CSCE 448/748 – Computational Photography

Camera and Image Formation

Nima Kalantari

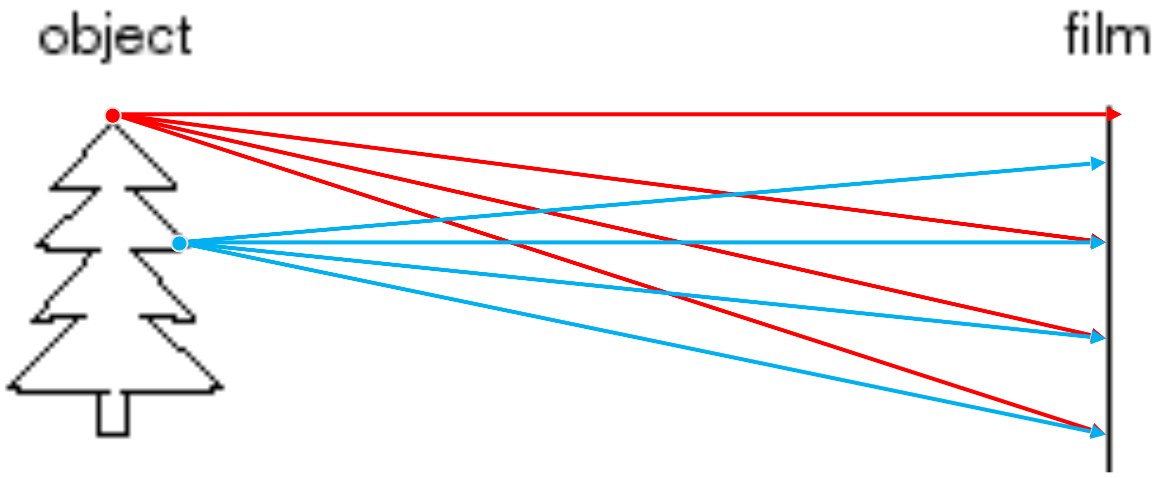
Many slides from Alexei A. Efros, James Hayes, Rob Fergus

Outline

- ➢ **Pinhole camera**
- ➢ **Lens**
- ➢ **Depth of field**
- ➢ **Field of view**
- ➢ **Exposure**
- ➢ **Digital camera**

How do we see the world?

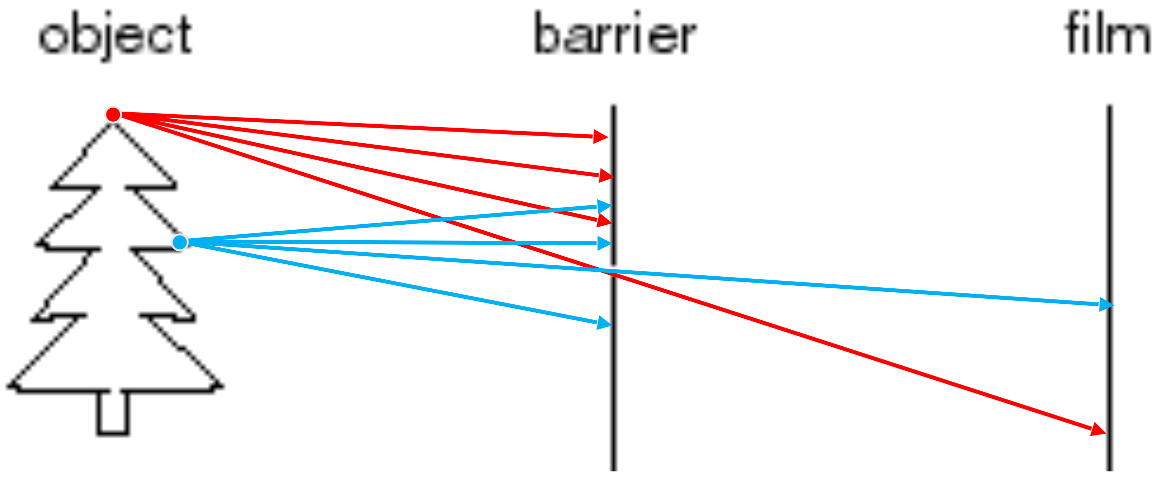
- Let's design a camera
  - Put a piece of film in front of an object
  - Do we get a reasonable image?



