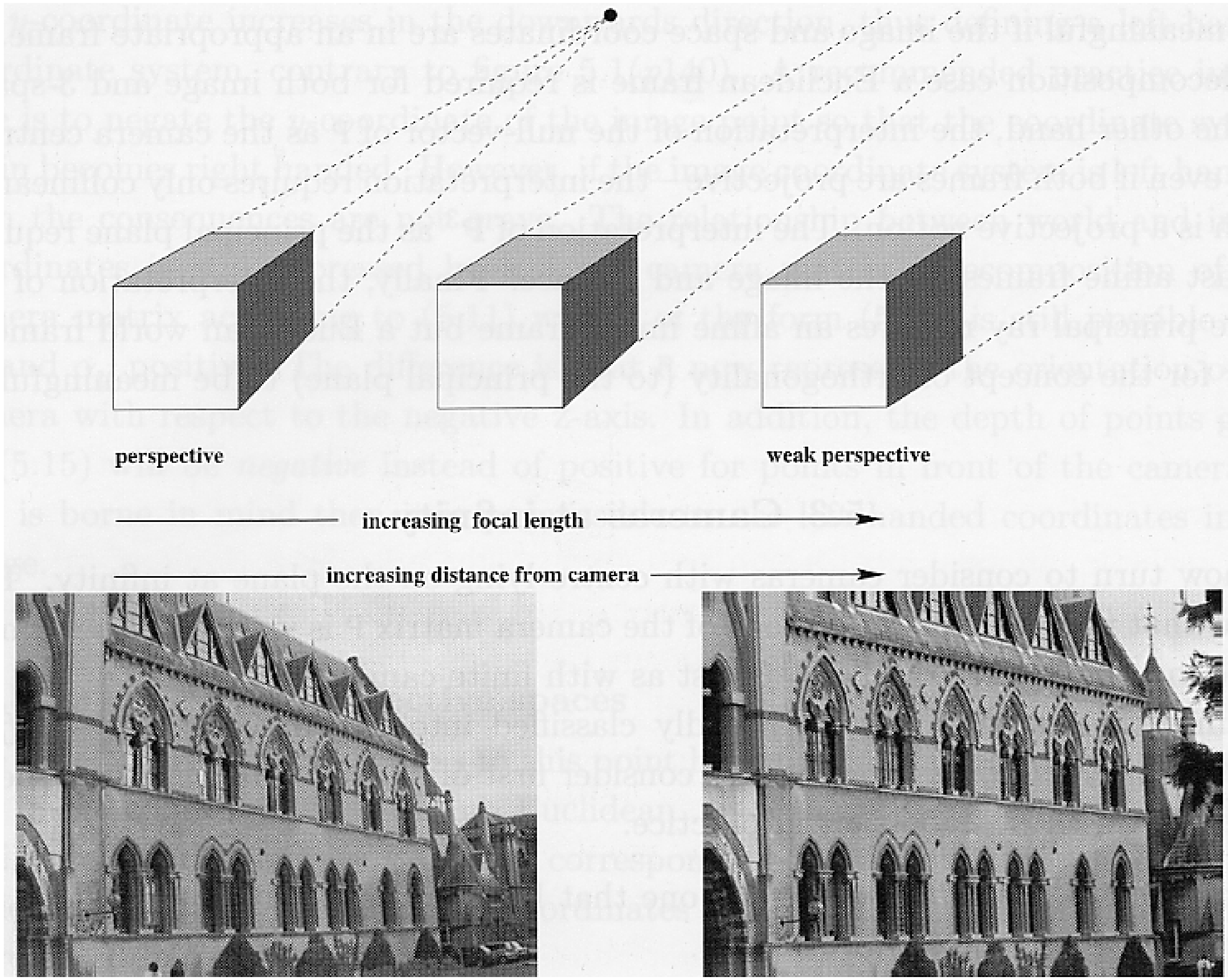

wide-angle


standard


telephoto

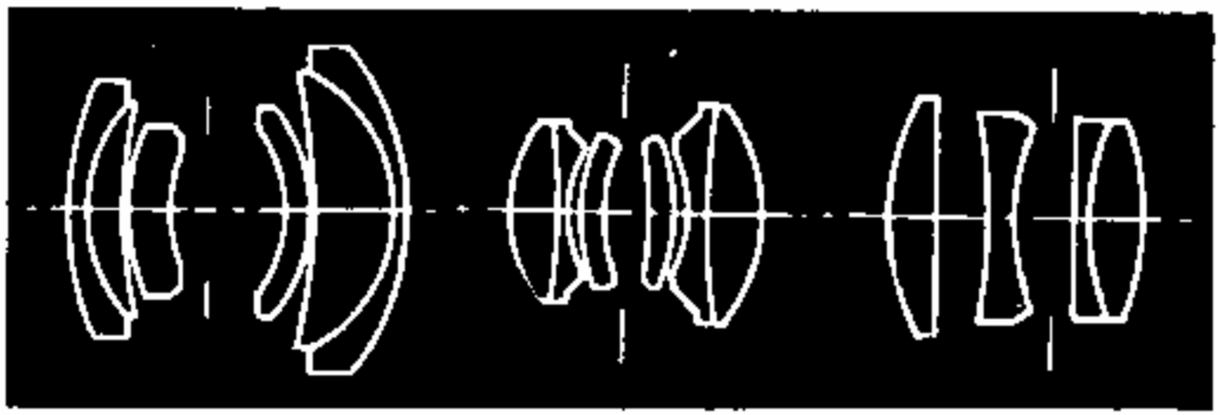
Source: F. Durand

Approximating an affine camera



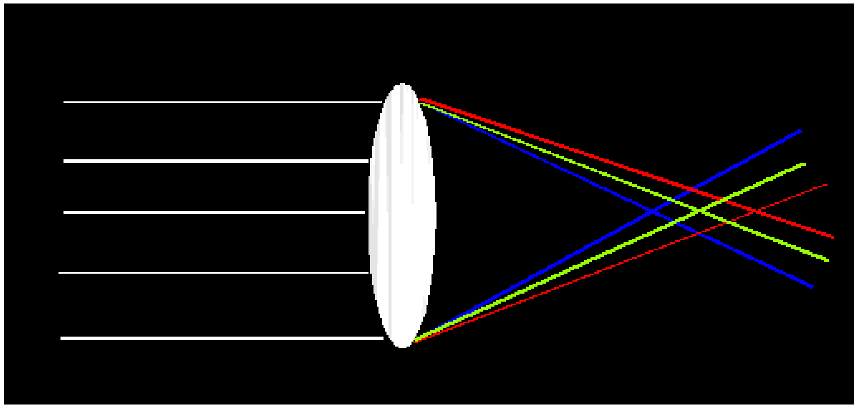
Source: Hartley & Zisserman

Real lenses



Lens Flaws: Chromatic Aberration

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



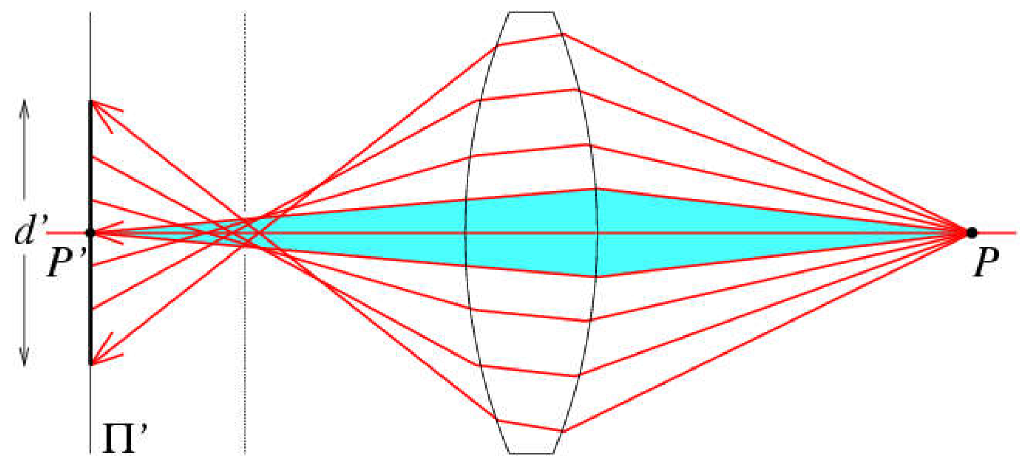
Near Lens Center

Near Lens Outer Edge

