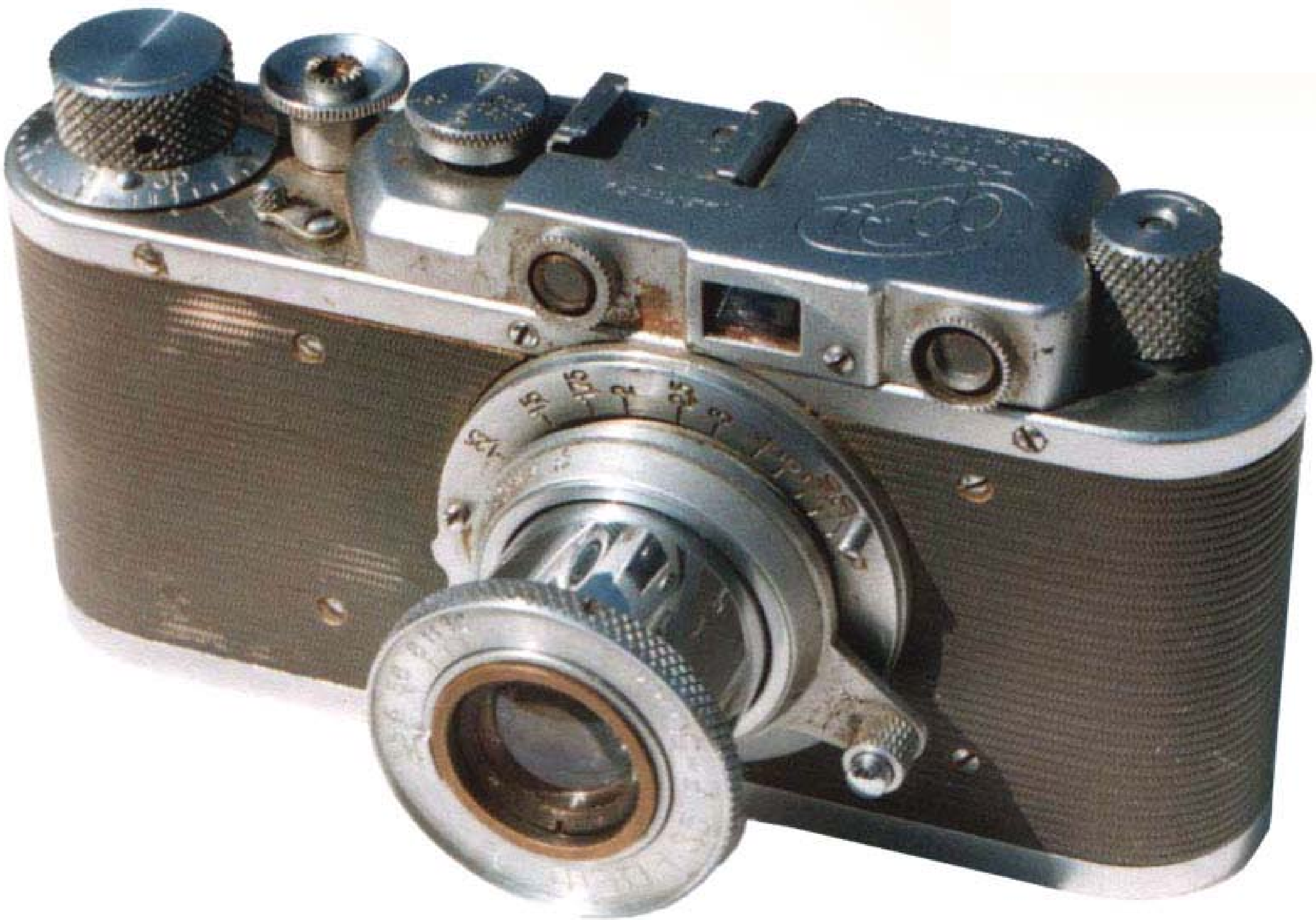
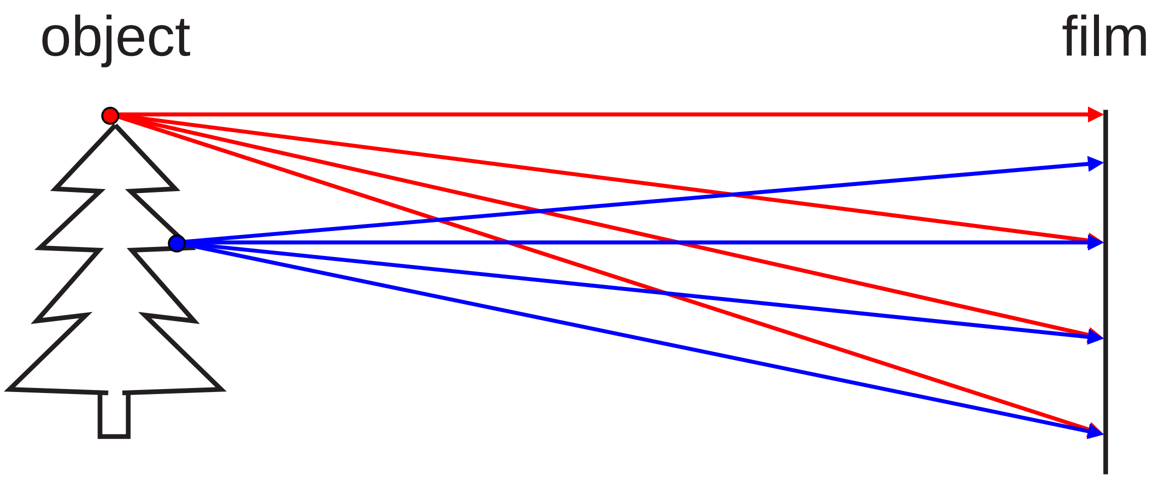
Today: The Camera



Overview

- The pinhole projection model
  - Qualitative properties
  - Perspective projection matrix
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Types of sensors
  - Color

How do we see the world?

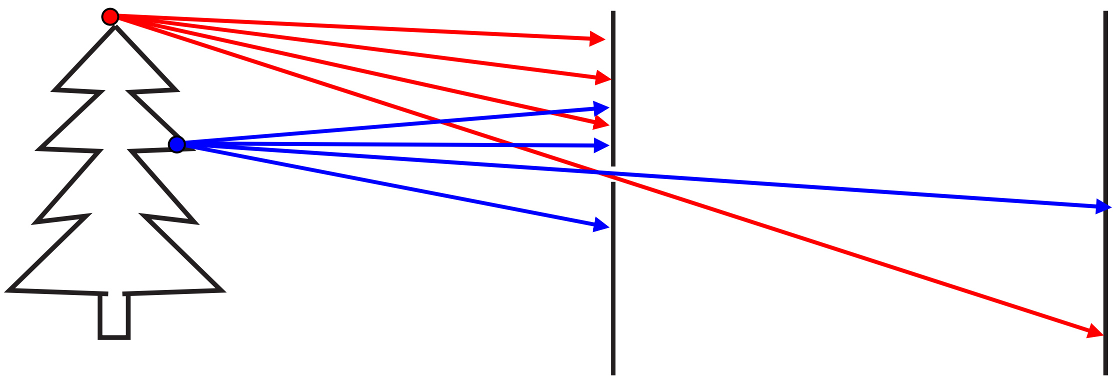


Let’s design a camera

- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?

Slide by Steve Seitz

Pinhole camera

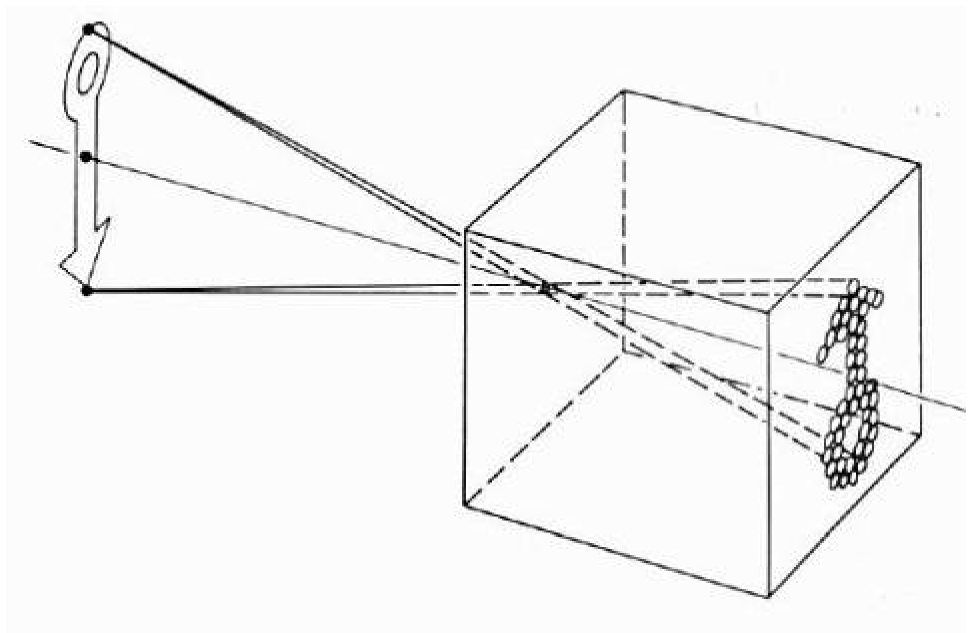


Add a barrier to block off most of the rays

- This reduces blurring
- The opening known as the **aperture**

Slide by Steve Seitz

Pinhole camera model



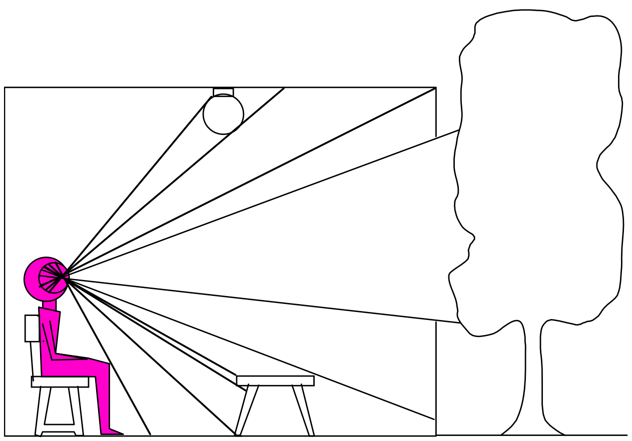
Pinhole model:

- Captures **pencil of rays** – all rays through a single point
- The point is called **Center of Projection (focal point)**
- The image is formed on the **Image Plane**

Slide by Steve Seitz

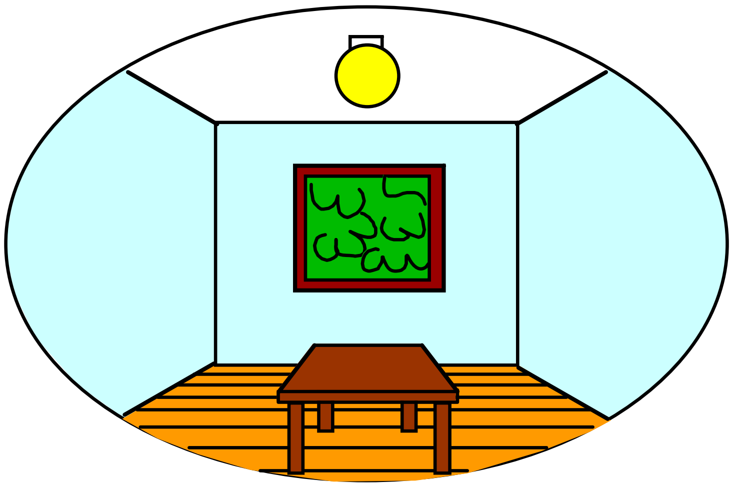
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

2D image



What have we lost?

- Angles
- Distances (lengths)

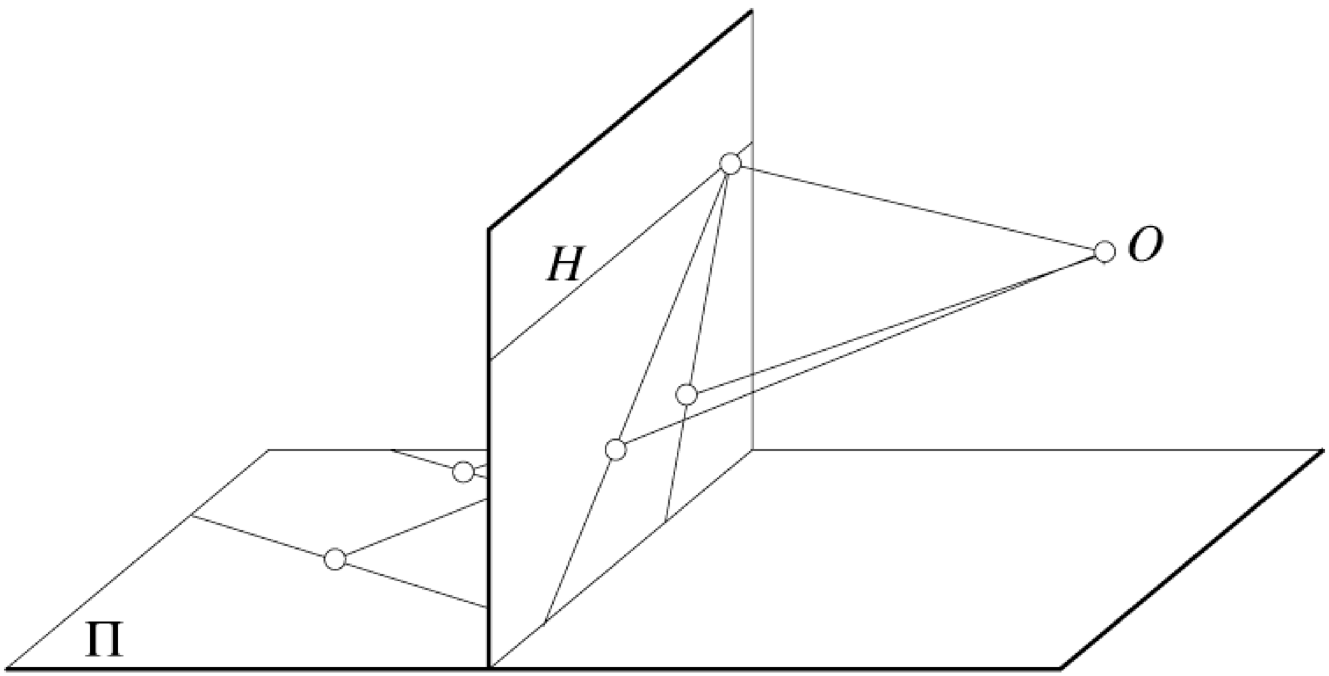
Slide by A. Efros

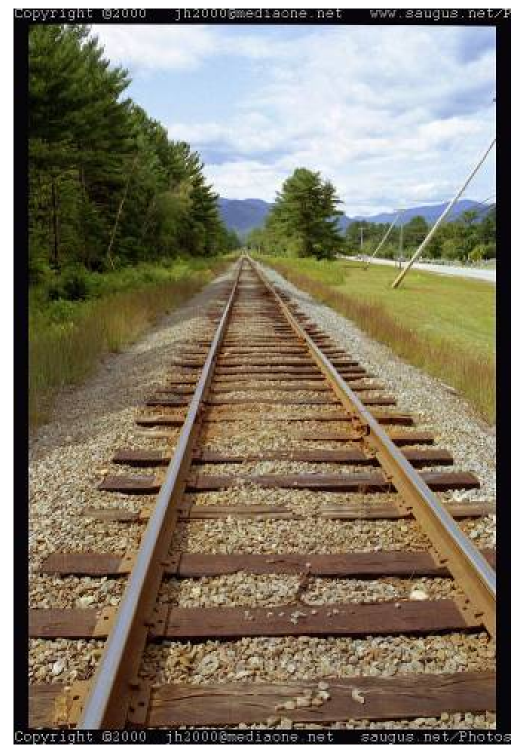
Projection properties

- Many-to-one: any points along same ray map to same point in image
- Points → points
  - But projection of points on focal plane is undefined
- Lines → lines (collinearity is preserved)
  - But line through focal point projects to a point
- Planes → planes (or half-planes)
  - But plane through focal point projects to line

Projection properties

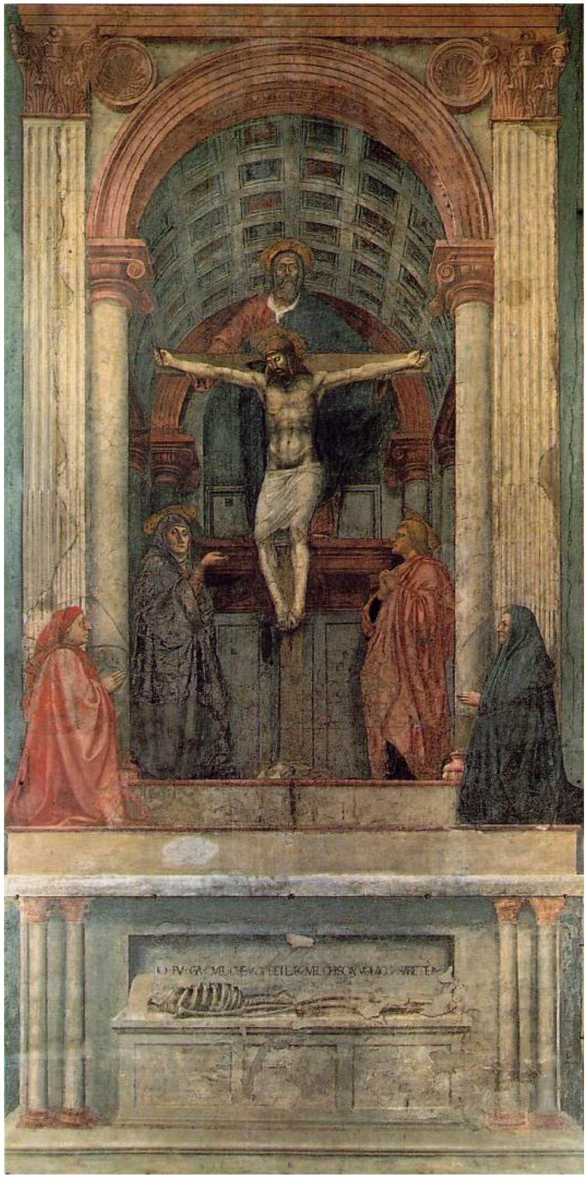
- Parallel lines converge at a vanishing point
  - Each direction in space has its own vanishing point
  - But parallels parallel to the image plane remain parallel
  - All directions in the same plane have vanishing points on the same line