Slide by Steve

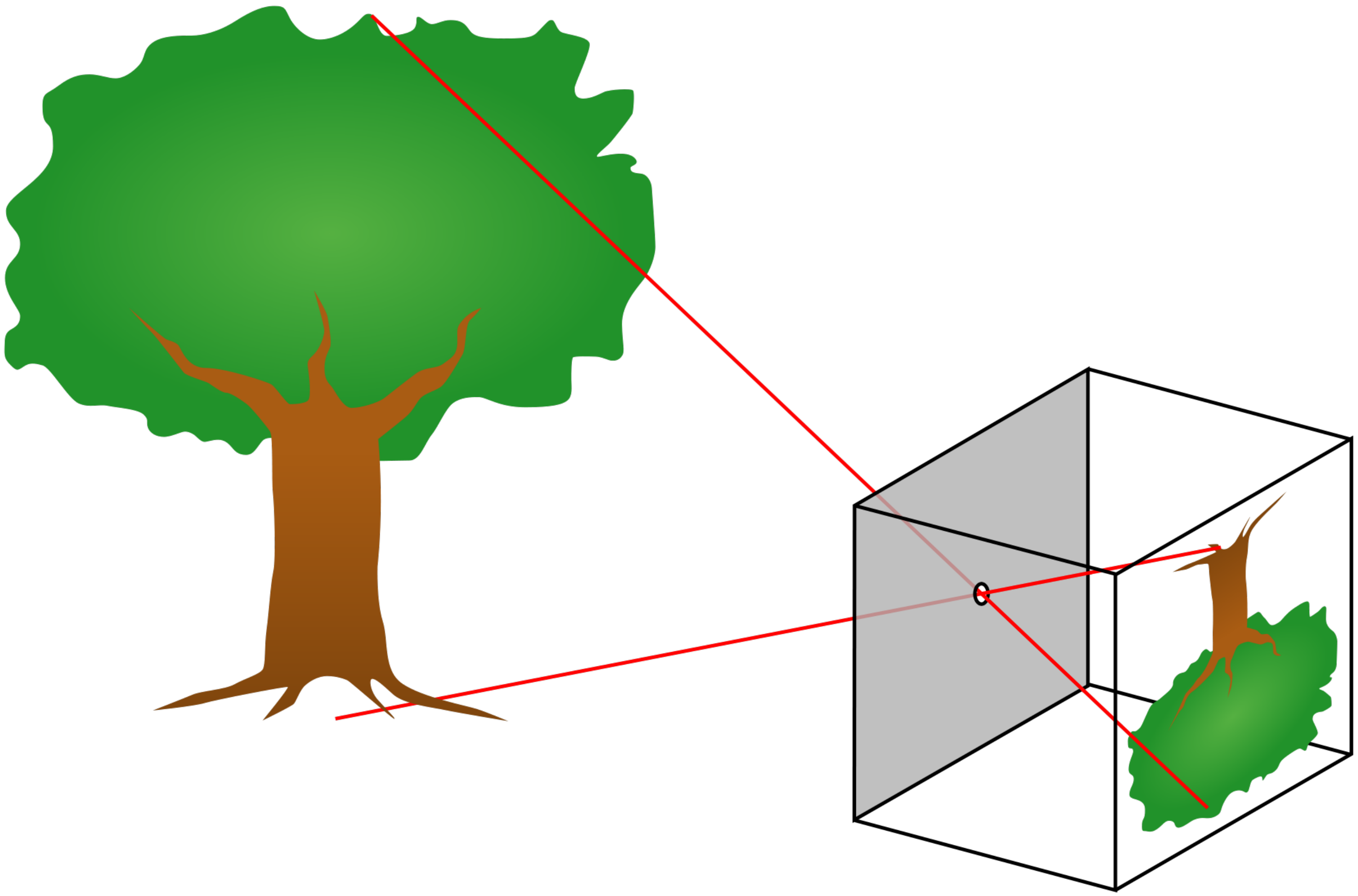
Pinhole camera

- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening known as the aperture
  - How does this transform the image?



Slide by Steve

Pinhole camera



By Greg Voth

Pinhole camera model

➢ **Pinhole model:**

- Captures pencil of rays – all rays through a single point
- The point is called Center of Projection (COP)
- The image is formed on the Image Plane (film/sensor)
- Image distance d is distance from COP to Image Plane