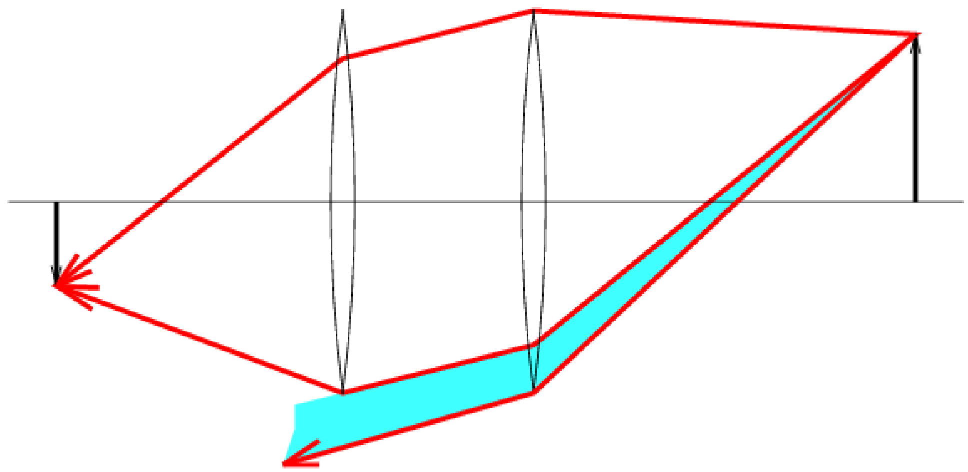
Lens flaws: Spherical aberration

Spherical lenses don't focus light perfectly

Rays farther from the optical axis focus closer

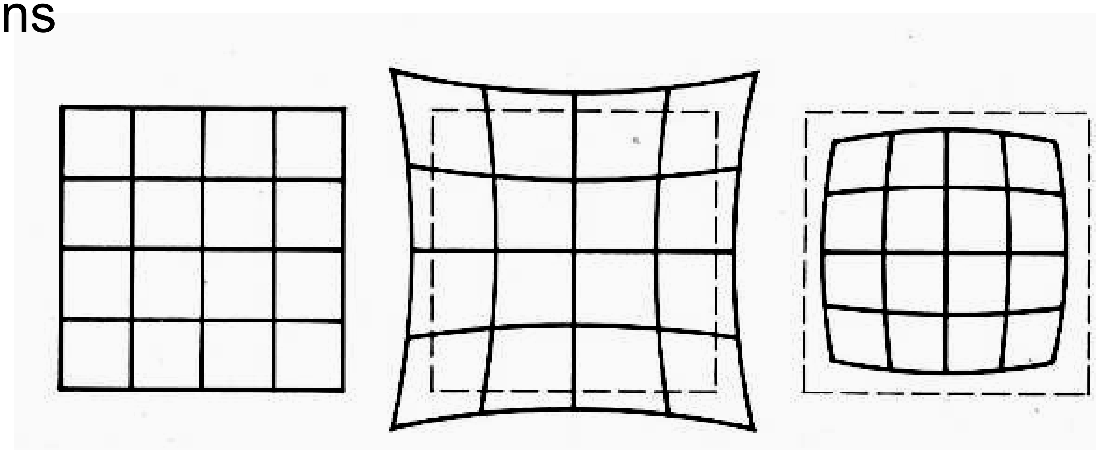


Lens flaws: Vignetting



Radial Distortion

- Caused by imperfect lenses
- Deviations are most noticeable for rays that pass through the edge of the lens



No distortion   Pin cushion   Barrel