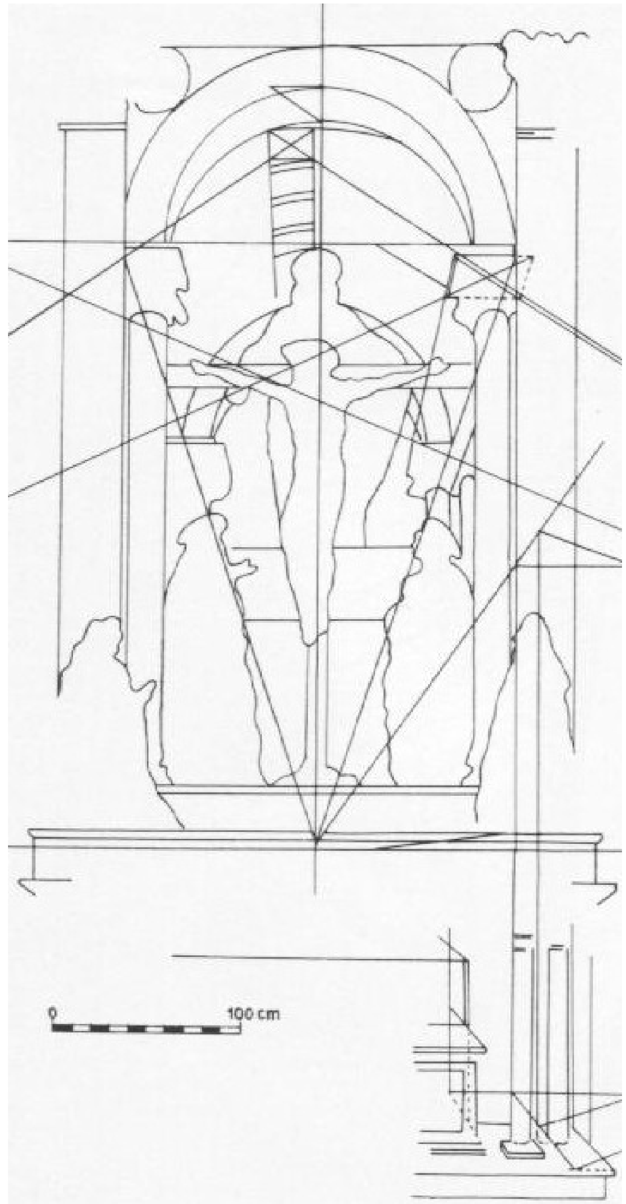




How do we construct the vanishing point/line?

One-point perspective



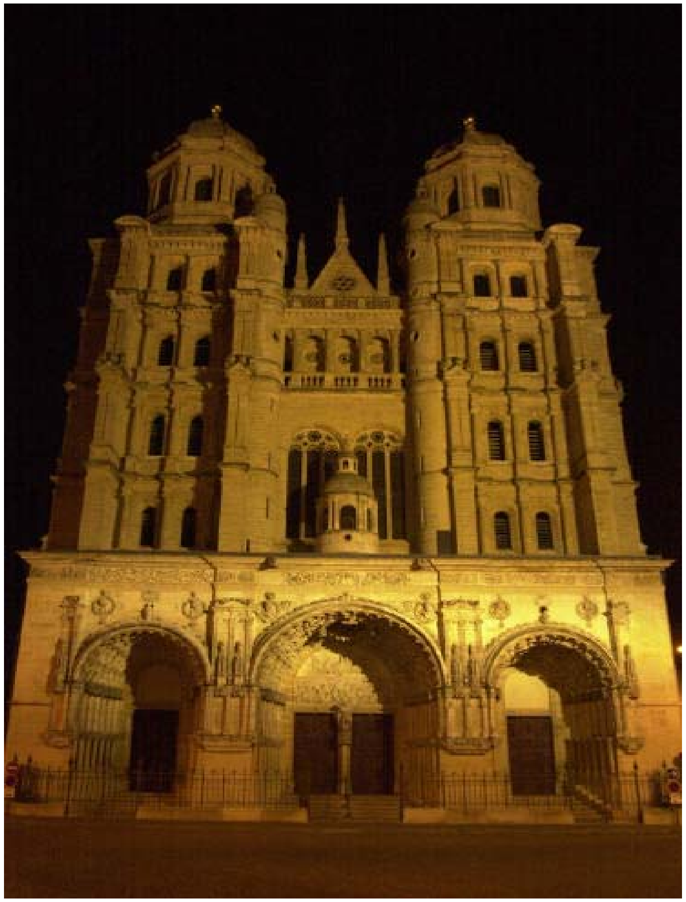


Masaccio, *Trinity*, Santa Maria Novella, Florence, 1425-28

First consistent use of perspective in Western art?

Perspective distortion

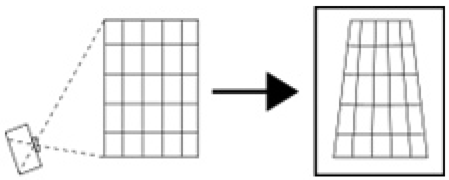
- Problem for architectural photography: converging verticals



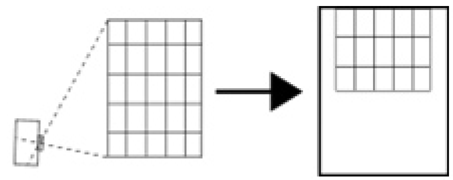
Source: F. Durand

Perspective distortion

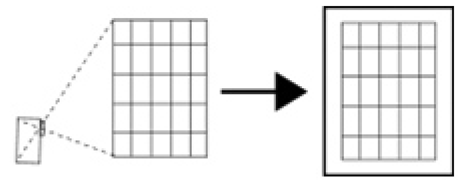
- Problem for architectural photography: converging verticals



Tilting the camera upwards results in converging verticals

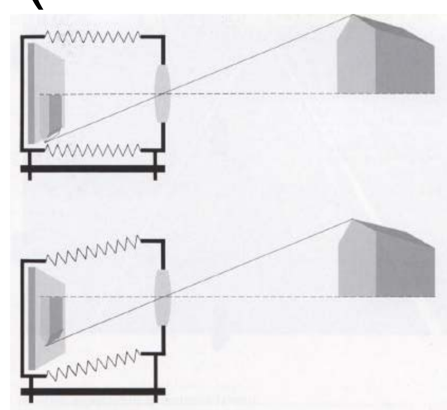


Keeping the camera level, with an ordinary lens, captures only the bottom portion of the building



Shifting the lens upwards results in a picture of the entire subject

- Solution: view camera (lens shifted w.r.t. film)



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

Source: F. Durand

Perspective distortion

- Problem for architectural photography: converging verticals
- Result:

Source: F. Durand

Perspective distortion

- However, converging verticals work quite well for horror movies…

Perspective distortion

- What does a sphere project to?

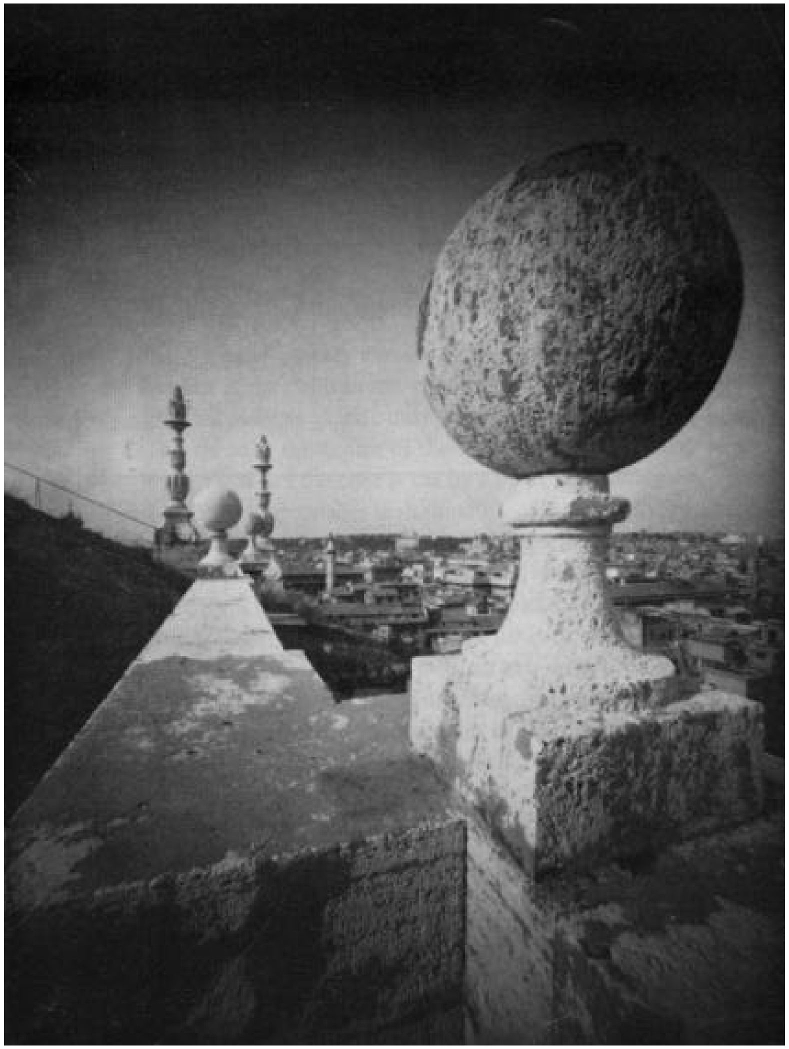
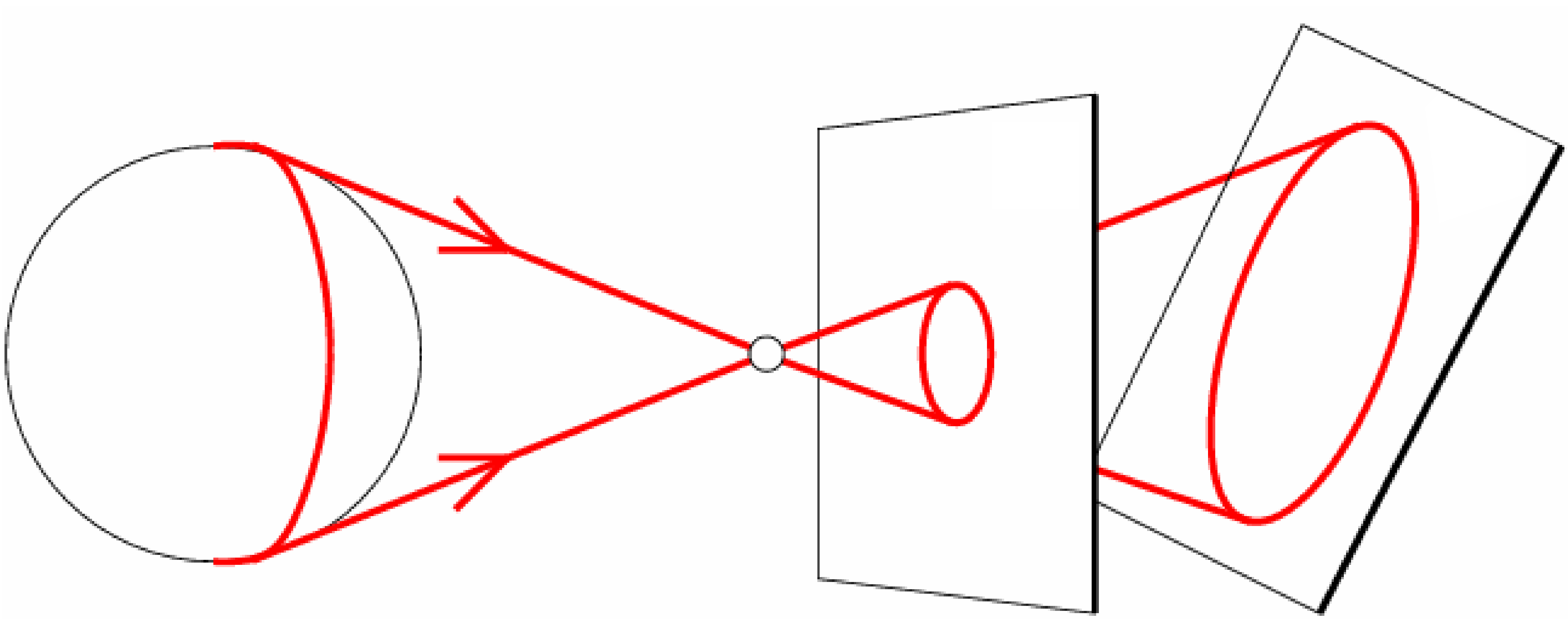


Image source: F. Durand

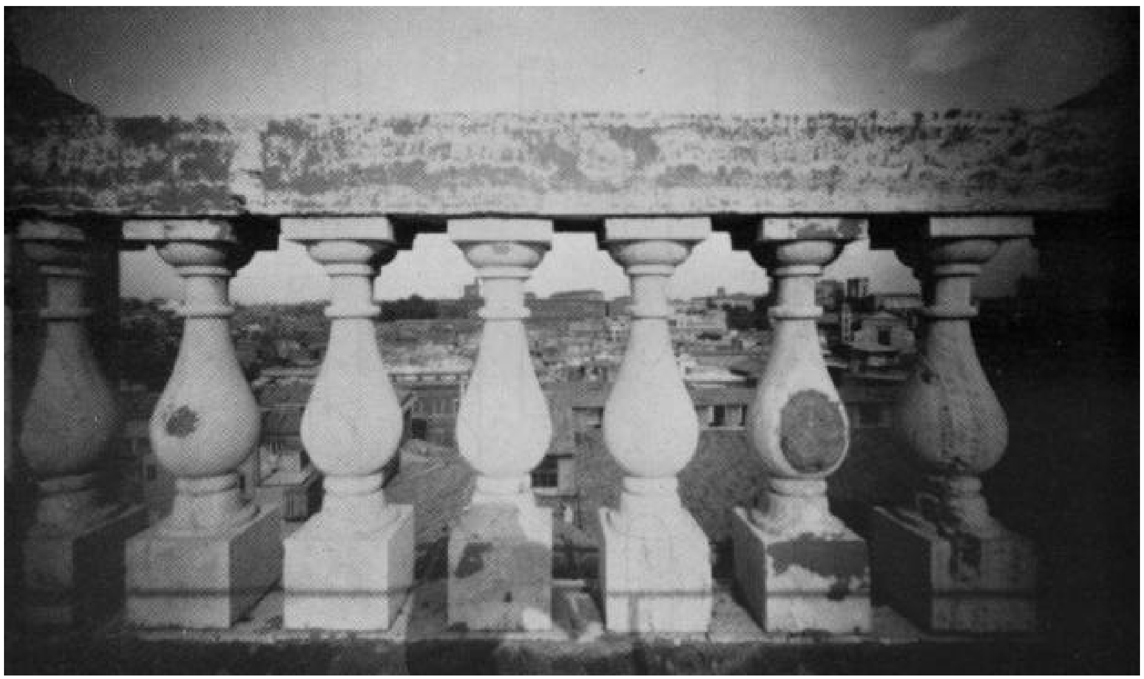
Perspective distortion

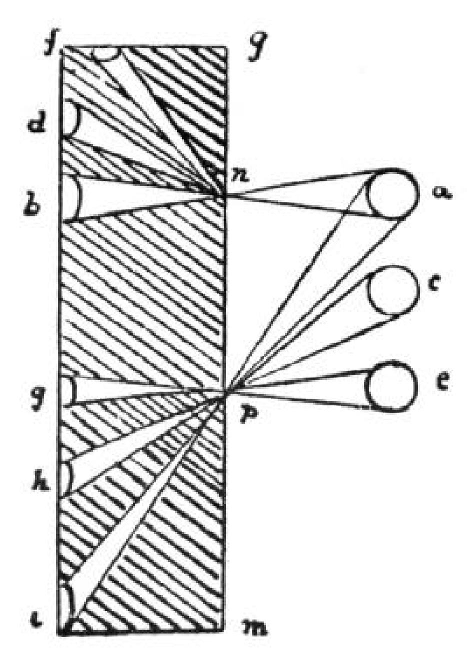
- What does a sphere project to?