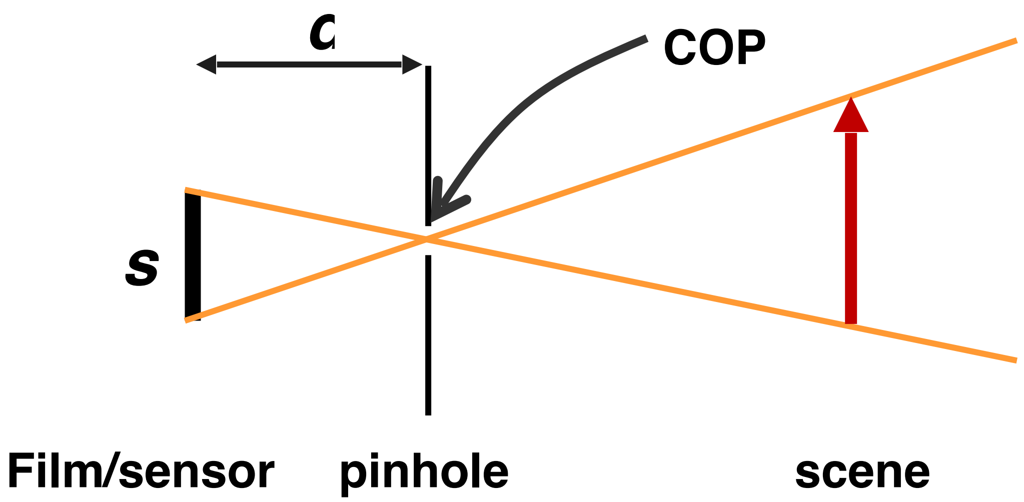


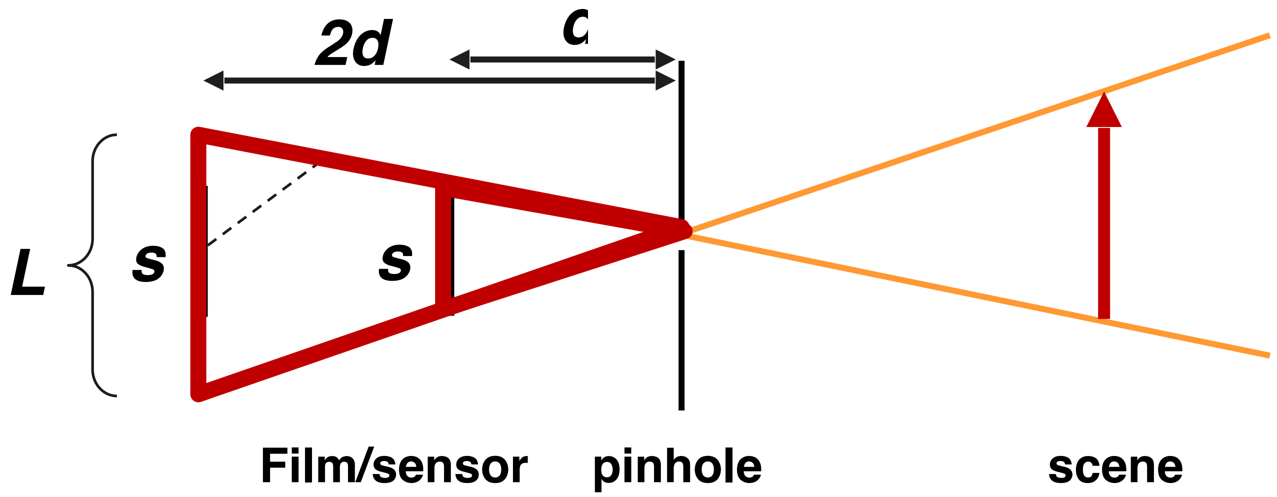
Image distance: pinhole optics

➢ **What happens when the image distance is doubled?**

— **Projected object height** is doubled

s = projected object height on sensor at distance d

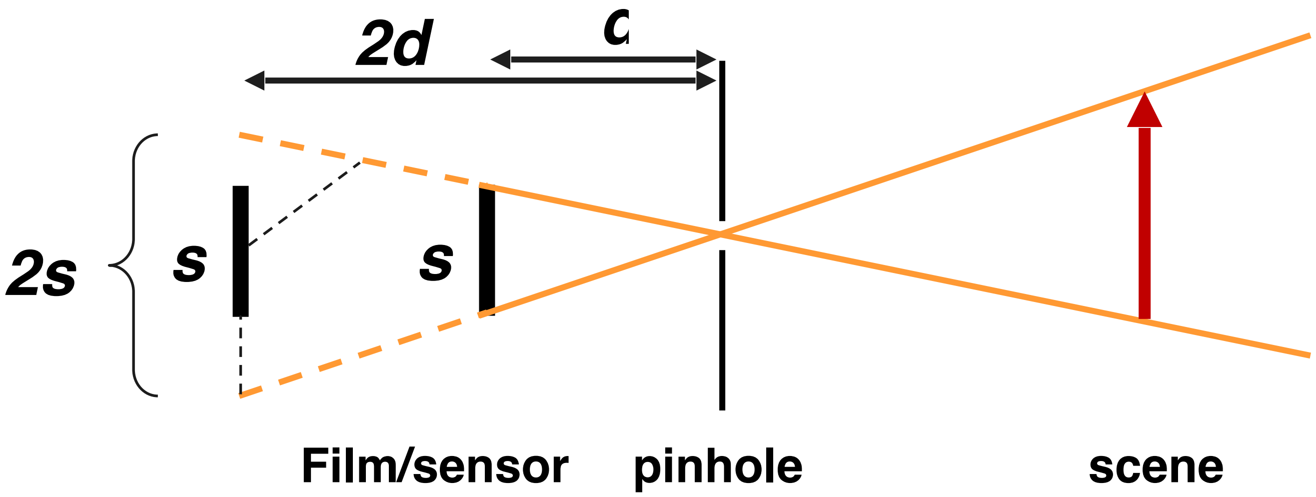
L = projected object height on sensor at distance 2d



$$\frac{L}{s} = \frac{2d}{d} = 2$$

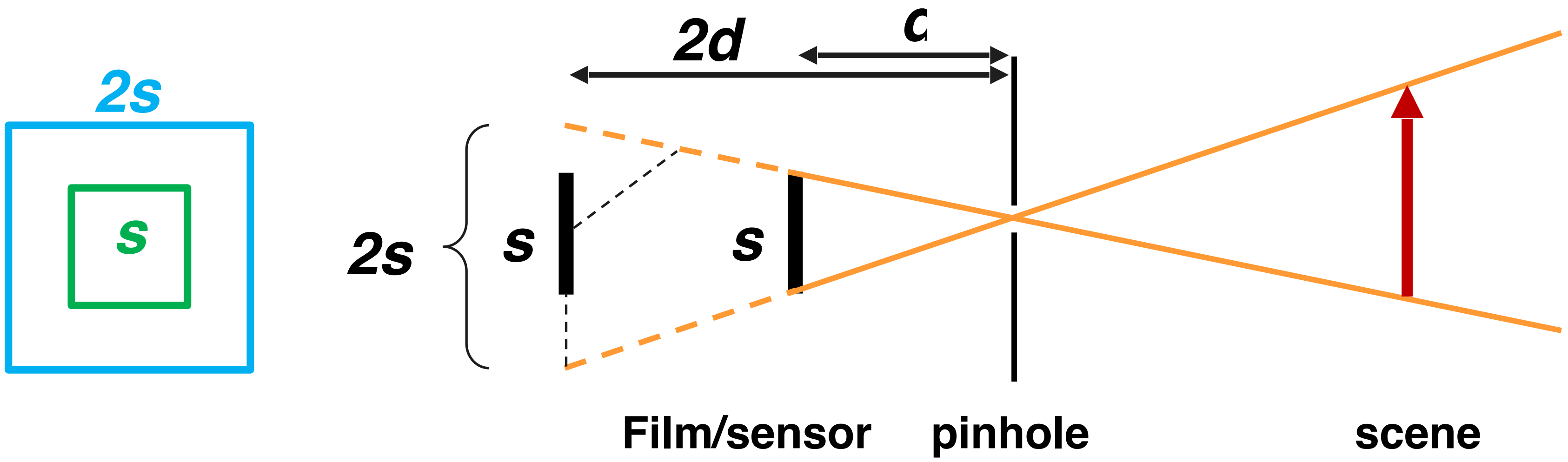
Image distance: pinhole optics

- What happens when the image distance is doubled?
  - Projected object height is doubled
  - Amount of light gathered



Amount of light gathered

- ➢ Let’s say a sensor of size s at distance d receives 1 unit of light
- ➢ How much light sensor of size 2s at distance 2d receives?
  - – 1 unit of light
- ➢ How about a sensor of size s at distance 2d?