Digital camera

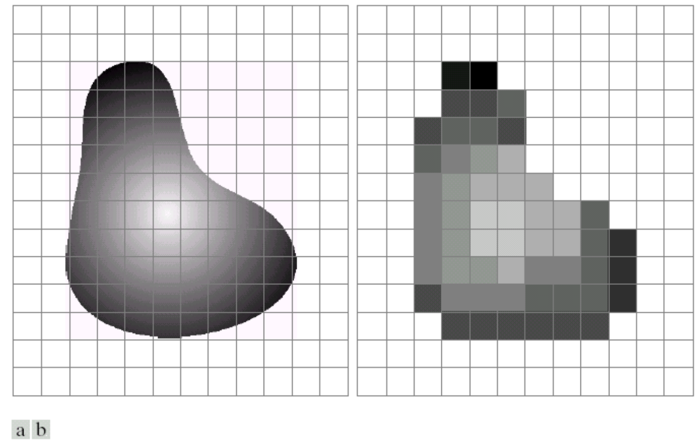


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

A digital camera replaces film with a sensor array

- Each cell in the array is light-sensitive diode that converts photons to electrons
- Two common types
  - **Charge Coupled Device** (CCD)
  - **Complementary metal oxide semiconductor** (CMOS)
- http://electronics.howstuffworks.com/digital-camera.htm