Perspective distortion

- The exterior columns appear bigger
- The distortion is not due to lens flaws
- Problem pointed out by Da Vinci

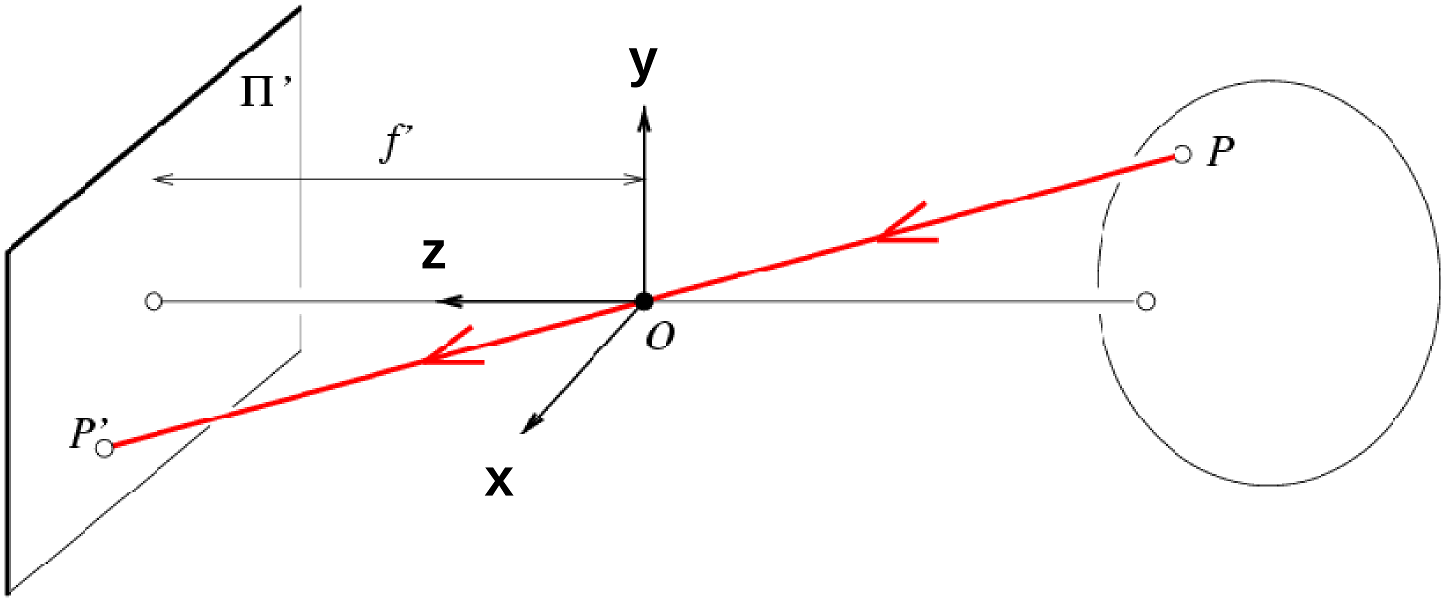




Slide by F. Durand

Perspective distortion: People

Modeling projection

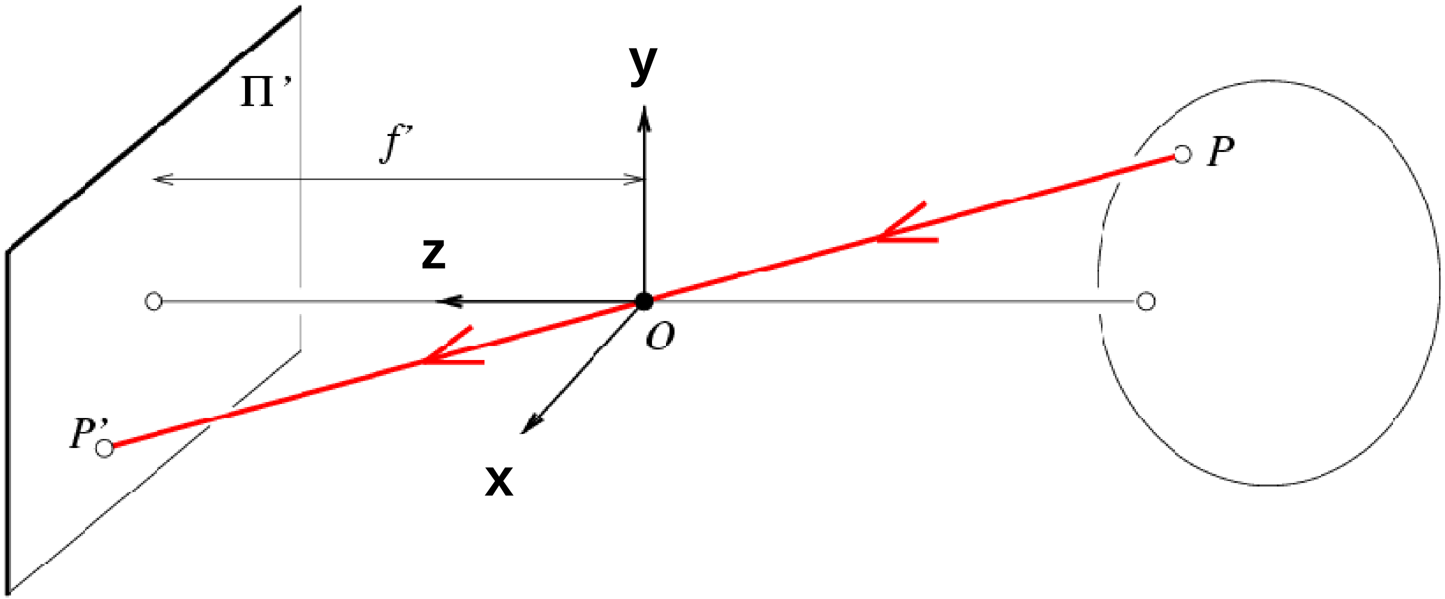


The coordinate system

- 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

Homogeneous coordinates

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

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

Perspective Projection Matrix

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

divide by the third coordinate

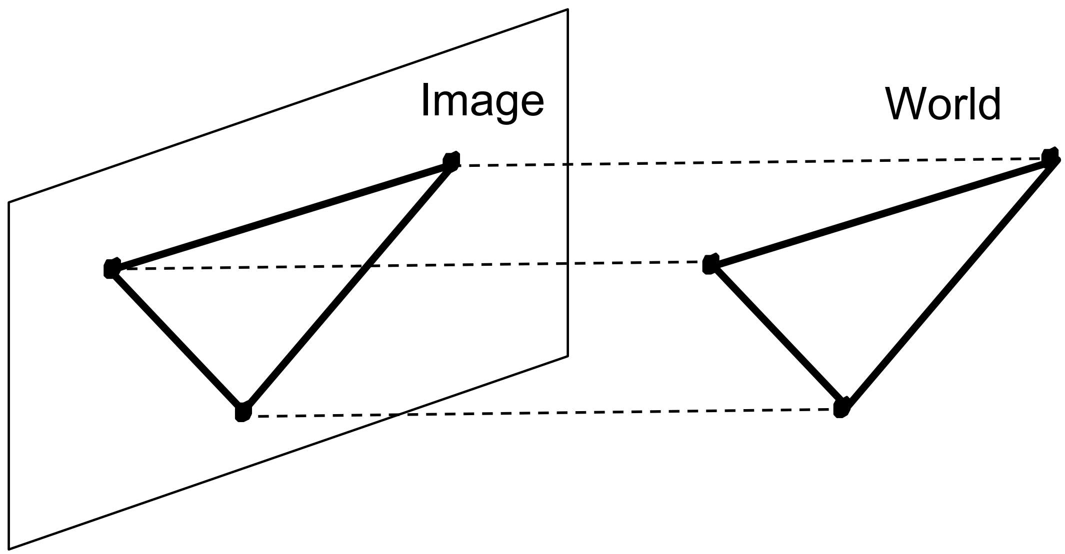
In practice: lots of coordinate transformations…

(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



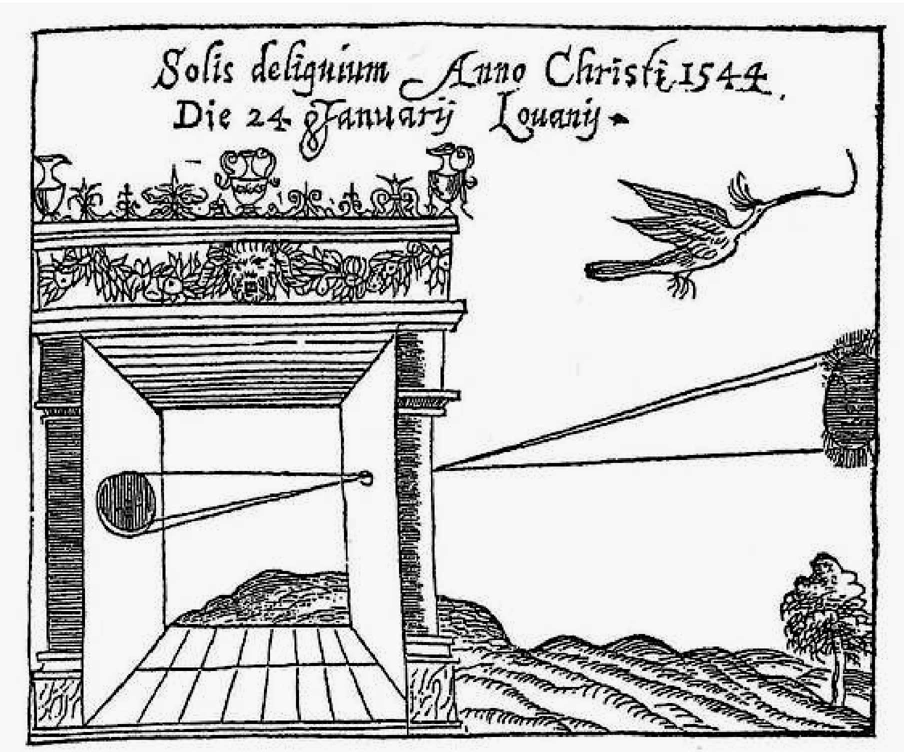
- Also called "parallel projection"
- What's the projection matrix?

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

Slide by Steve Seitz

Building a real camera

Camera Obscura

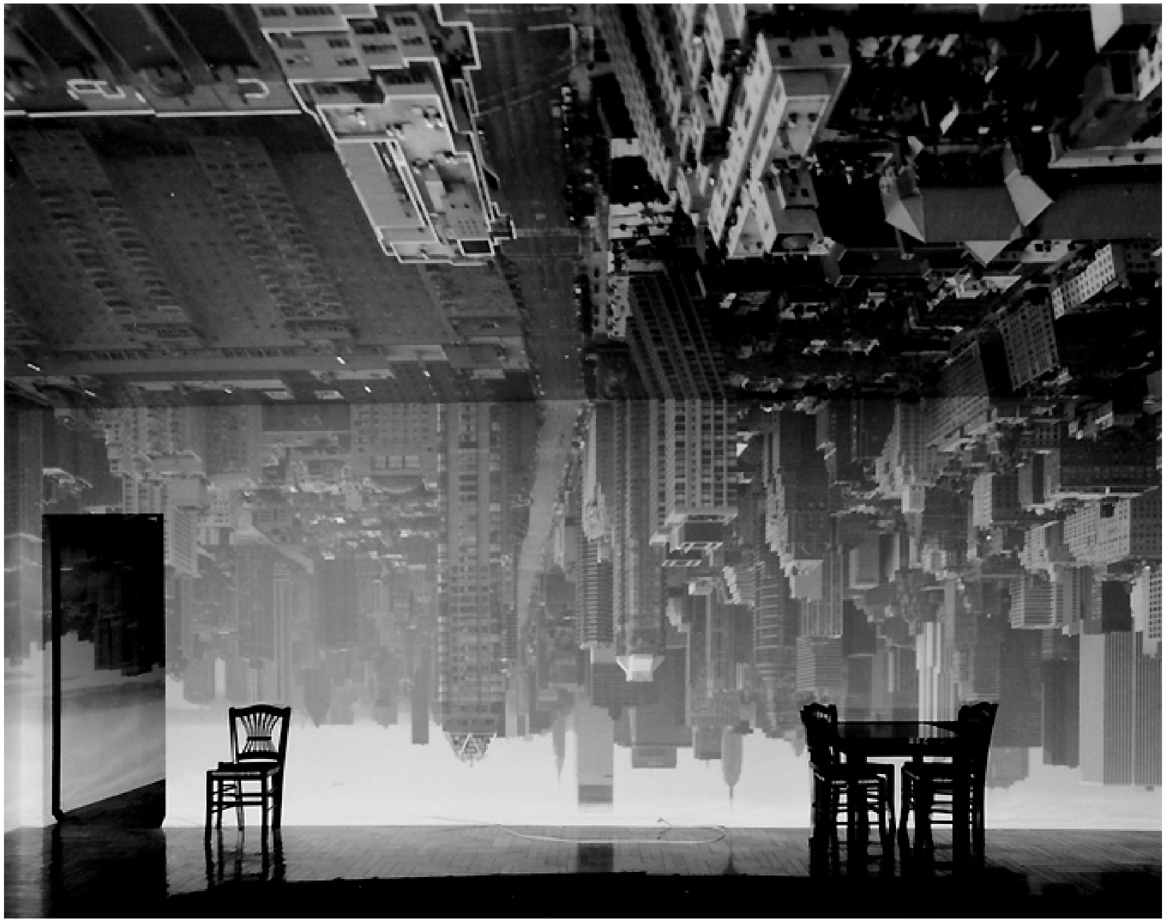


Gemma Frisius, 1558

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

Source: A. Efros

Abelardo Morell



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

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

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

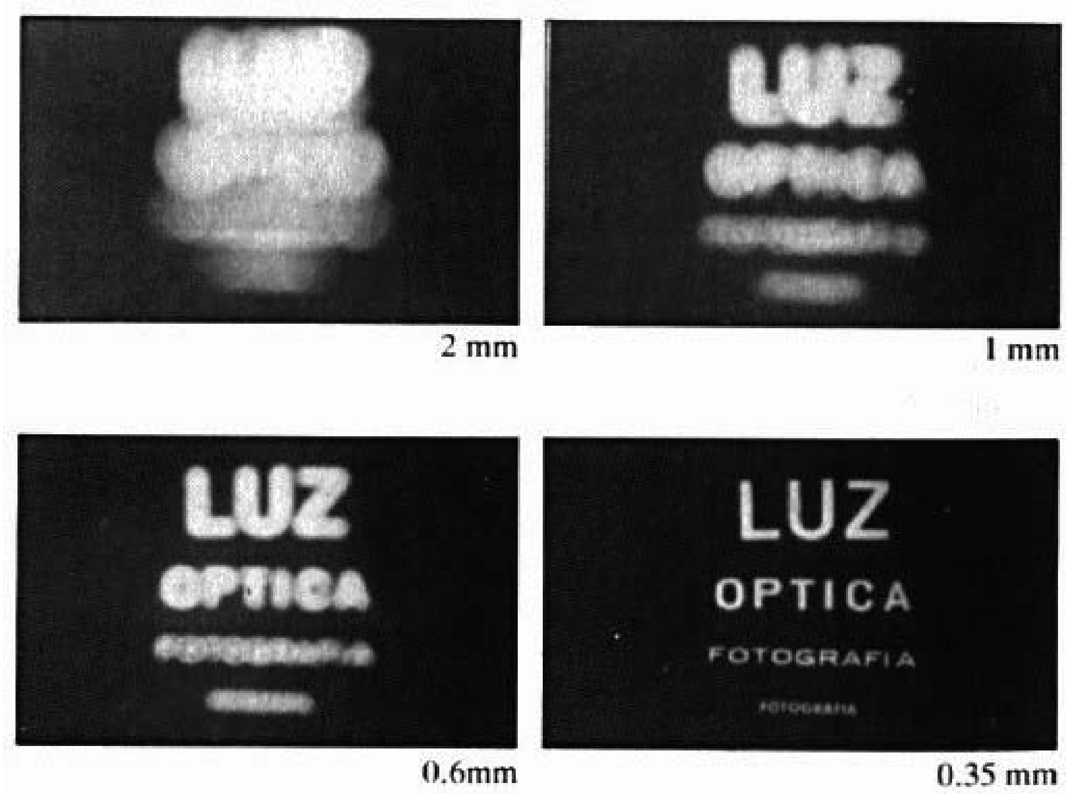
Home-made pinhole camera

Why so blurry?

Slide by A. Efros

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

Shrinking the aperture

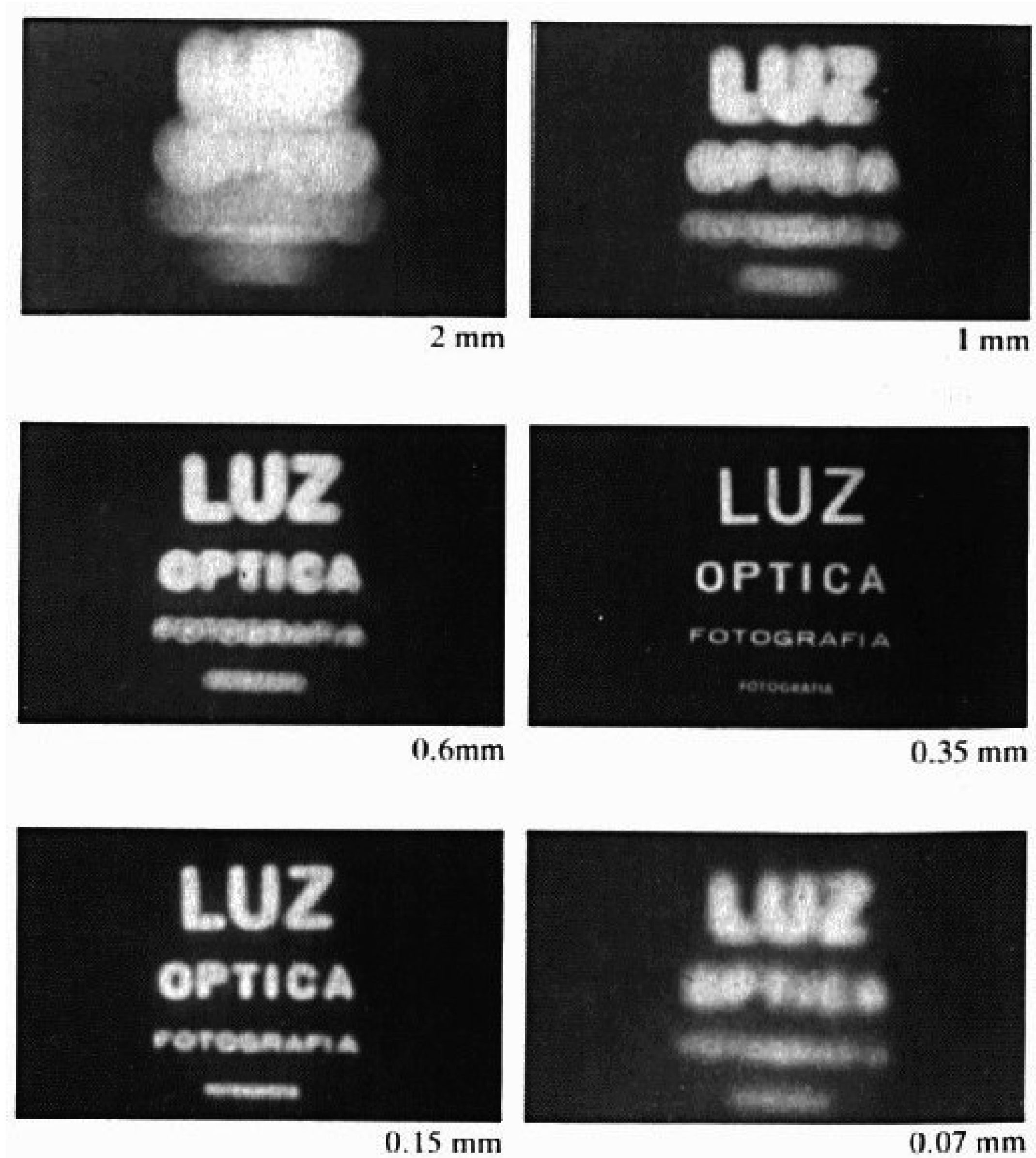


Why not make the aperture as small as possible?