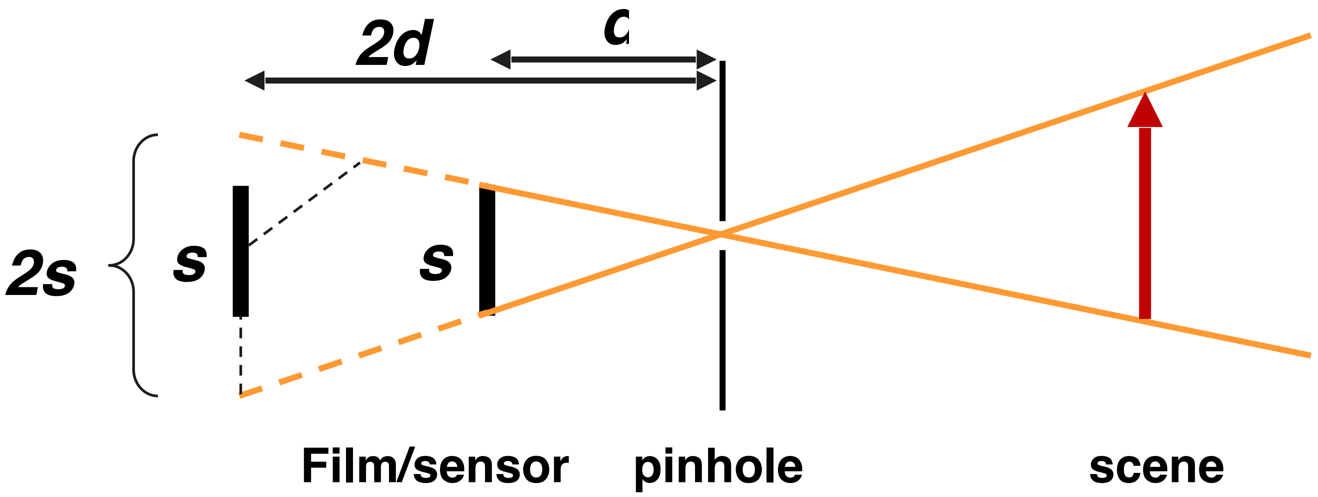


$$\frac{s^2}{(2s)^2} = \frac{x}{1}$$

$$x = \frac{1}{4}$$

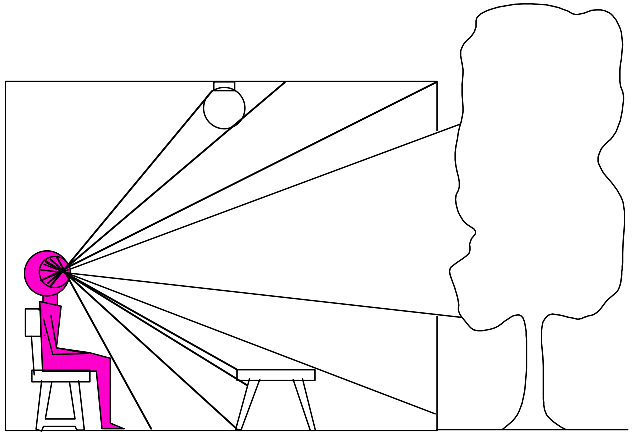
Image distance: pinhole optics

- What happens when the image distance is doubled?
  - Projected object height is doubled
  - Amount of light gathered is divided by 4

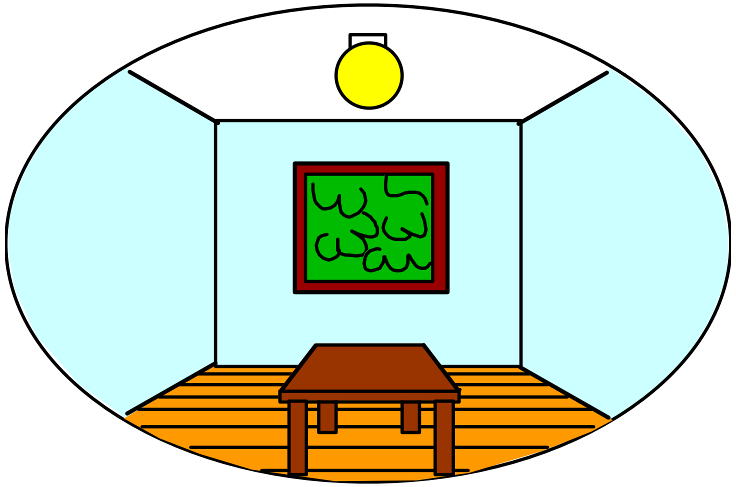


Dimensionality Reduction Machine (3D to 2D)

- **But there is a problem …**

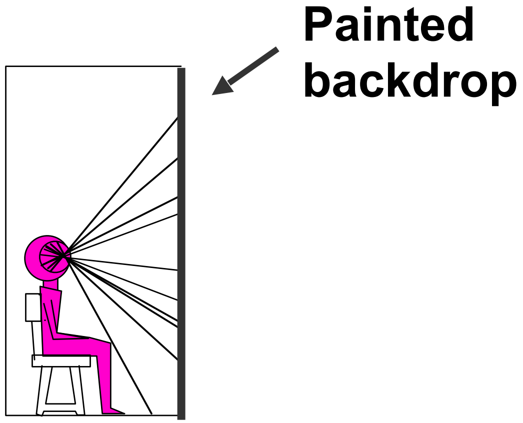


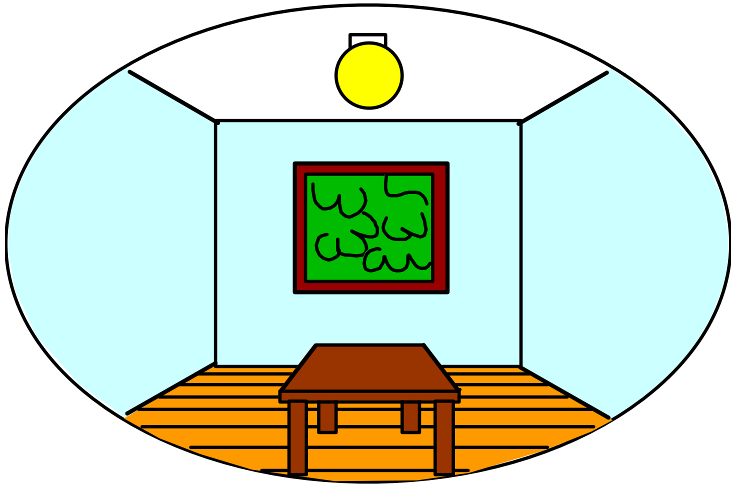
Point of observation



3D world ***2D image***

How we see the world





3D world ***2D image***

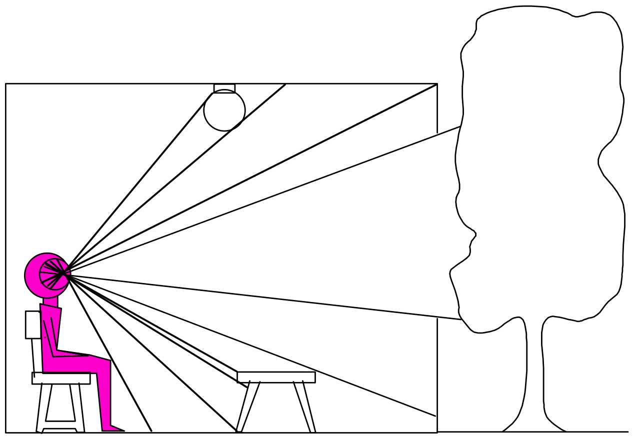
Fooling the eye

Fooling the eye

Making of 3D sidewalk art: http://www.youtube.com/watch?v=3SNYtd0Ayt0

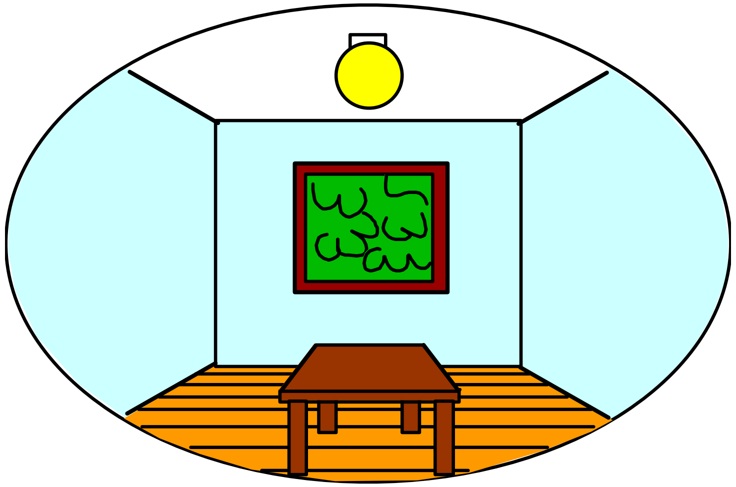
Dimensionality Reduction Machine (3D to 2D)