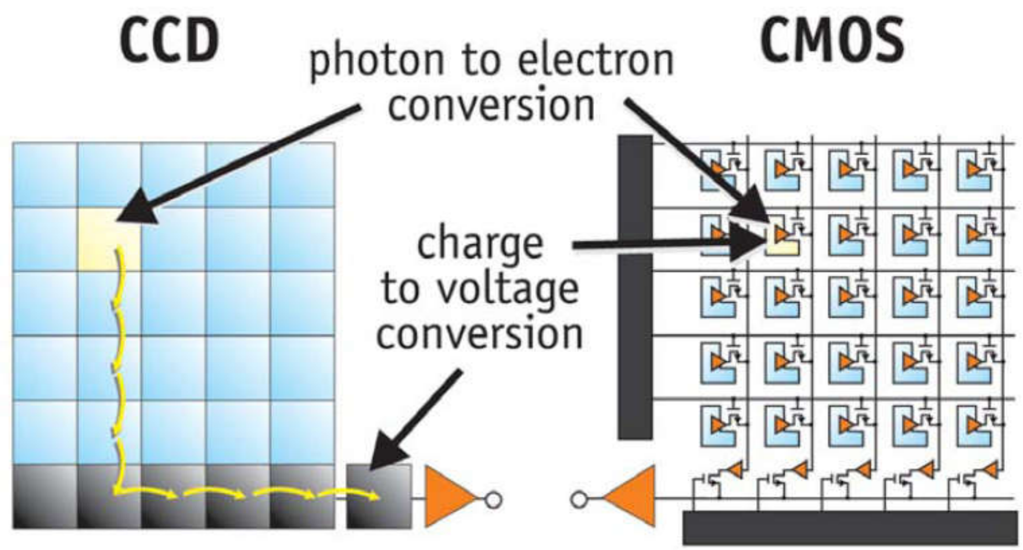
Slide by Steve Seitz

CCD vs. CMOS

CCD: transports the charge across the chip and reads it at one corner of the array. An **analog-to-digital converter (ADC)** then turns each pixel's value into a digital value by measuring the amount of charge at each photosite and converting that measurement to binary form

CMOS: uses several transistors at each pixel to amplify and move the charge using more traditional wires. The CMOS signal is digital, so it needs no ADC.

http://electronics.howstuffworks.com/digital-camera.htm



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.

http://www.dalsa.com/shared/content/pdfs/CCD_vs_CMOS_Litwiller_2005.pdf

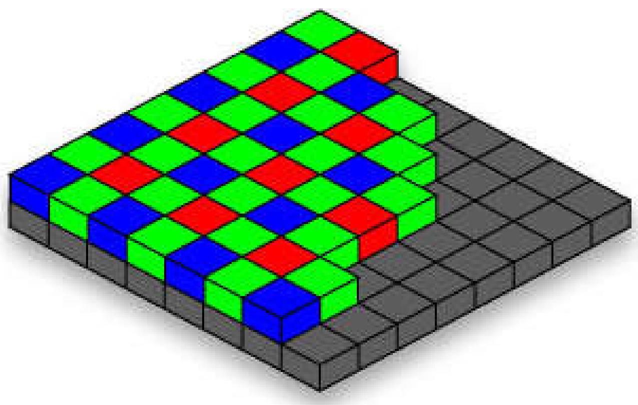
CCD vs. CMOS

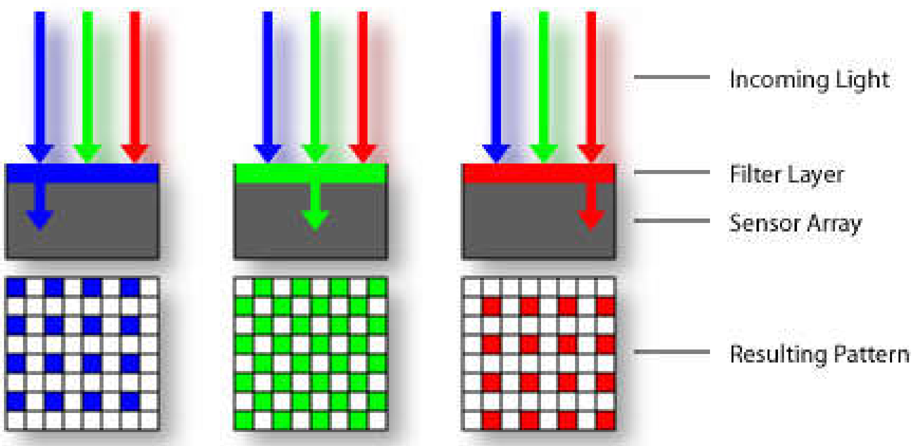
CCD	**CMOS**
Mature technology	Recent technology
High production cost	Lower production cost (but…)
High power consumption	Low power
Higher fill rate	Lower fill rate (less sensitive)
Lower noise	Higher noise
Higher resolution	Lower resolution
Blooming	Per pixel amplification
Sequential readout	Random pixel access
	Smart pixels
	On chip integration with other components

Source: M. Pollefeys

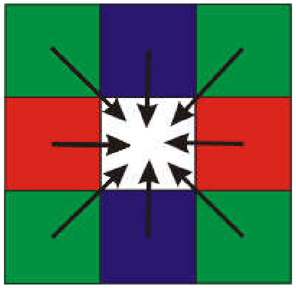
Color sensing in camera: Color filter array

Bayer grid





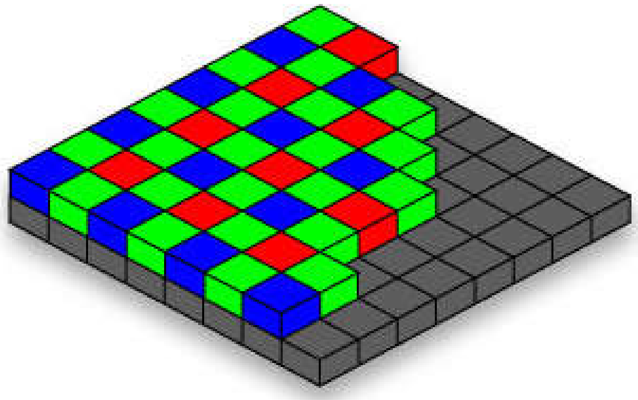
Estimate missing components from neighboring values (demosaicing)