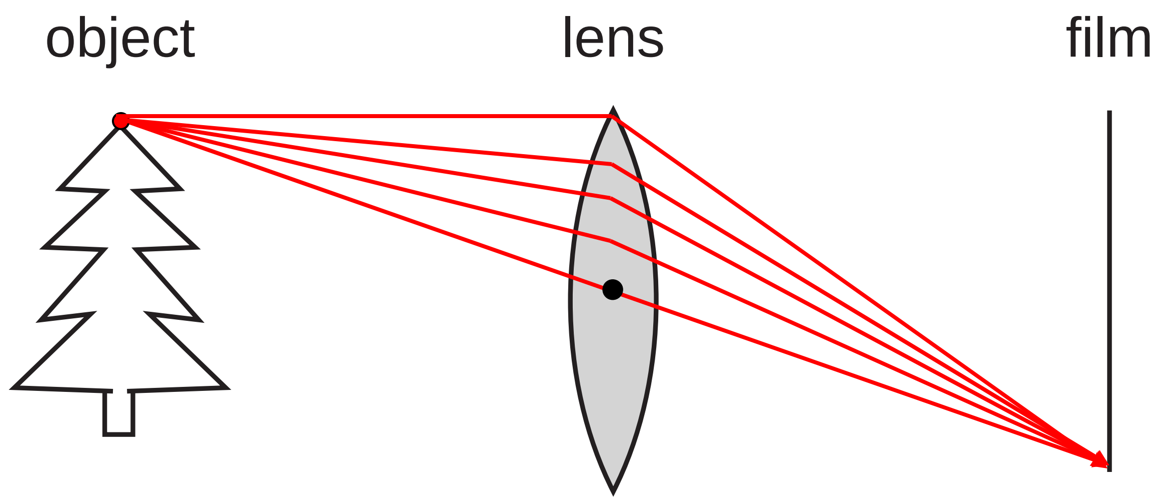
- Less light gets through
- Diffraction effects…

Slide by Steve Seitz

Shrinking the aperture



Adding a lens

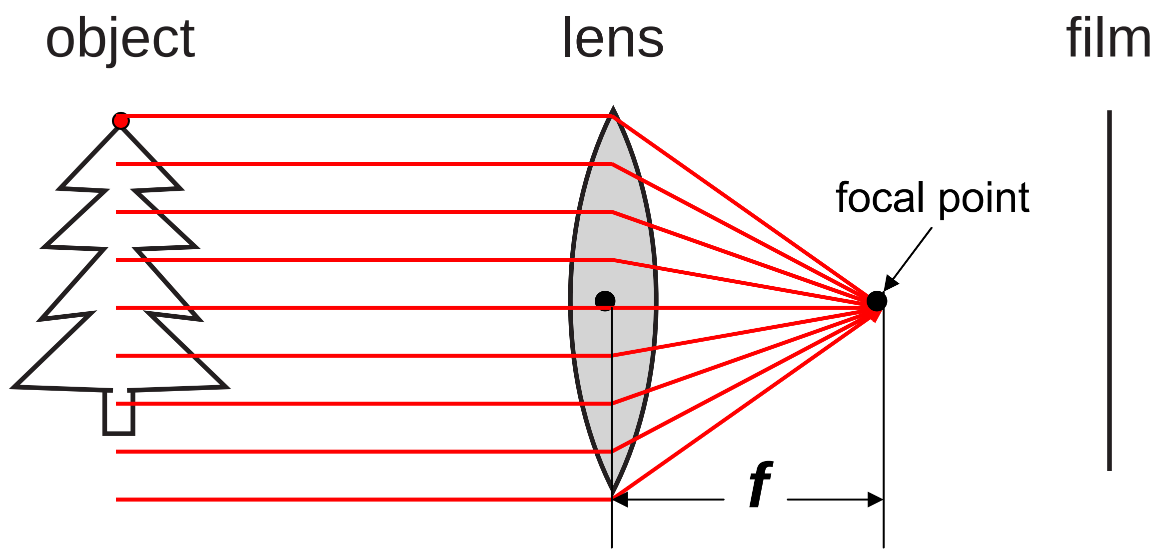


A lens focuses light onto the film

- Rays passing through the center are not deviated

Slide by Steve Seitz

Adding a lens

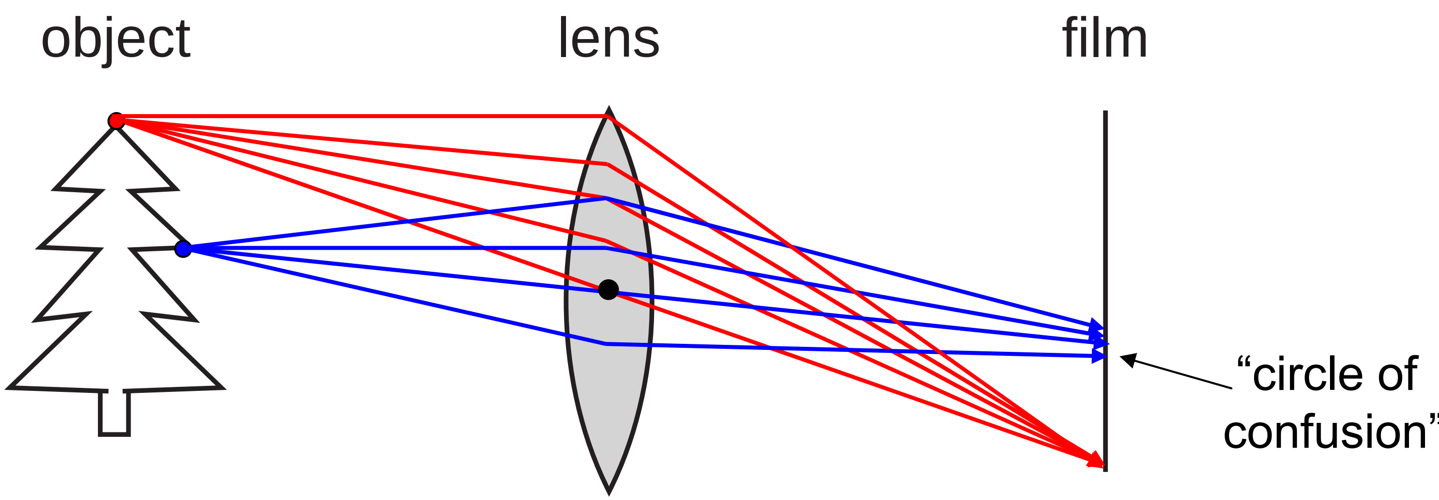


A lens focuses light onto the film

- 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

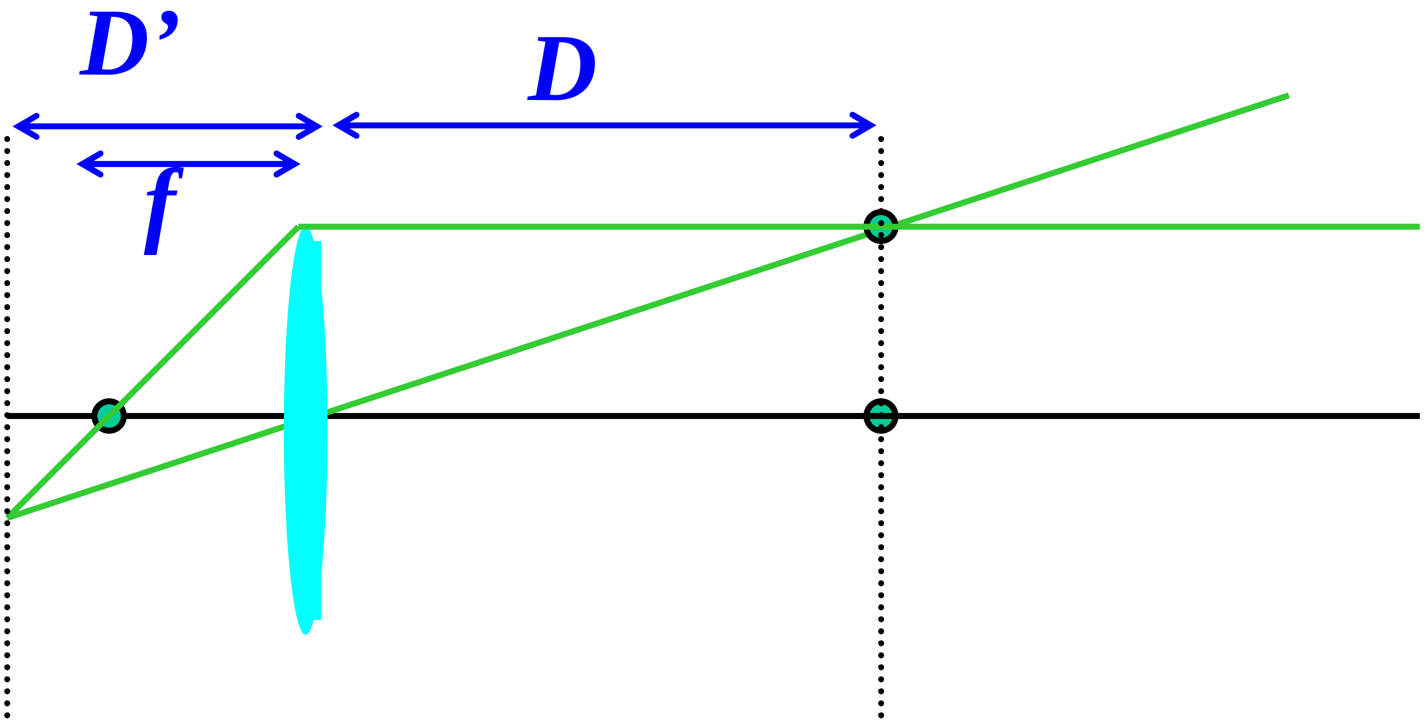


A lens focuses light onto the film

- 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

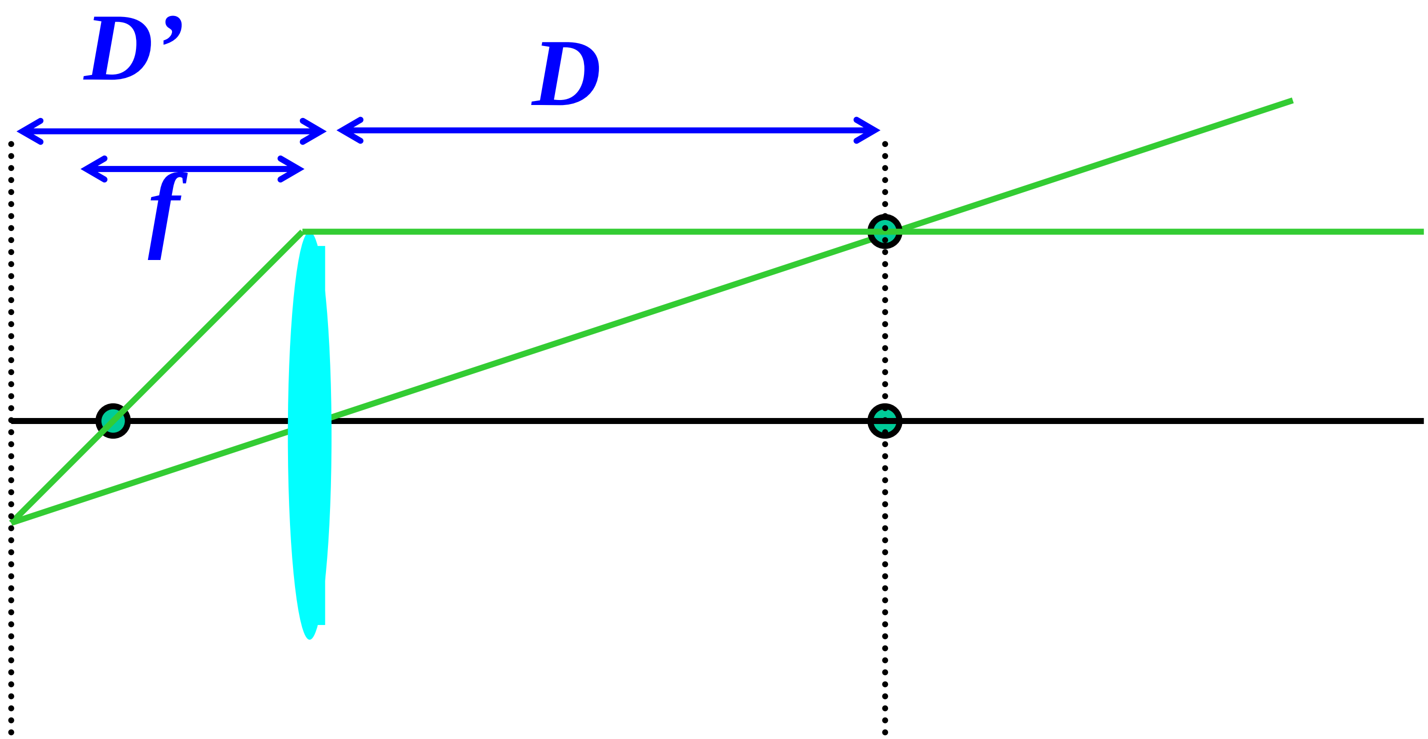
Thin lens formula



Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

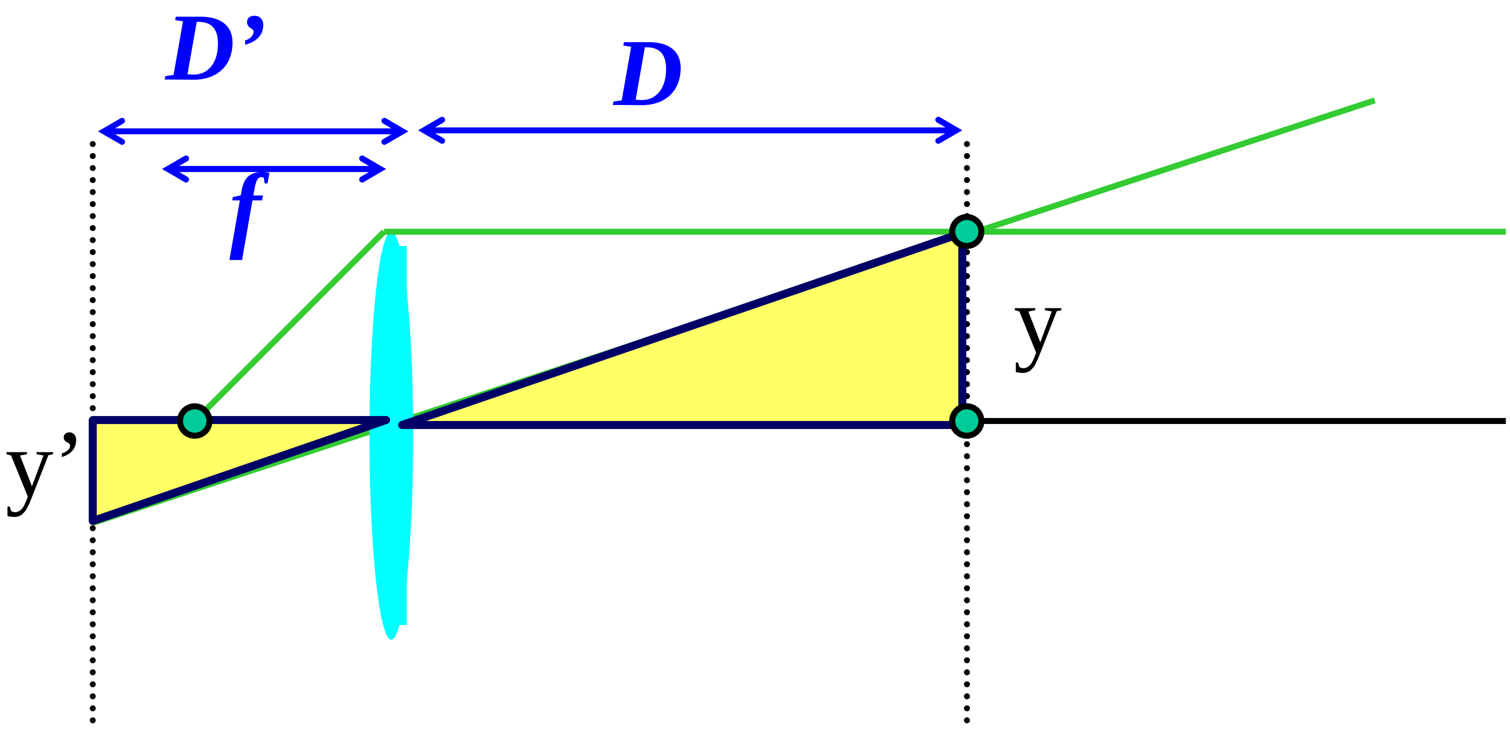


Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

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



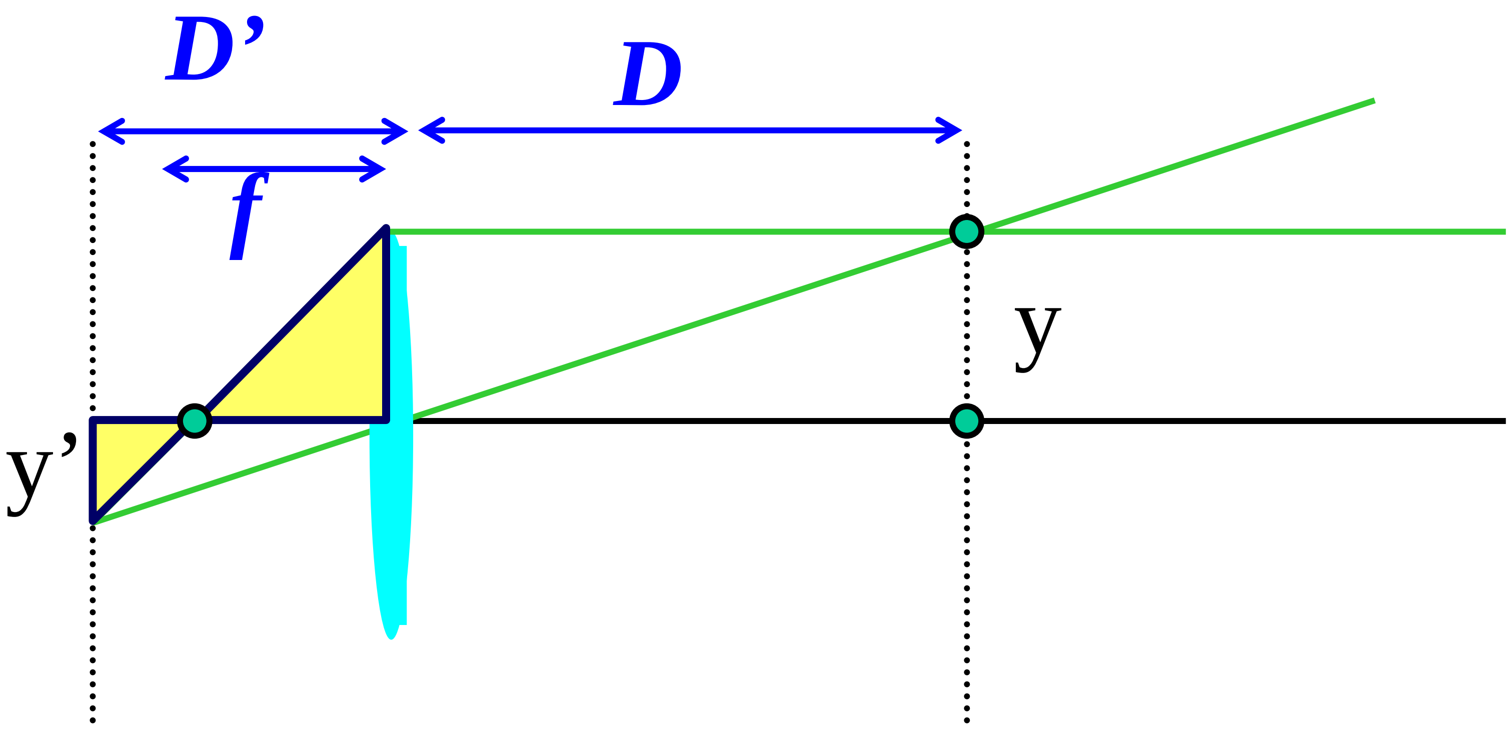
Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