- **What have we lost?**
  - Depth
  - lengths
  - Angles



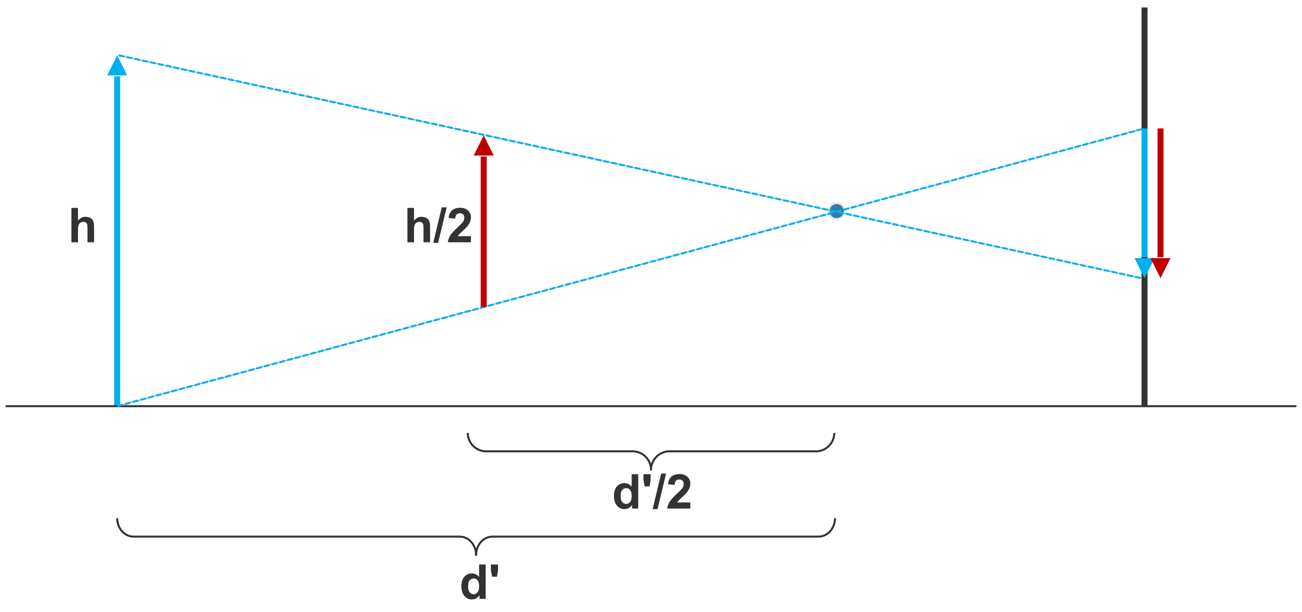
Point of observation

3D world

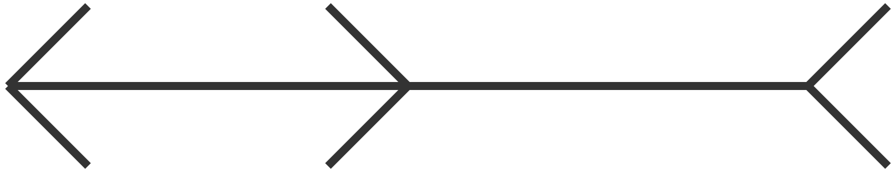


2D image

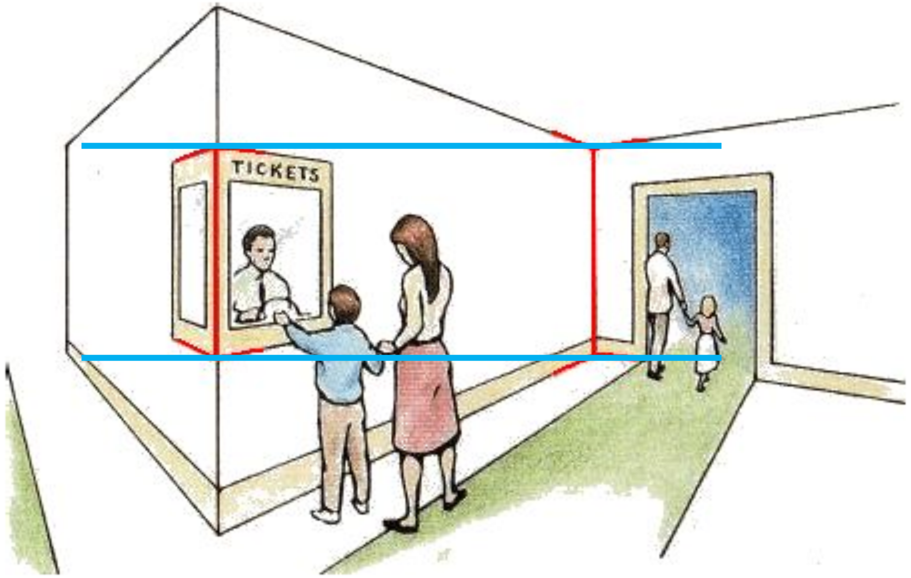
Lengths can’t be trusted...



...but humans adapt!