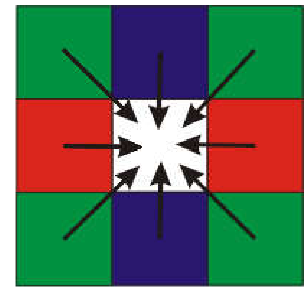
Source: Steve Seitz

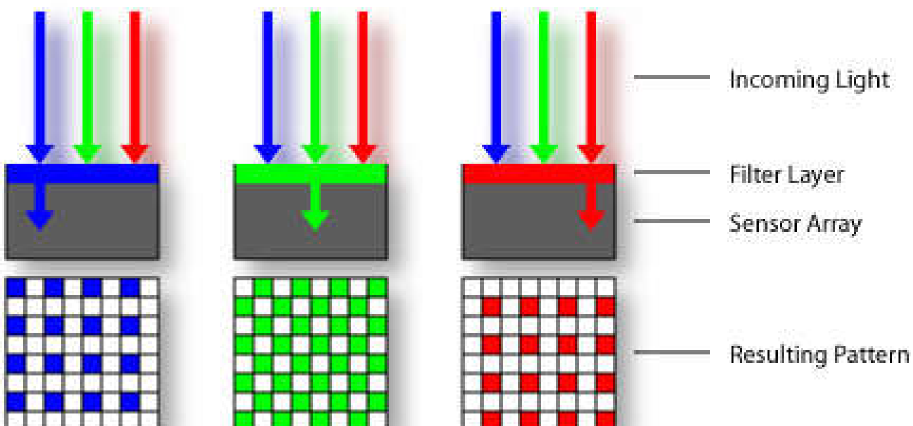
Color sensing in camera: Color filter array

Bayer grid

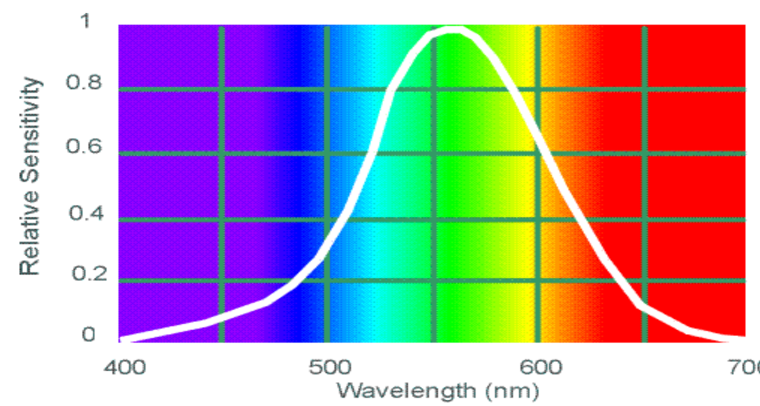


Estimate missing components from neighboring values (demosaicing)





Why more green?