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

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

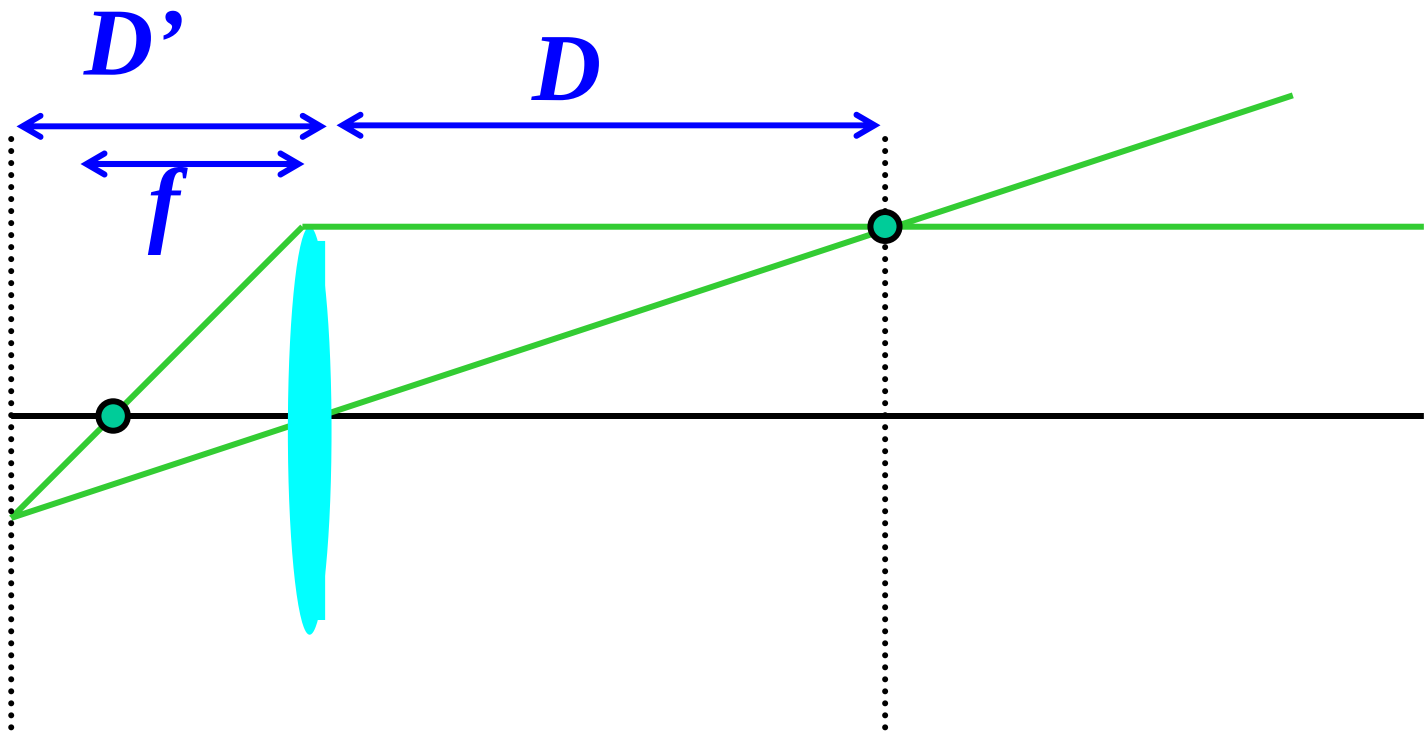


Frédo Durand's slide

Thin lens formula

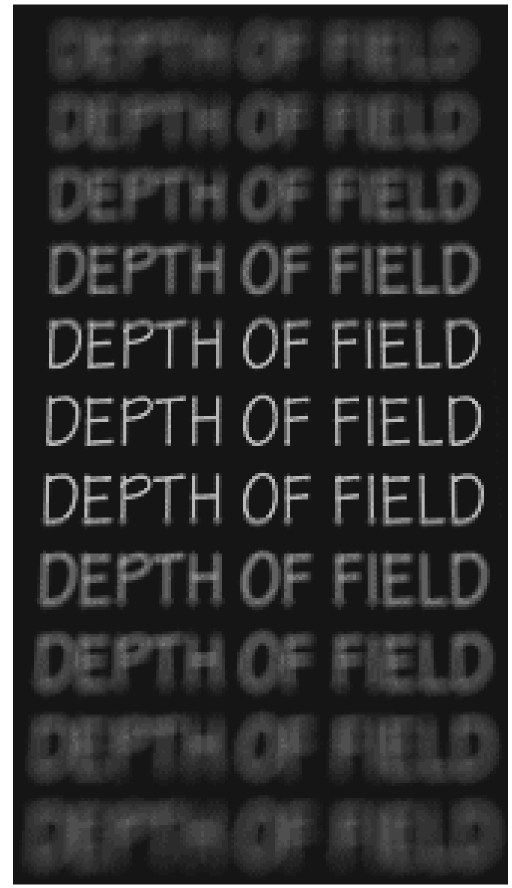
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

Any point satisfying the thin lens equation is in focus.