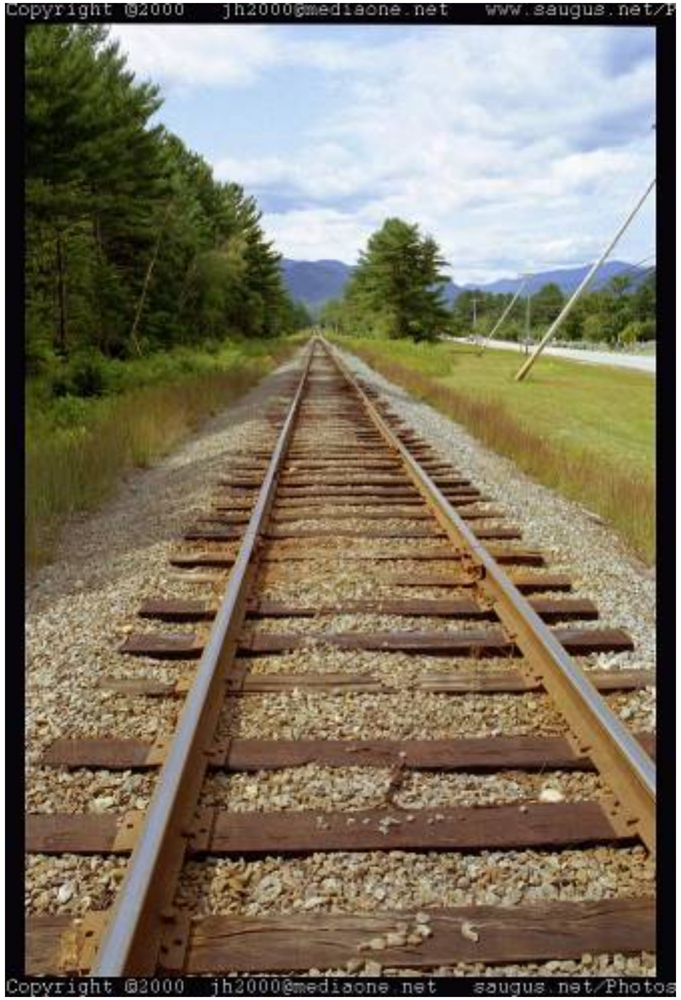
Müller-Lyer Illusion



We do not make measurements in the image plane

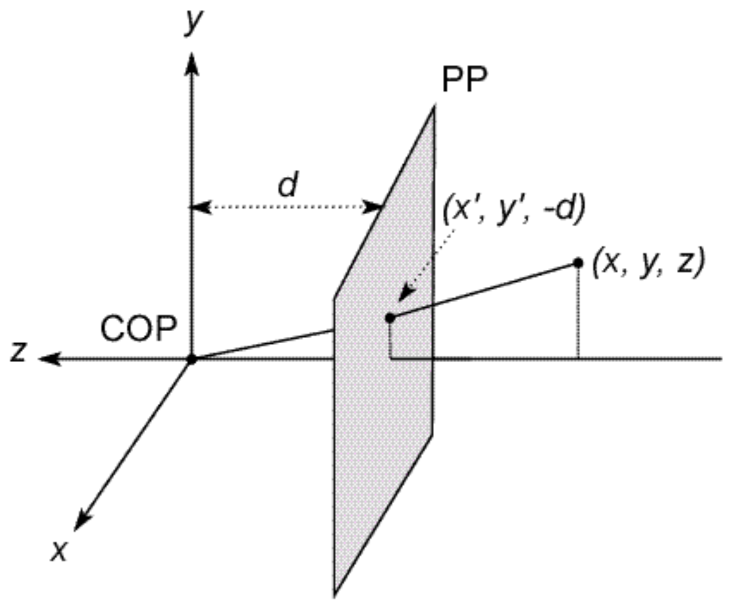
http://www.michaelbach.de/ot/sze_muelue/index.html

Angles can't be trusted...



Modeling projection (perspective)

- **The coordinate system**
  - We will use the pinhole model as an approximation
  - Put the optical center (Center Of Projection) at the origin
  - Put the image plane (Projection Plane) in front of the COP
    - Why?
  - The camera looks down the negative z axis
    - We need this if we want right-handed-coordinates



Slide by Steve Seitz

Left- and right-hand coordinates

- ➢ **With left hand: left hand coordinate**
- ➢ **With right hand: right hand coordinate**

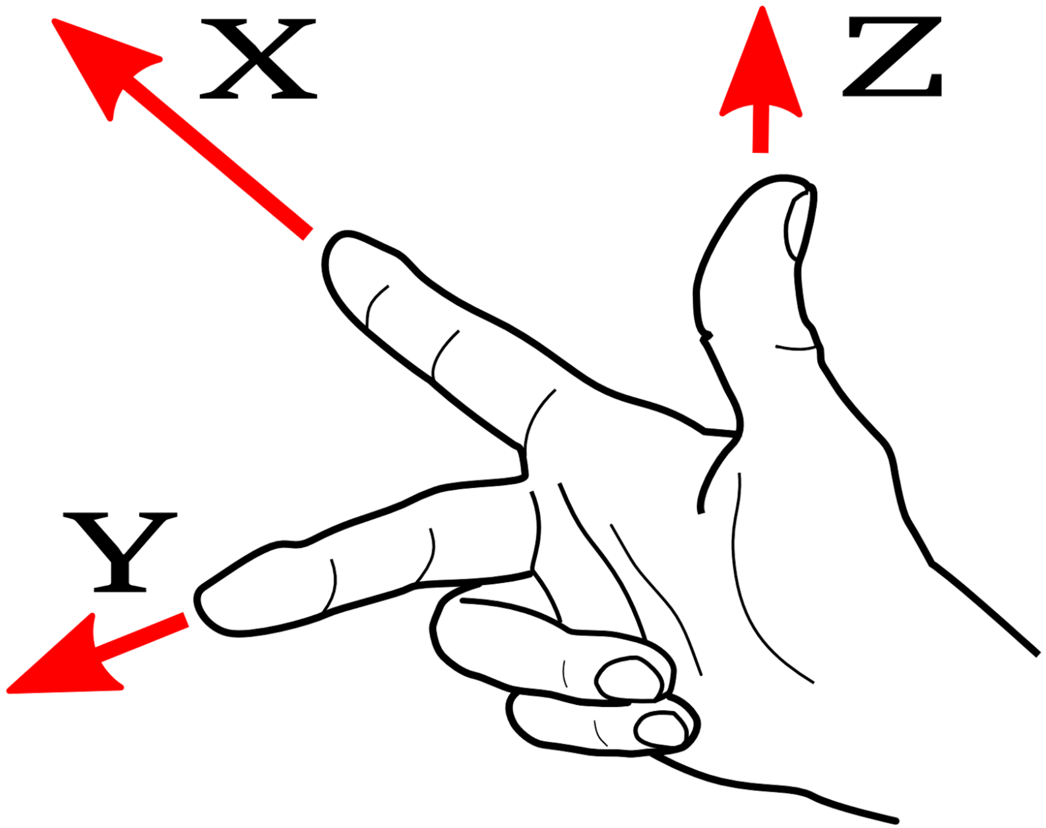
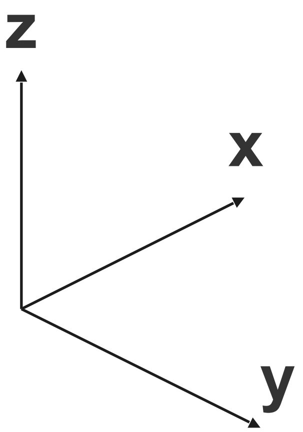
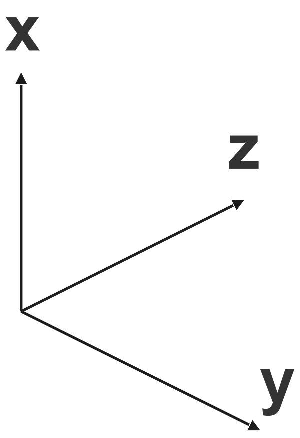