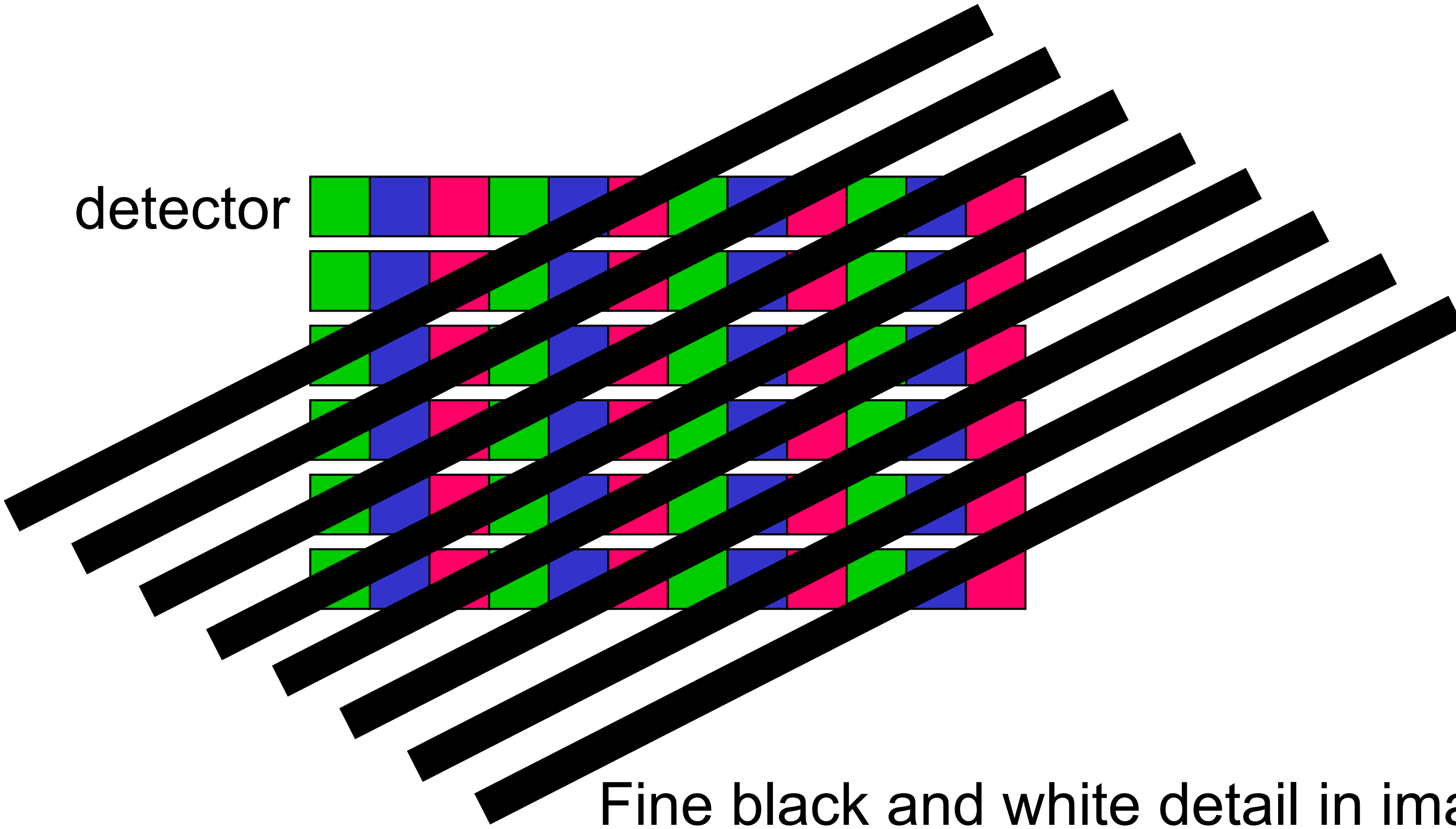
Human Luminance Sensitivity Function

Source: Steve Seitz

Problem with demosaicing: color moire

Slide by F. Durand

The cause of color moire

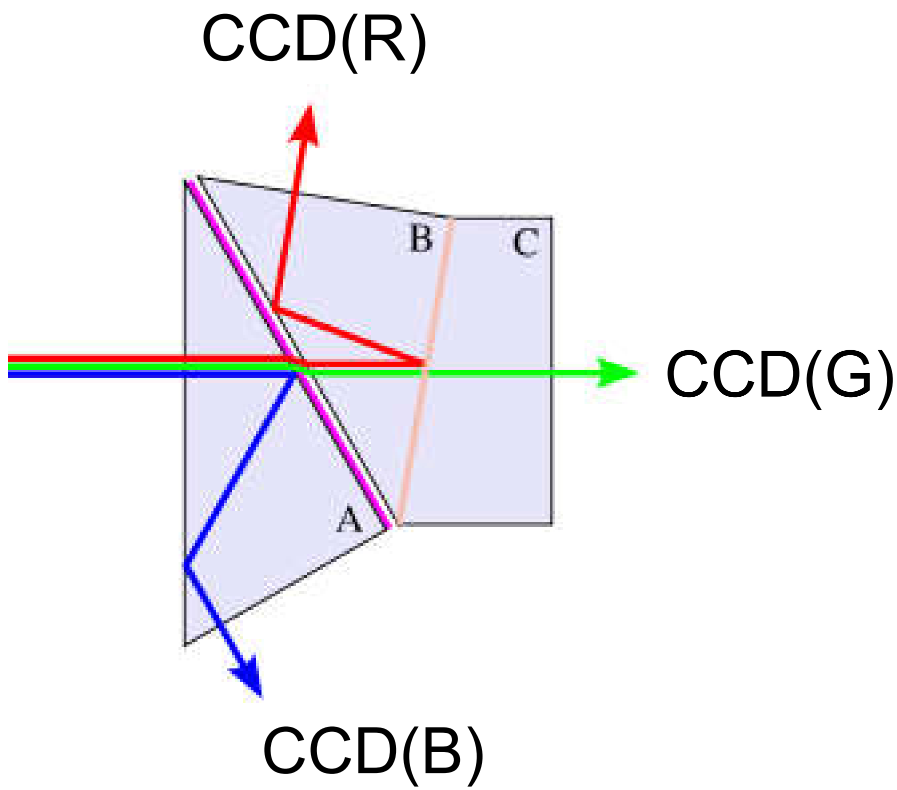


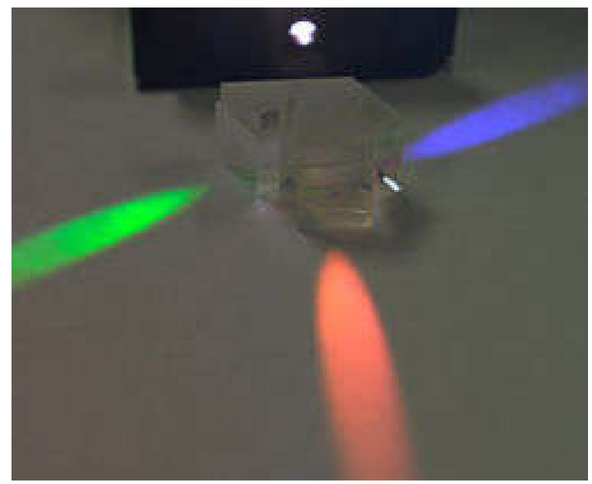
Fine black and white detail in image misinterpreted as color information

Slide by F. Durand

Color sensing in camera: Prism

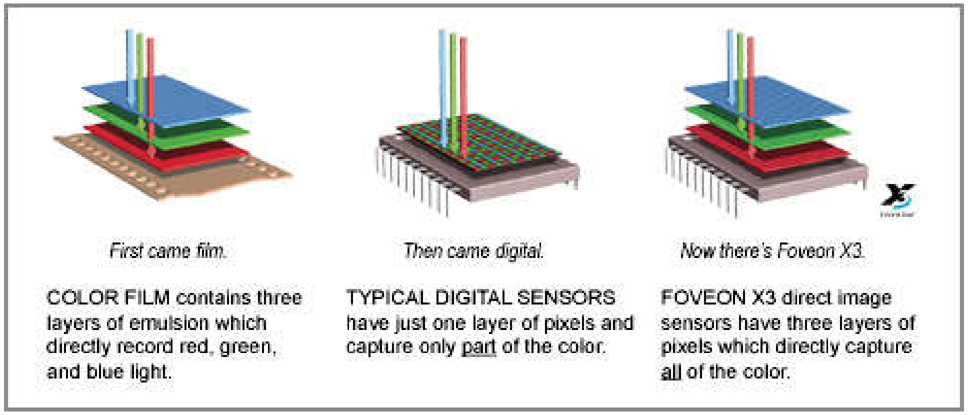
- Requires three chips and precise alignment
- More expensive

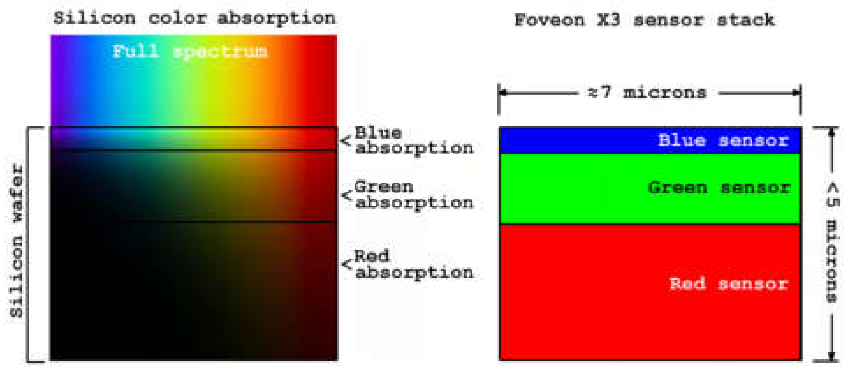




Color sensing in camera: Foveon X3