Frédo Durand's slide

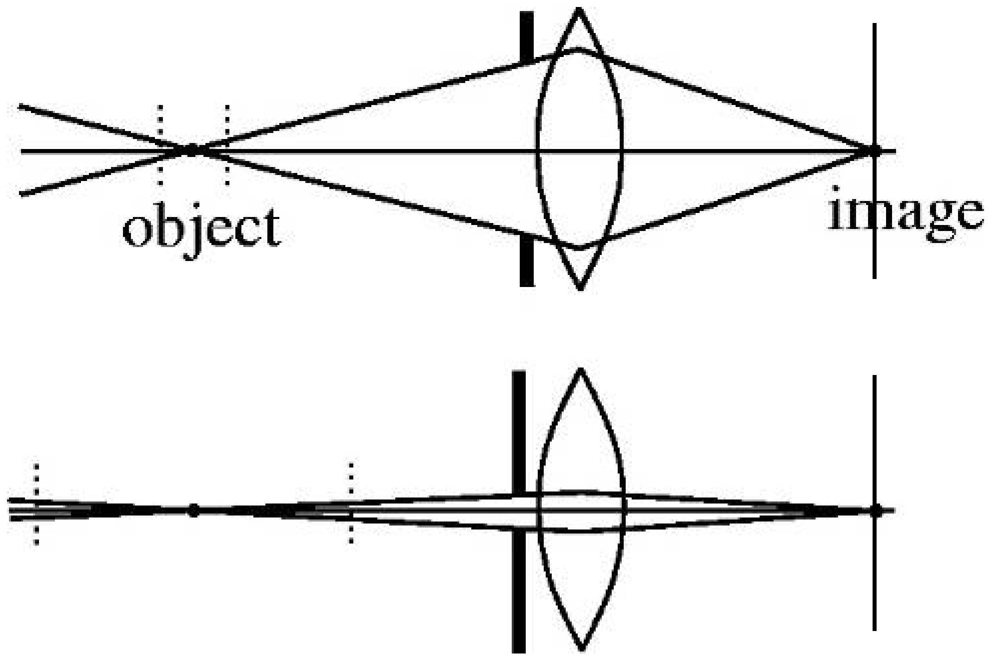
Depth of Field



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

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

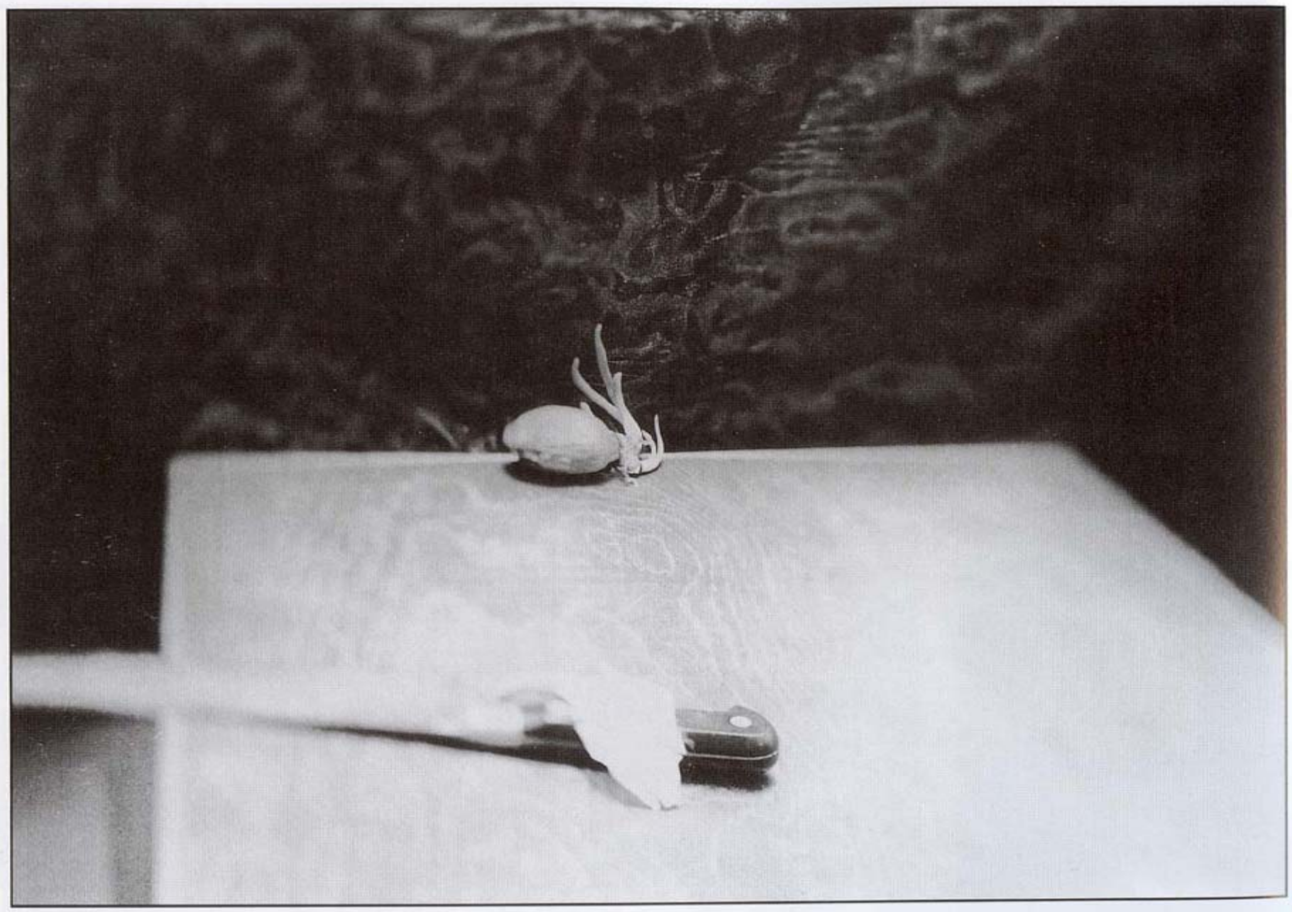
Large aperture = small DOF

Small aperture = large DOF

Slide by A. Efros

Manipulating the plane of focus

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

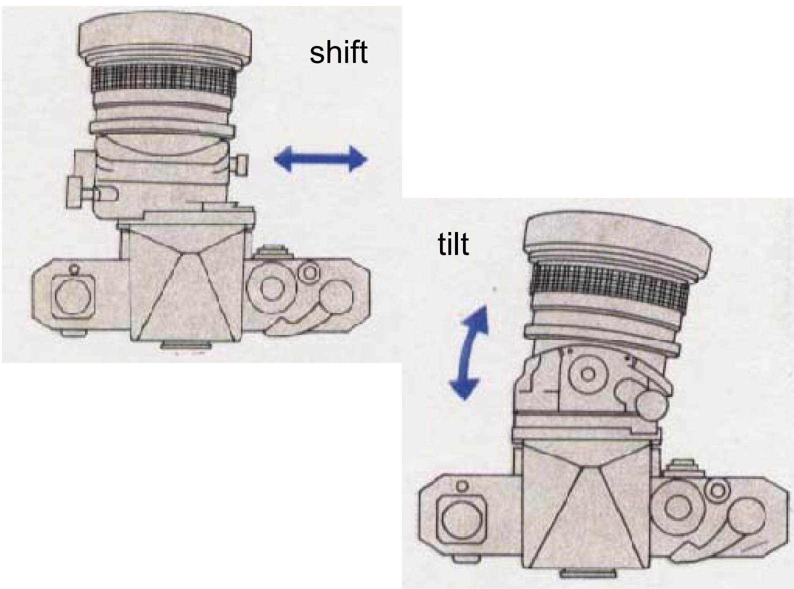


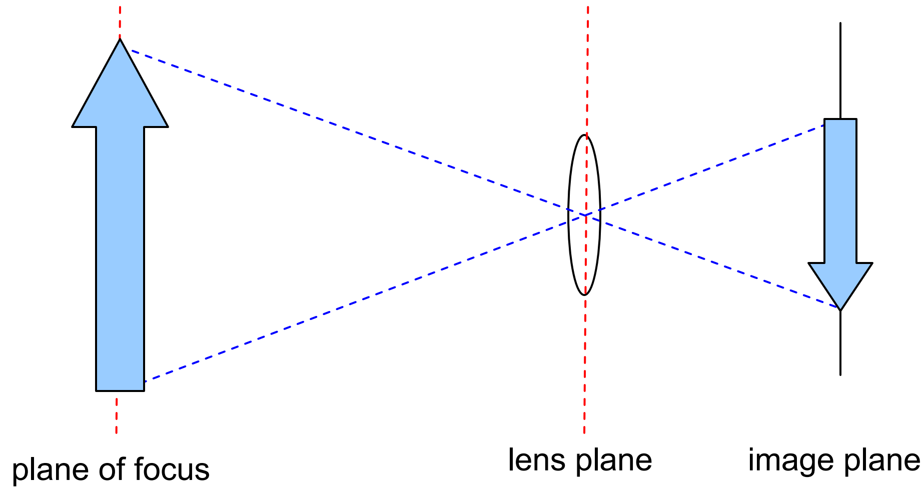
JAN GROOVER Untitled, 1985

Source: F. Durand

Tilt-shift lenses

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

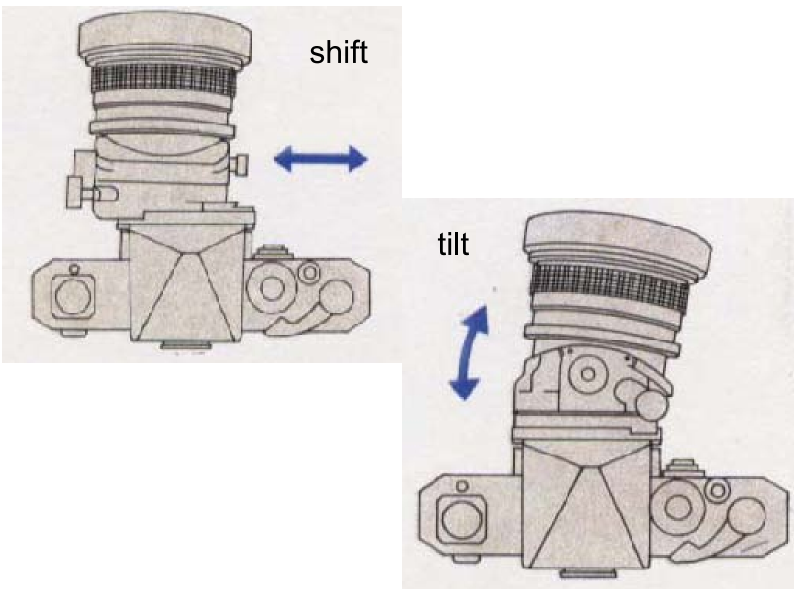


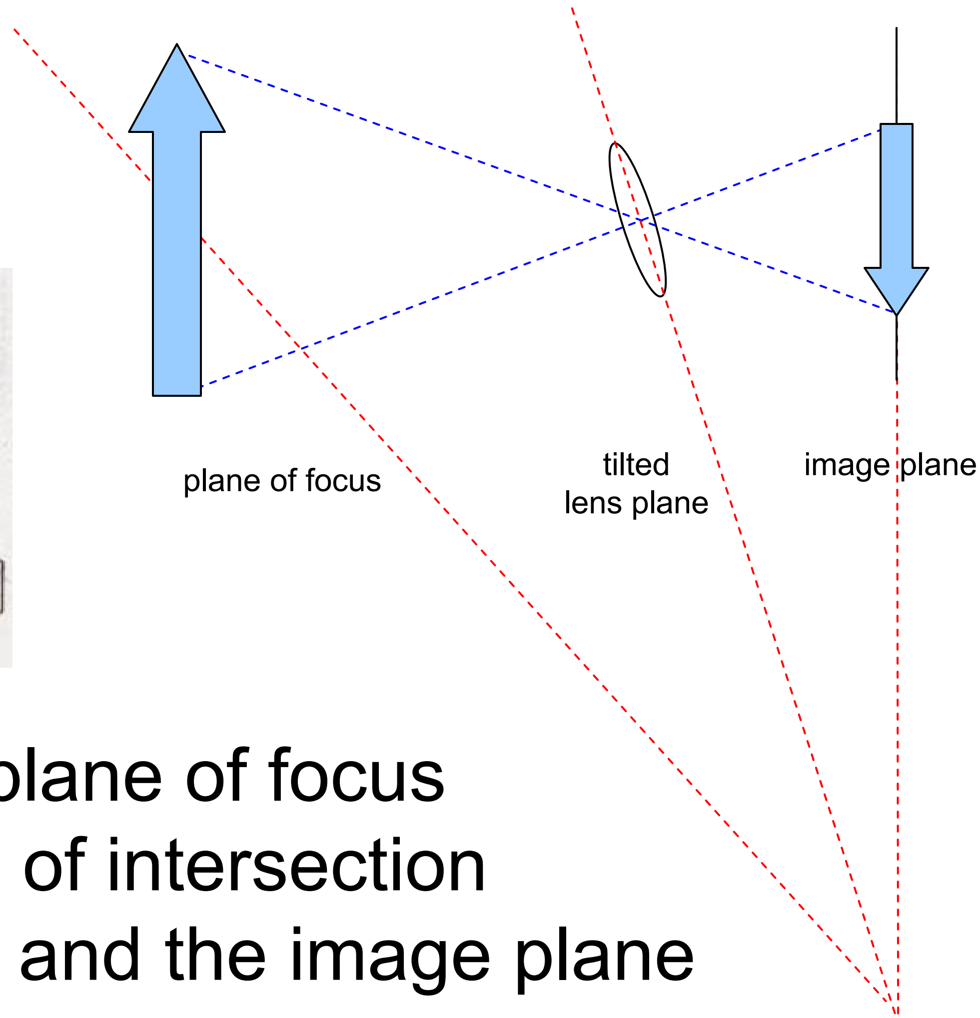


- Standard setup: plane of focus is parallel to image plane and lens plane

Tilt-shift lenses

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

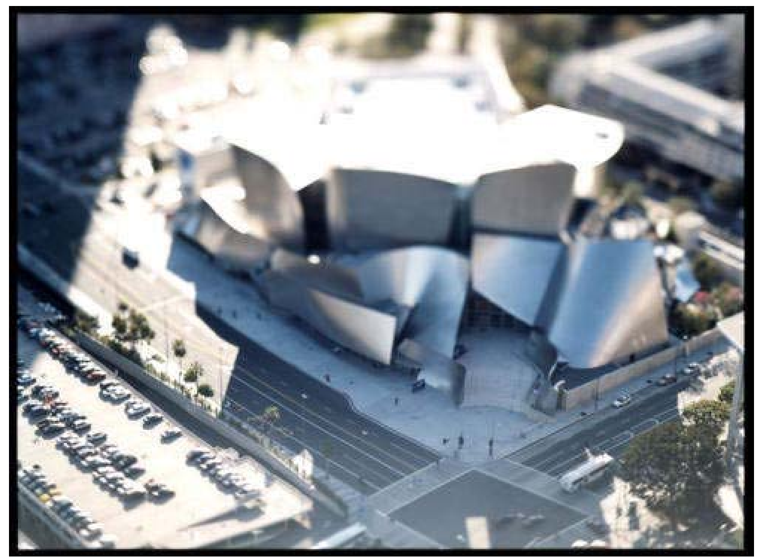




- Scheimpflug principle: plane of focus passes through the line of intersection between the lens plane and the image plane

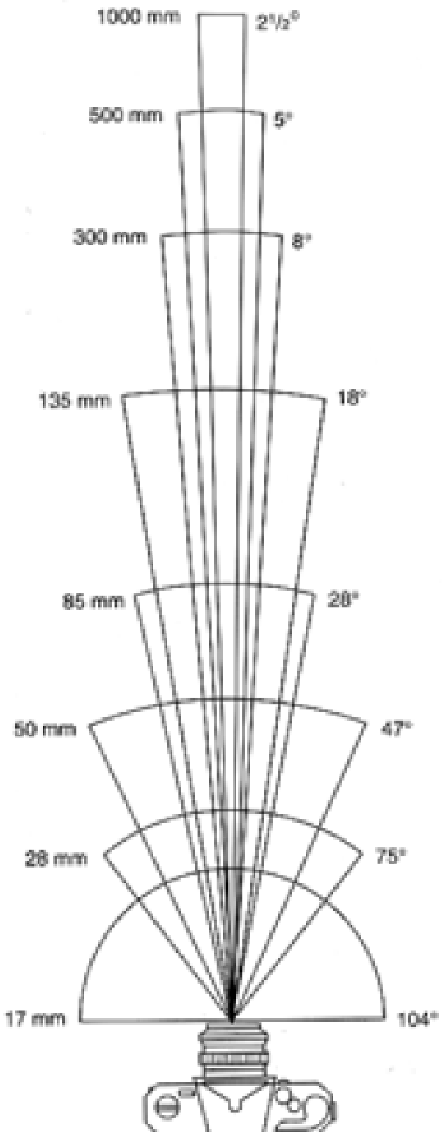
“Fake miniatures”

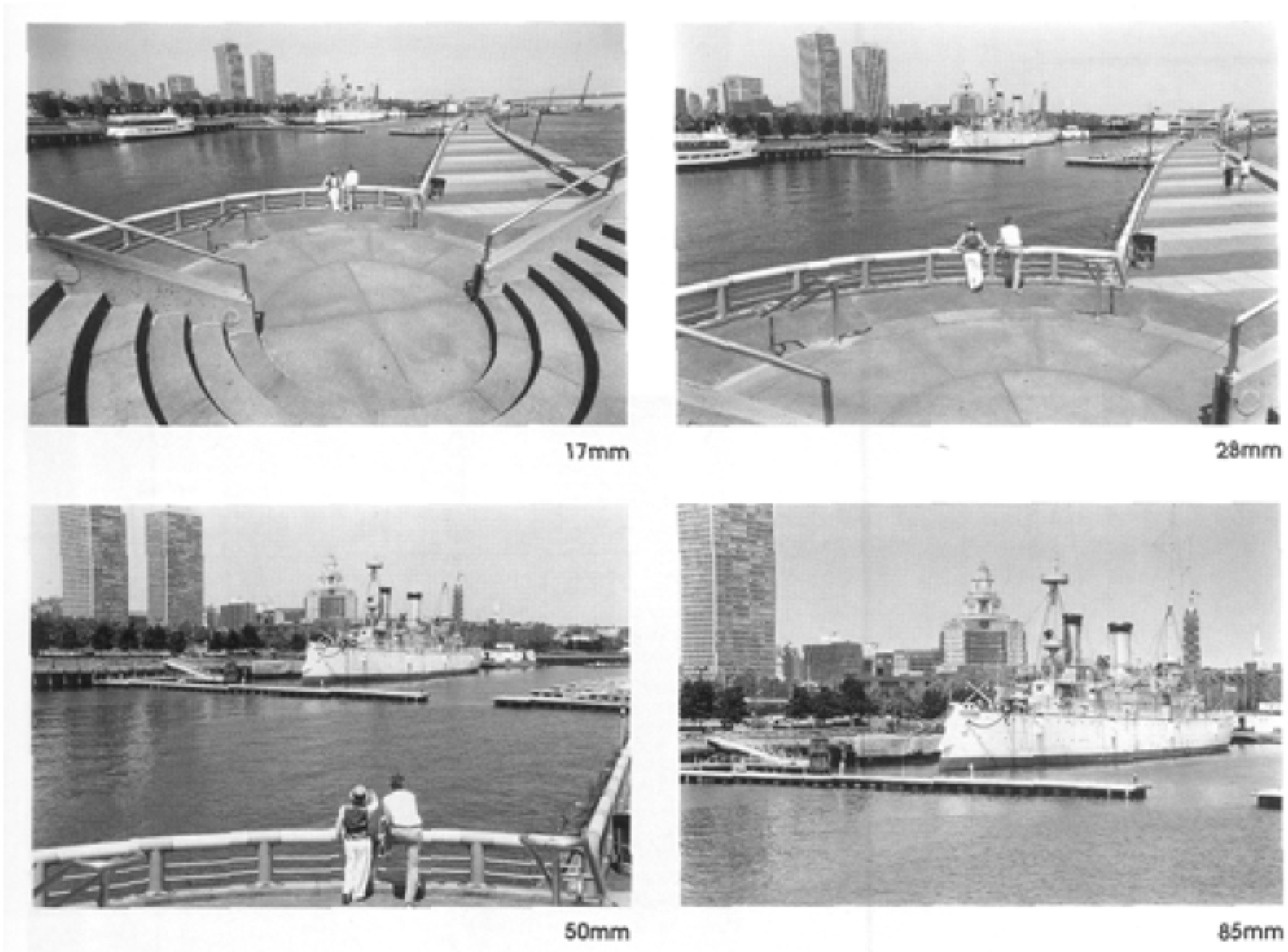


Olivo Barbieri: http://www.metropolismag.com/cda/story.php?artid=1760

Field of View (Zoom)

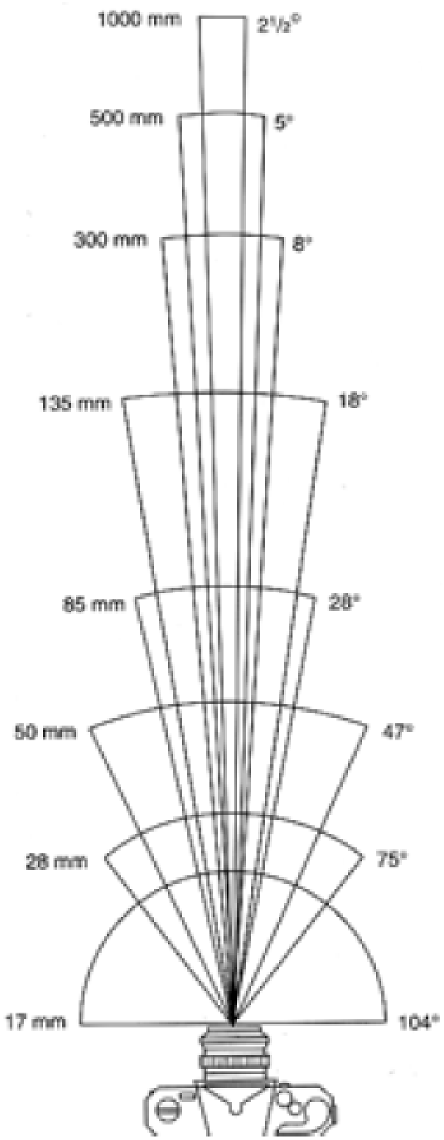


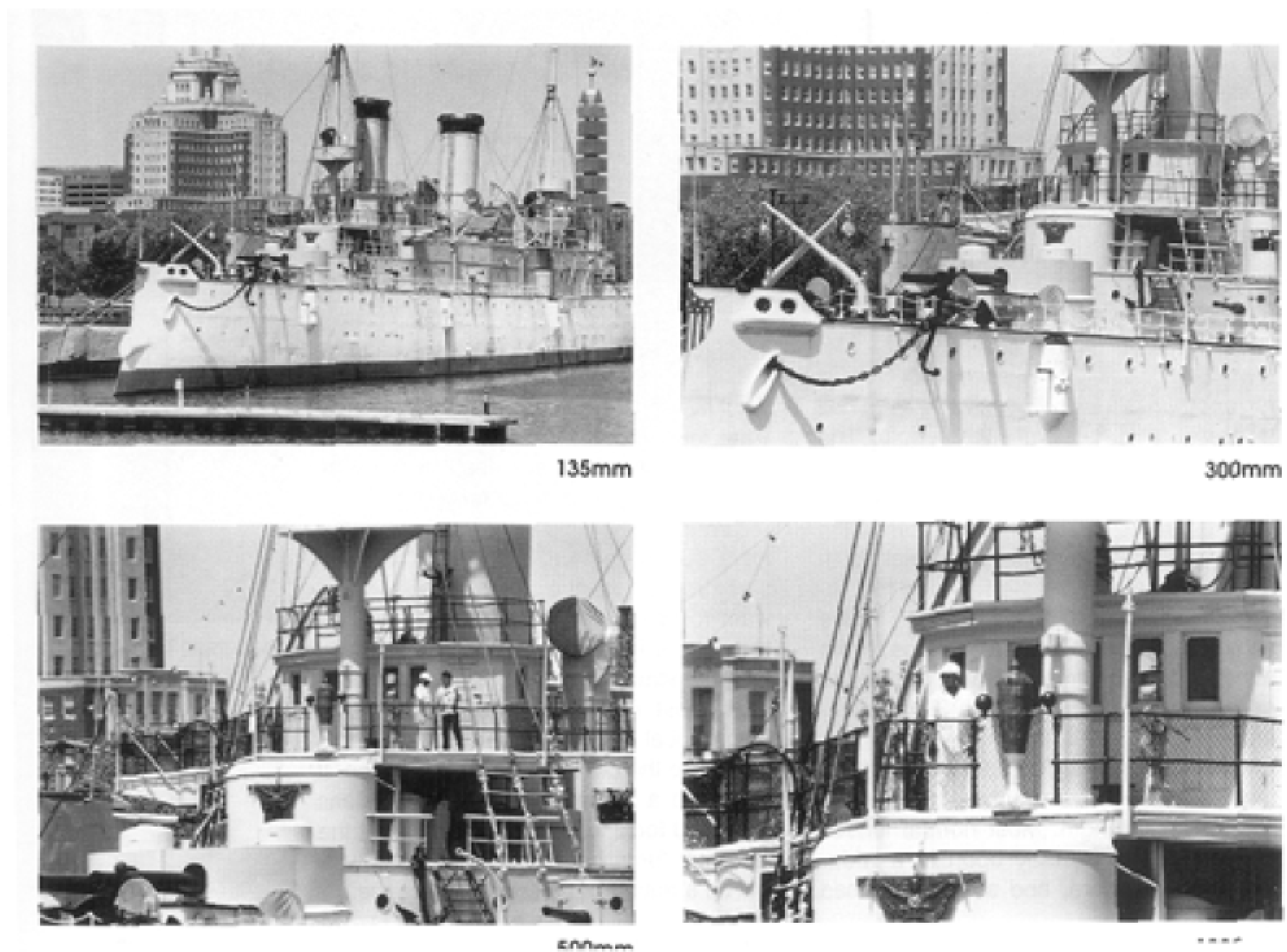


From London and Upton

Slide by A. Efros

Field of View (Zoom)

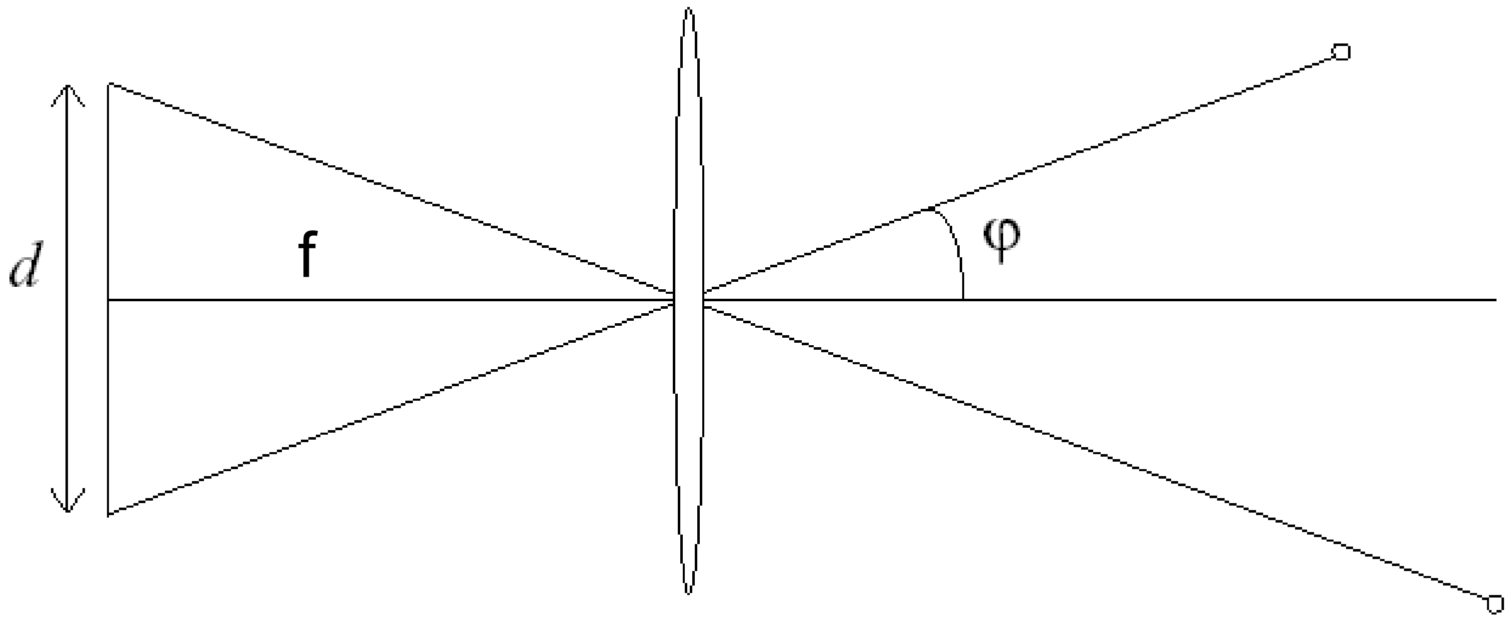




From London and Upton

Slide by A. Efros

Field of View



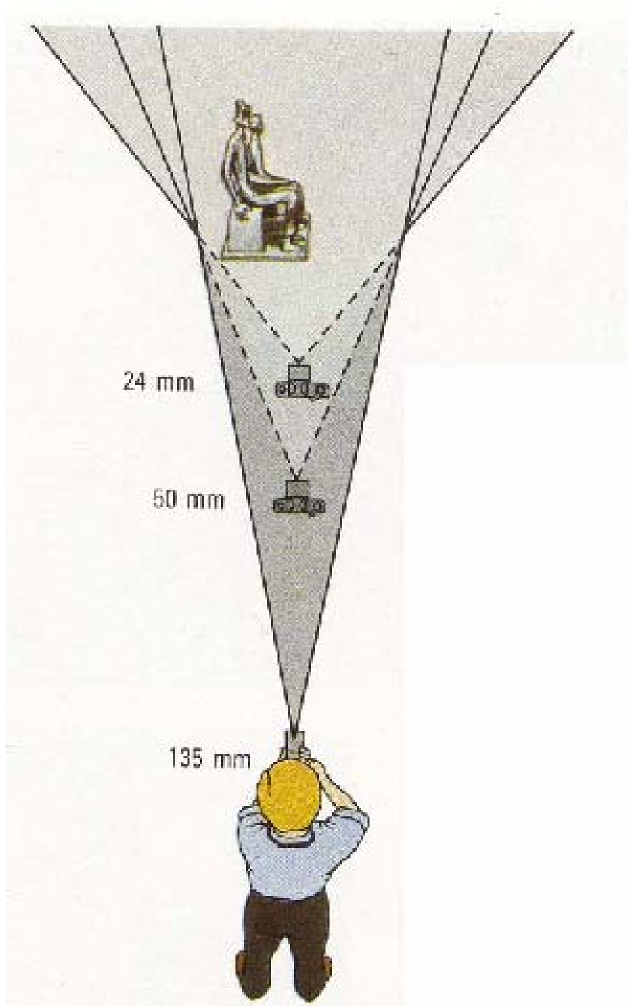
FOV depends on focal length and size of the camera retina