Image from Drew Noaks

Examples



Left-handed



Right-handed

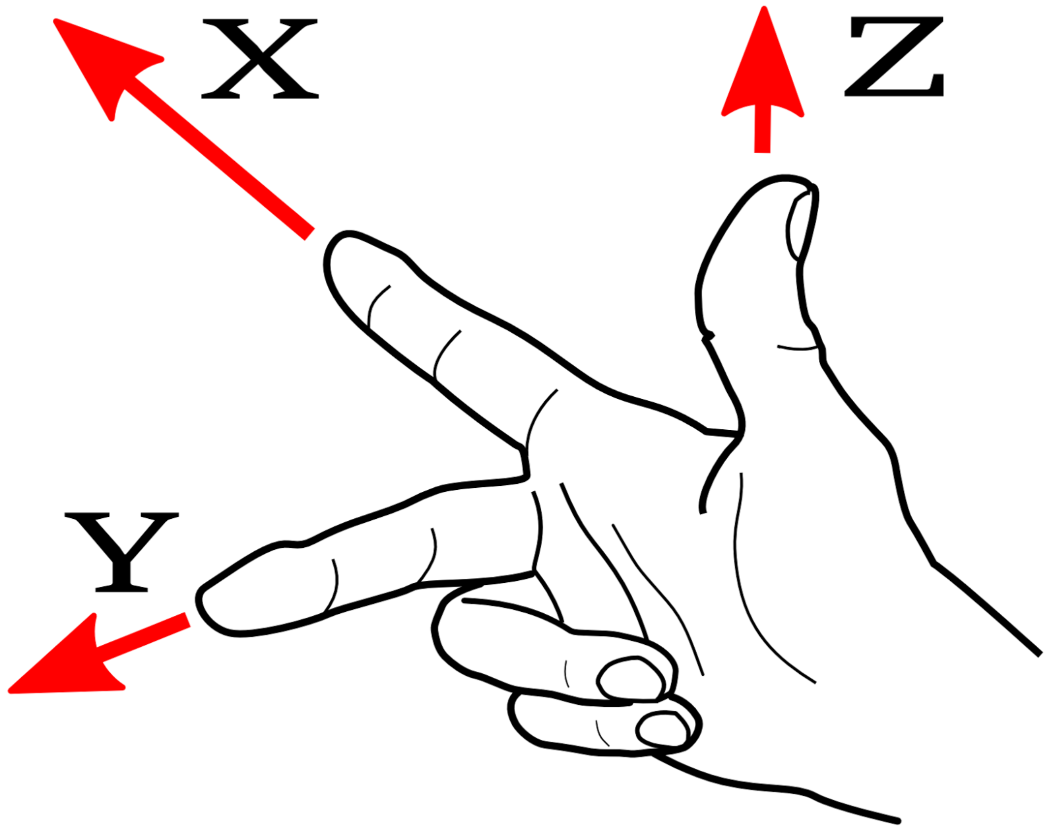


Image from Drew Noaks

Modeling projection (perspective)

➢ **Projection equations**

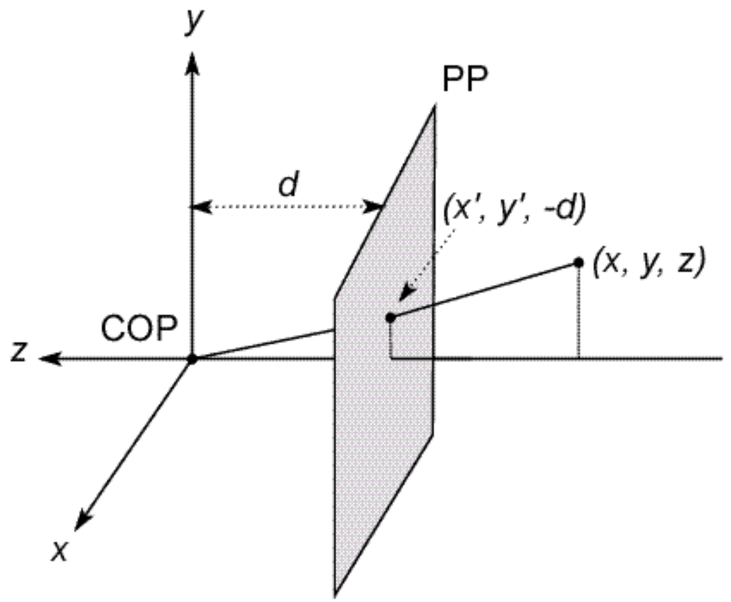
– **Compute intersection with PP of ray from (x,y,z) to COP**

– **Derived using similar triangles**

$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z},\ -d)$$

– **We get the projection by ignoring the last coordinate:**

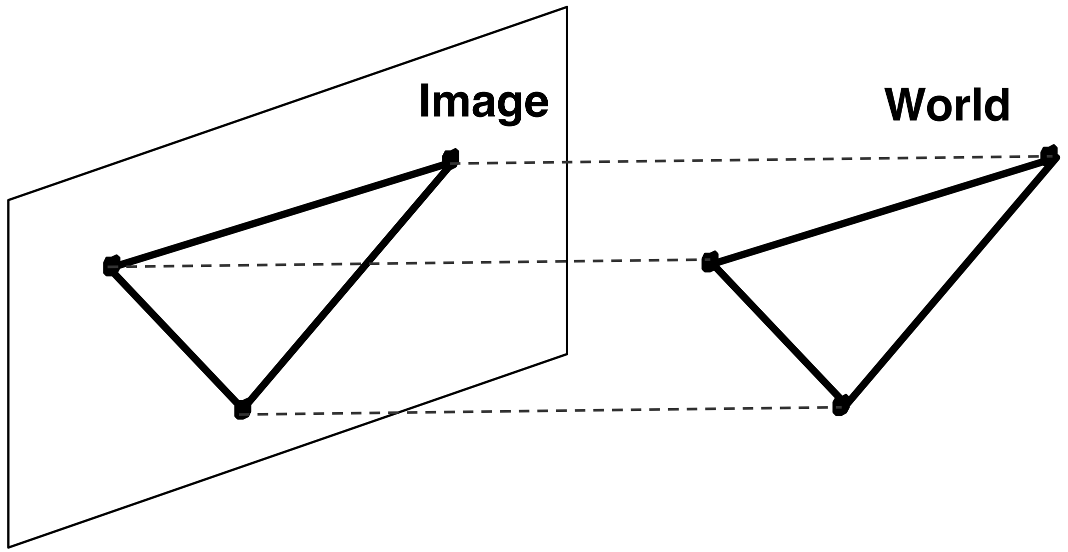
$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z})$$