- CMOS sensor
- Takes advantage of the fact that red, blue and green light penetrate silicon to different depths

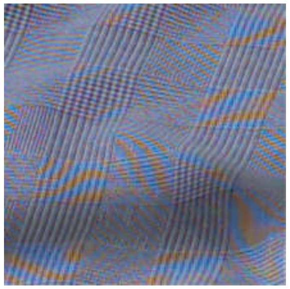


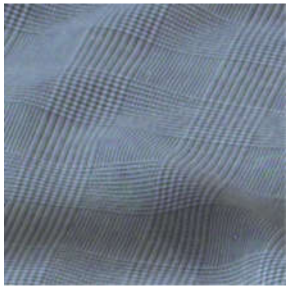


http://www.foveon.com/article.php?a=67

http://en.wikipedia.org/wiki/Foveon_X3_sensor

better image quality



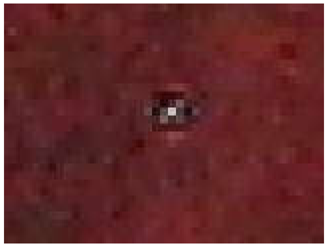


Source: M. Pollefeys

Issues with digital cameras

Noise

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

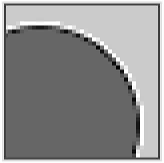


Resolution: Are more megapixels better?