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

Smaller FOV = larger Focal Length

Slide by A. Efros

Field of View / Focal Length

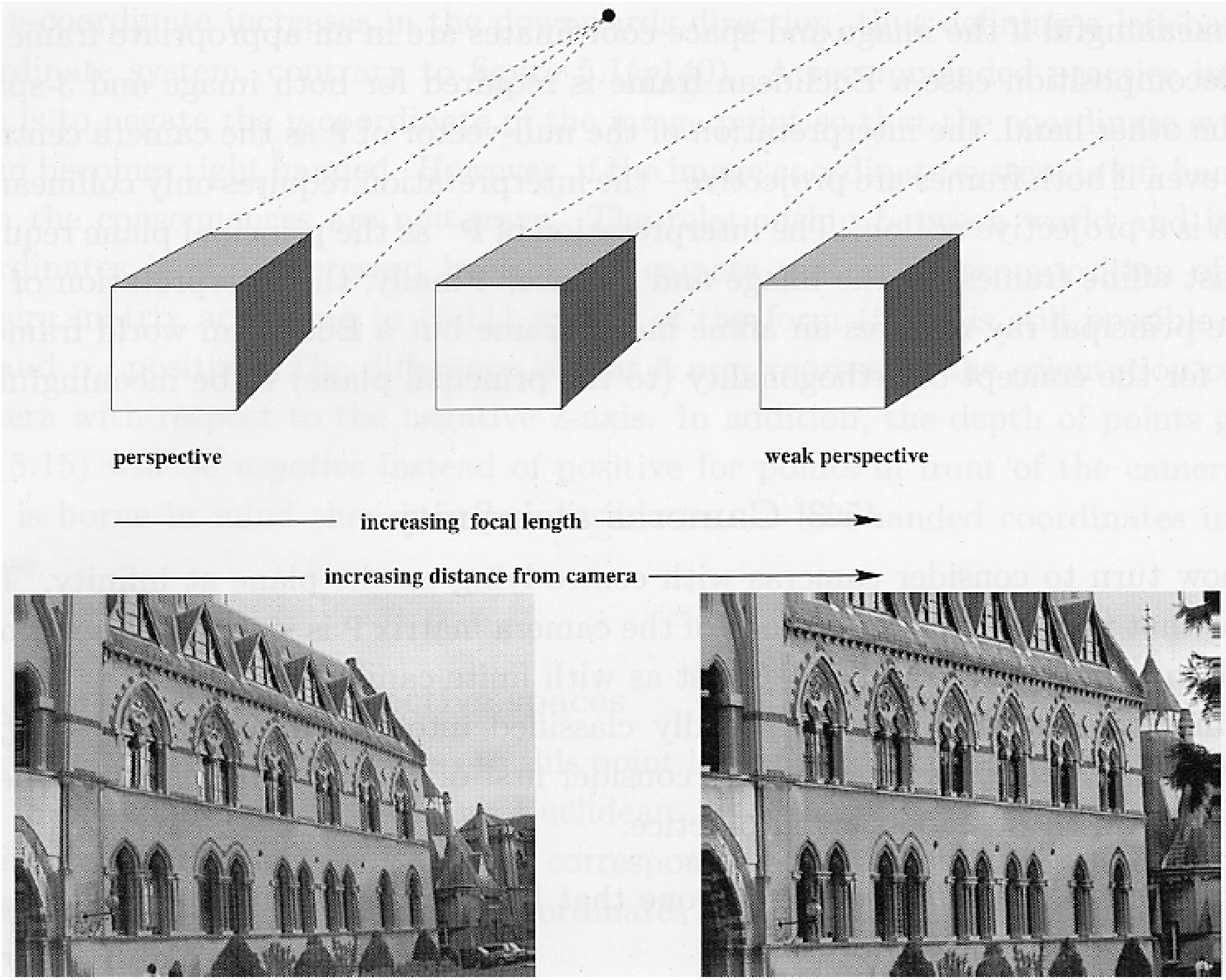


Large FOV, small f
Camera close to car

Small FOV, large f
Camera far from the car

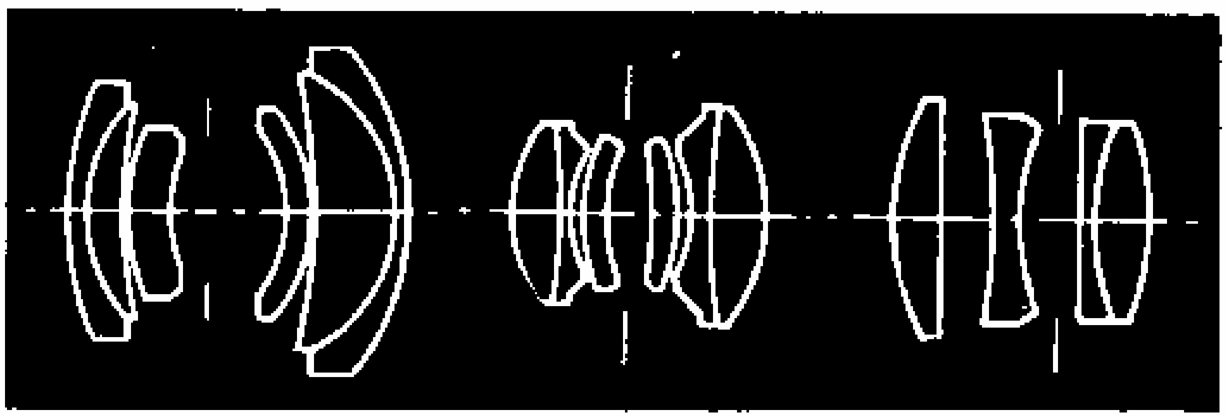
Sources: A. Efros, F. Durand

Approximating an affine camera



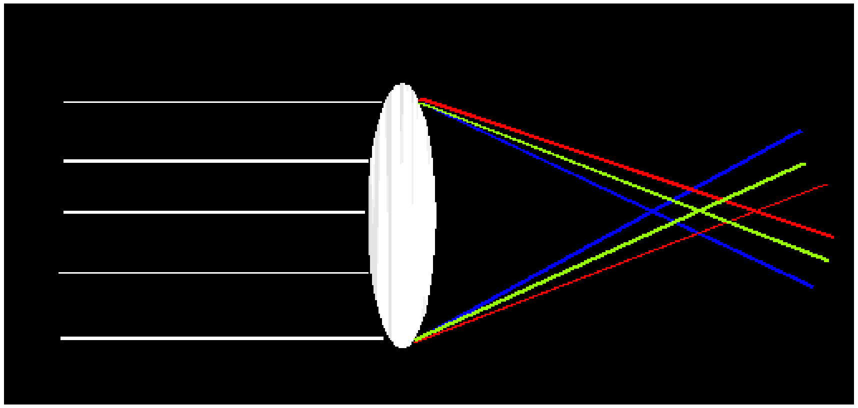
Source: Hartley & Zisserman

Real lenses



Lens Flaws: Chromatic Aberration

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



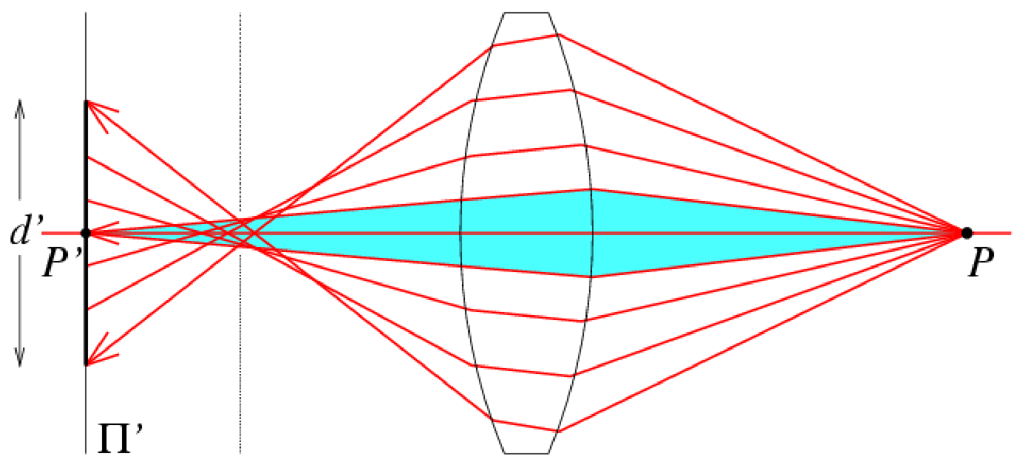
Near Lens Center

Near Lens Outer Edge

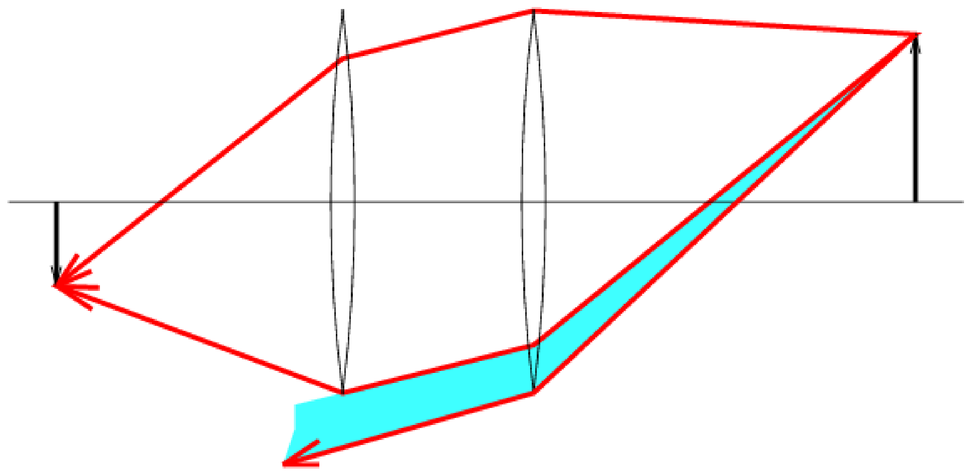
Lens flaws: Spherical aberration

Spherical lenses don't focus light perfectly

- Rays farther from the optical axis focus closer

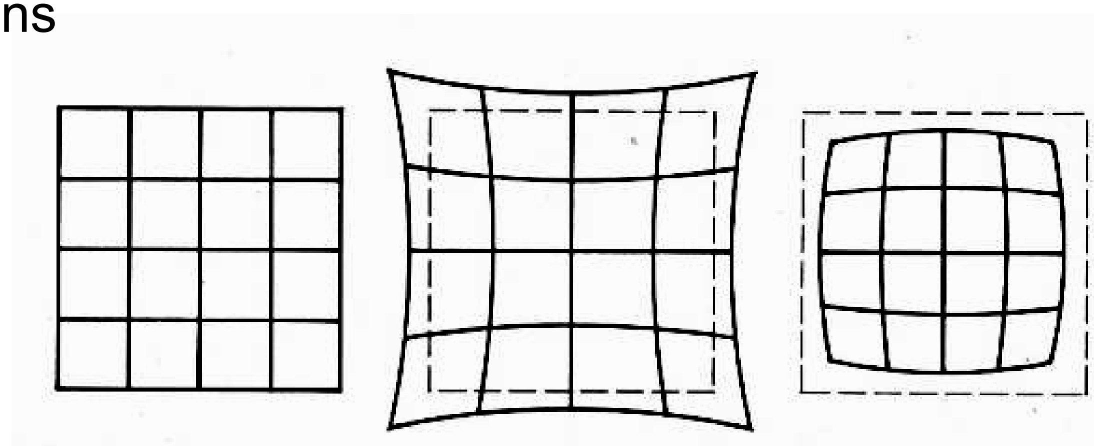


Lens flaws: Vignetting

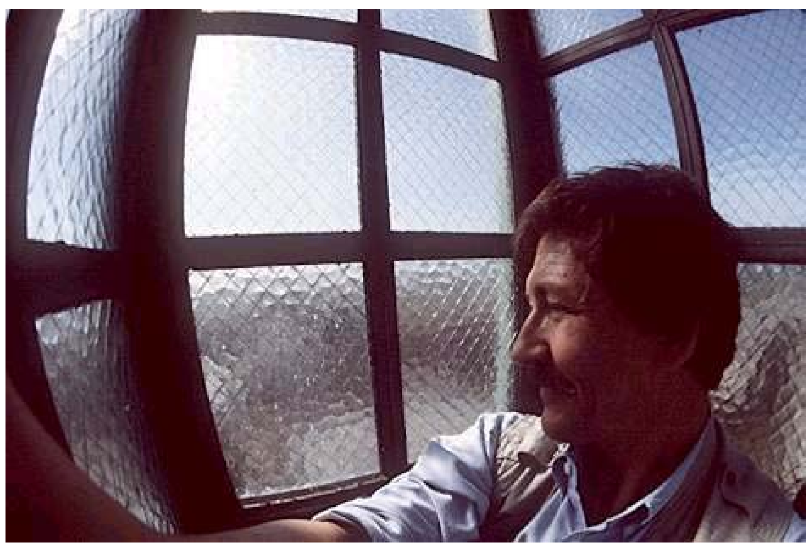


Radial Distortion

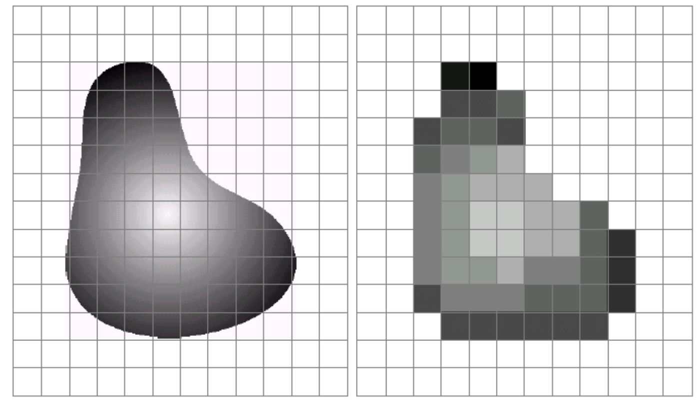
- Caused by imperfect lenses
- Deviations are most noticeable for rays that pass through the edge of the lens



No distortion Pin cushion Barrel



Digital camera



a b

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

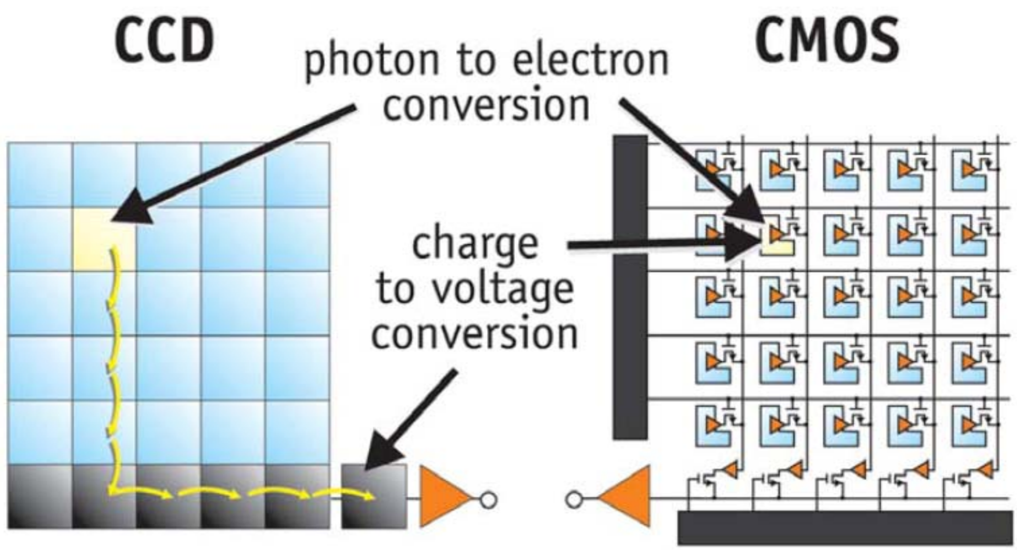
Slide by Steve Seitz

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

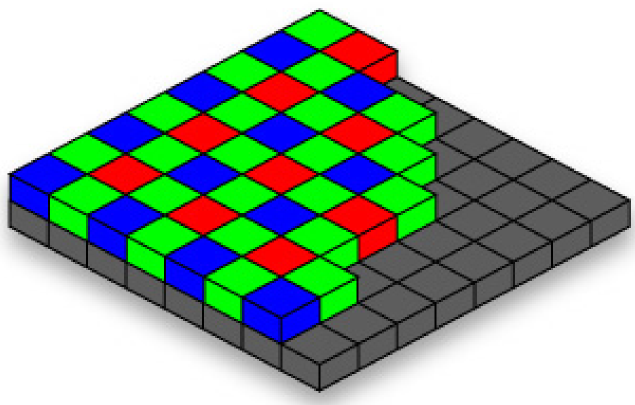


CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

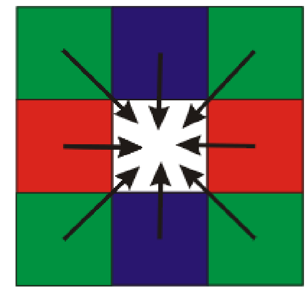
http://www.dalsa.com/shared/content/pdfs/CCD_vs_CMOS_Litwiller_2005.pdf