- requires higher quality lens
- noise issues

In-camera processing

- oversharpening can produce halos



RAW vs. compressed

- file size vs. quality tradeoff

Blooming

- charge overflowing into neighboring pixels

Color artifacts

- purple fringing from microlenses, artifacts from Bayer patterns
- white balance

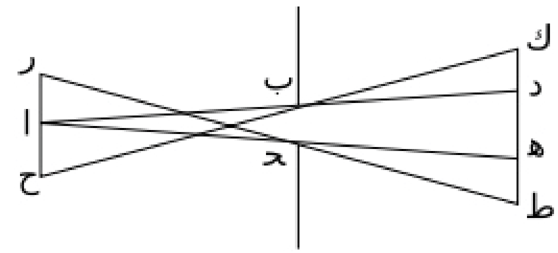
More info online:

- http://electronics.howstuffworks.com/digital-camera.htm
- http://www.dpreview.com/

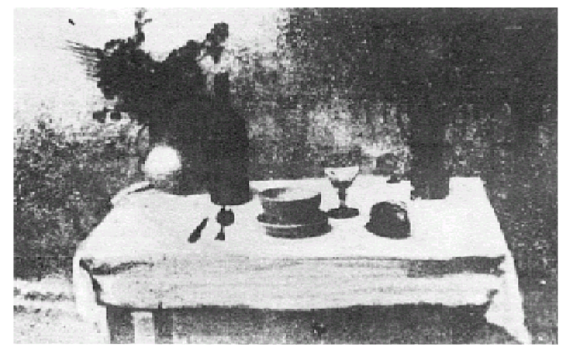
Slide by Steve Seitz

Historical context

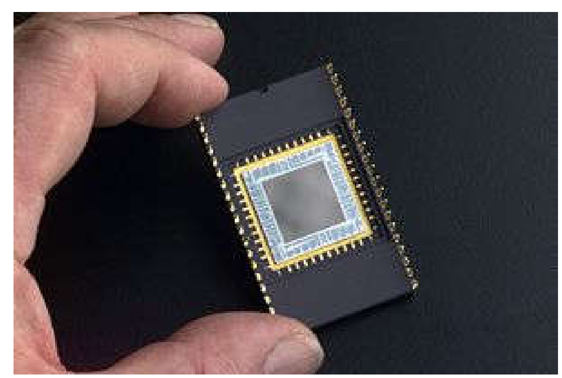
- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic 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)



Alhacen's notes



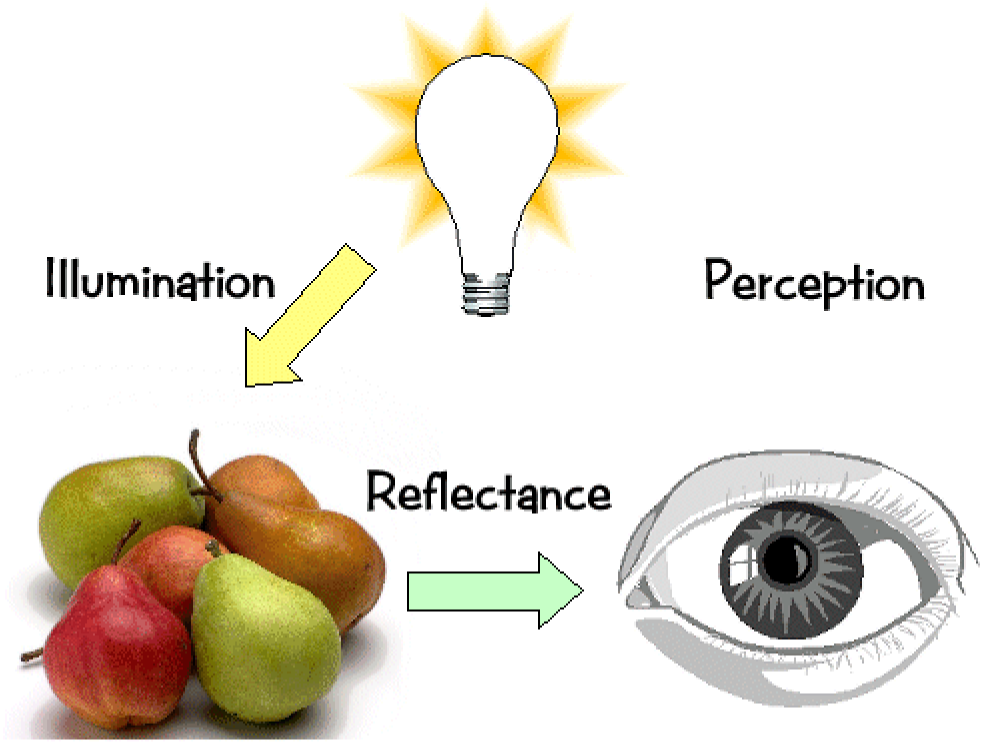
Niepce, "La Table Servie," 1822



CCD chip

Next time

Light and color



Slide by Steve Seitz