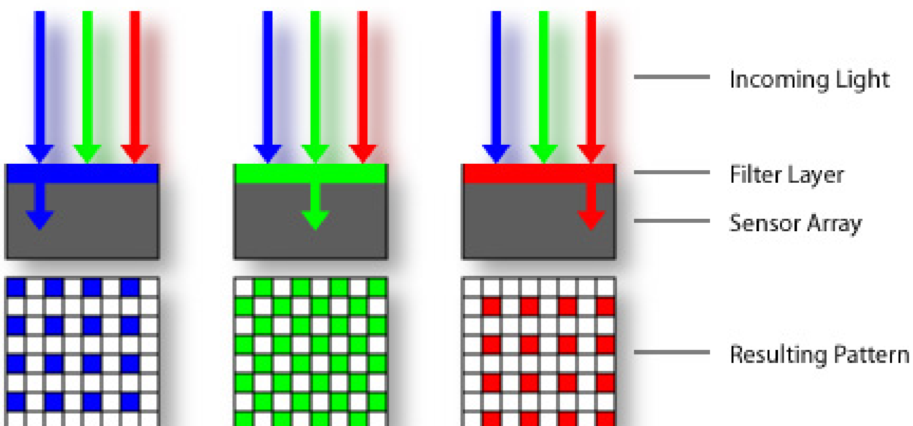
Color sensing in camera: Color filter array

Bayer grid

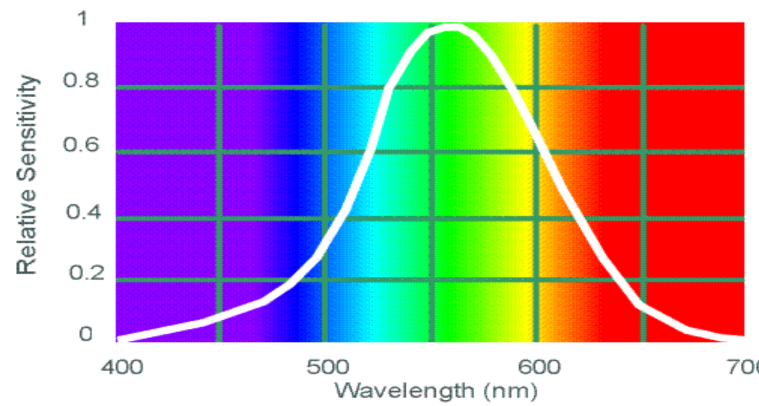


Estimate missing components from neighboring values (demosaicing)





Why more green?



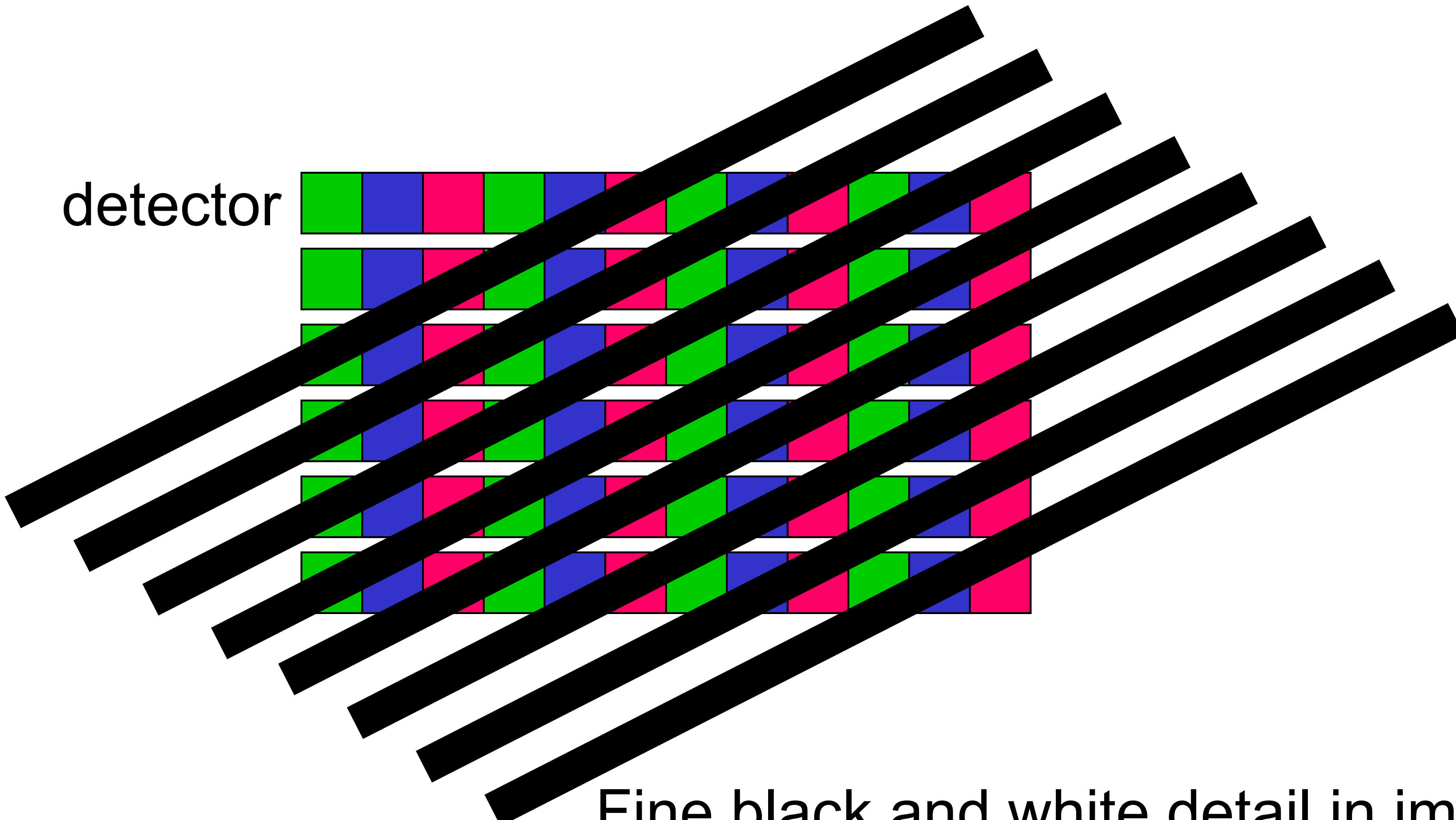
Human Luminance Sensitivity Function

Source: Steve Seitz

Problem with demosaicing: color moire

Slide by F. Durand

The cause of color moire

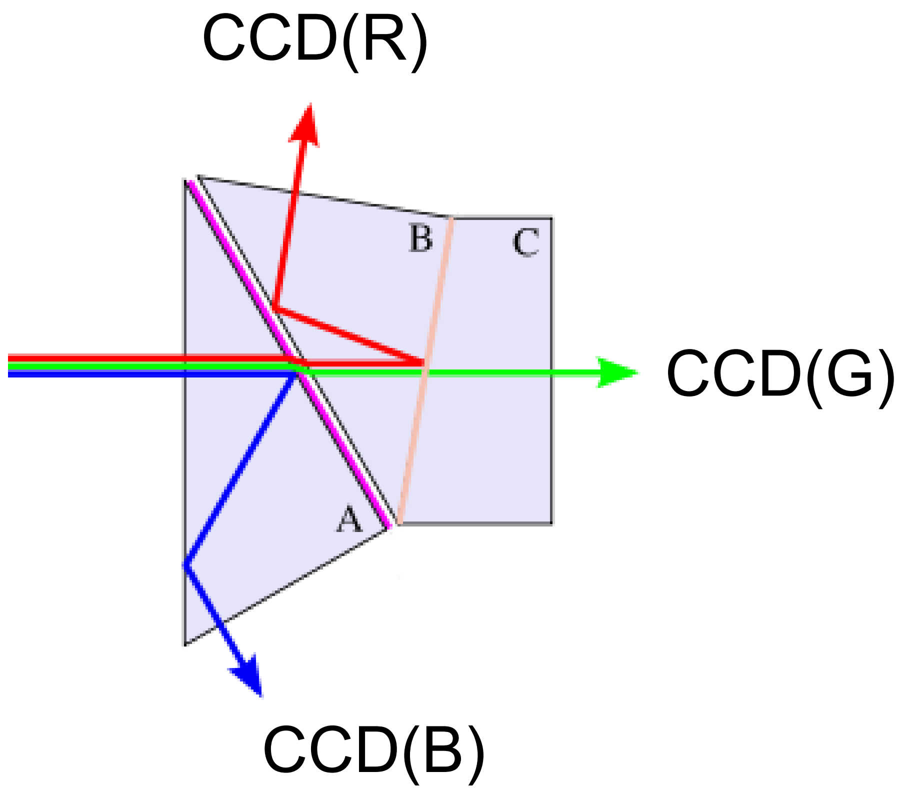


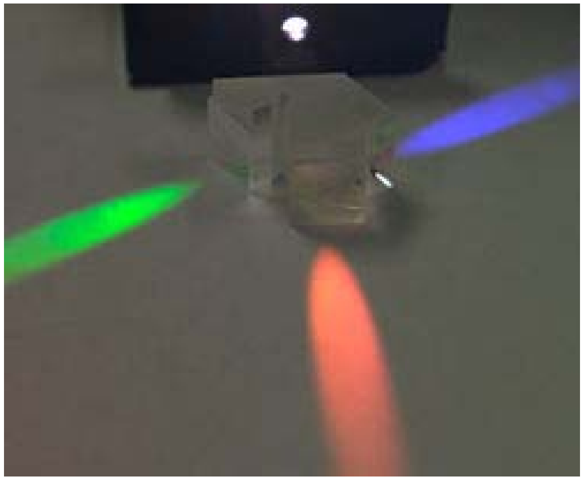
Fine black and white detail in image misinterpreted as color information

Slide by F. Durand

Color sensing in camera: Prism

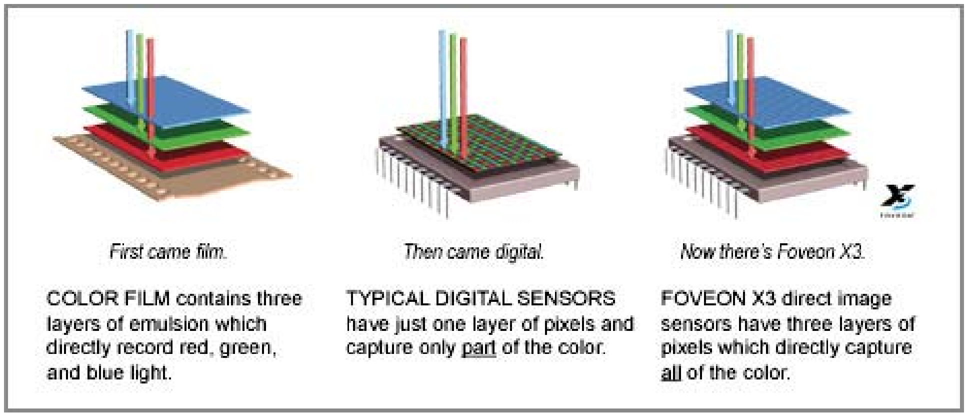
- Requires three chips and precise alignment
- More expensive

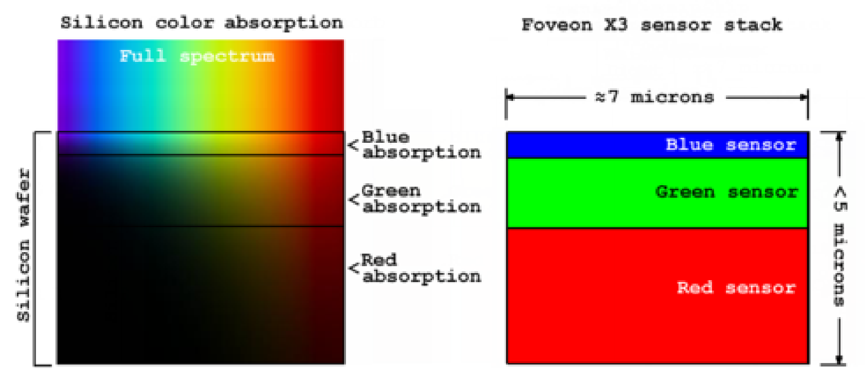




Color sensing in camera: Foveon X3

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

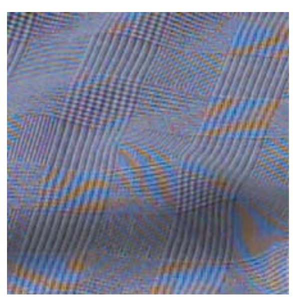


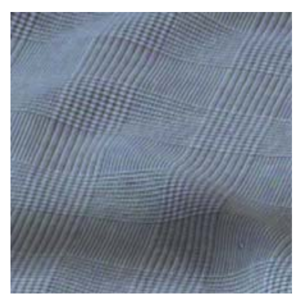


http://www.foveon.com/article.php?a=67

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

better image quality



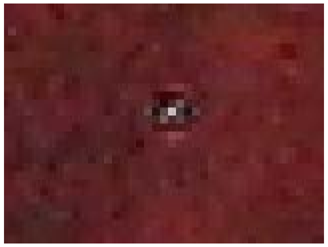


Source: M. Pollefeys

Issues with digital cameras

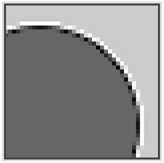
Noise

- 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

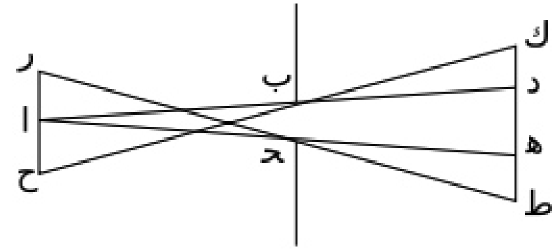
More info online:

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

Slide by Steve Seitz

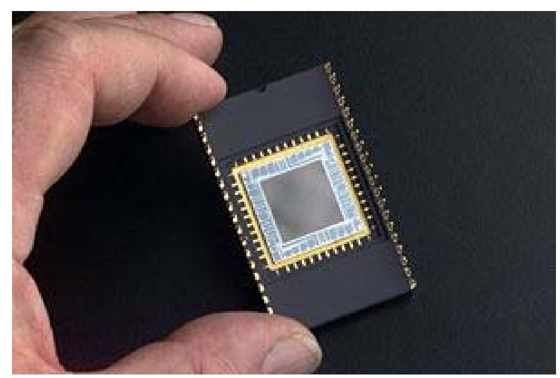
Historical context

- **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

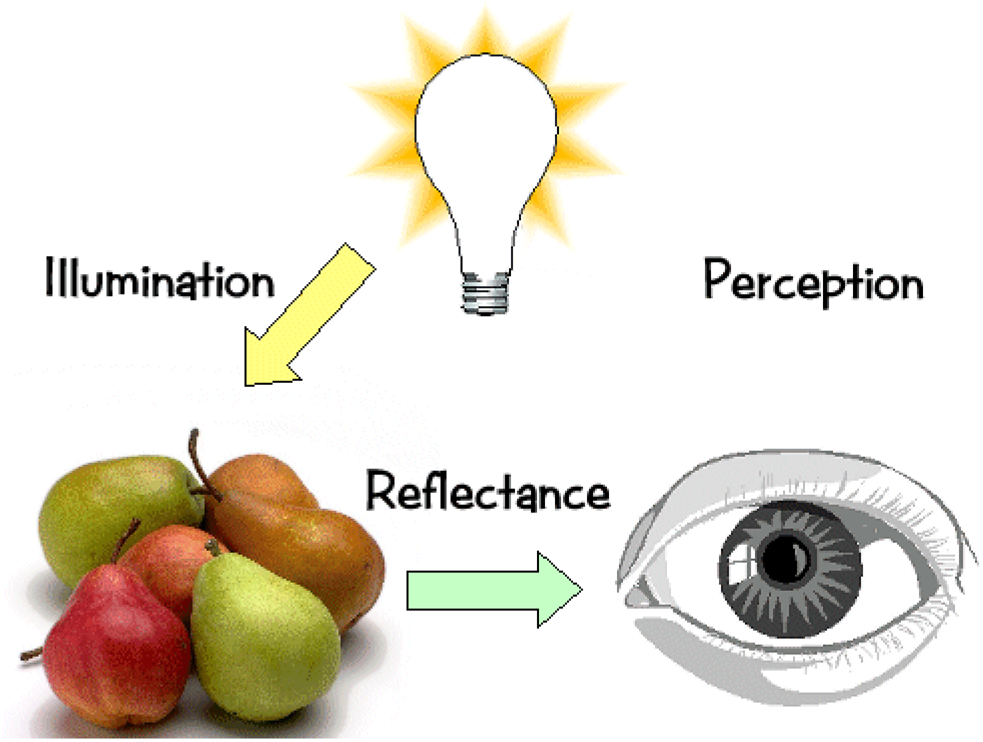
Niepce, "La Table Servie," 1822



CCD chip

Next time

Light and color



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