Slide by Steve Seitz

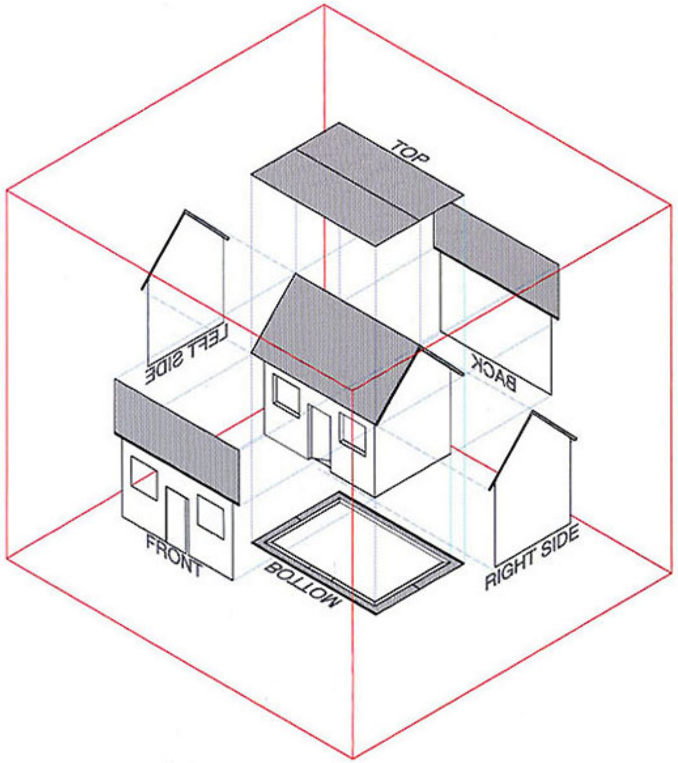
Orthographic Projection

- Drop the z coordinate
- Also called "parallel projection"
  - $x' = x$
  - $y' = y$



Orthographic Projection

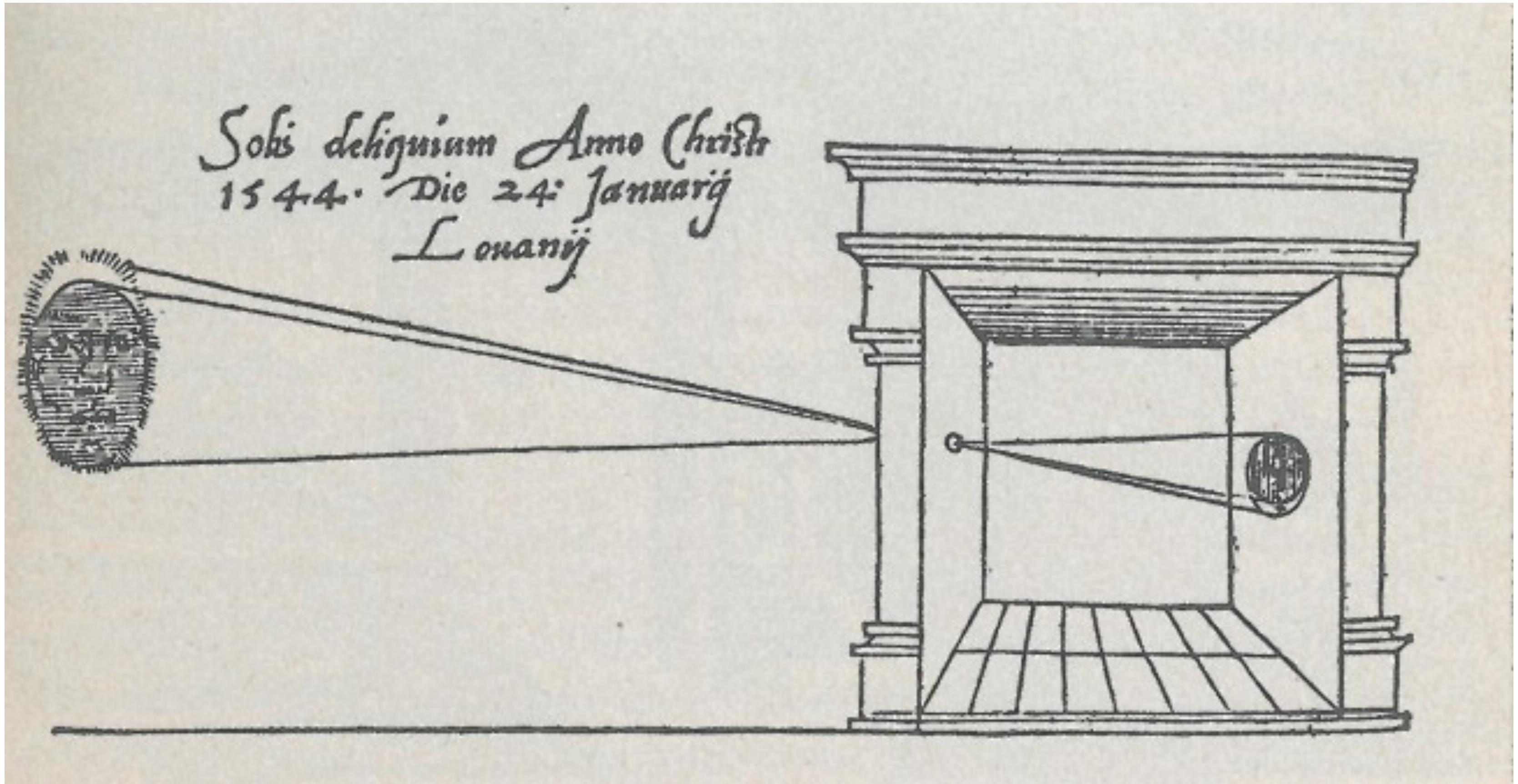
- Parallel lines remain parallel
- Application in technical drawing
- Projection in real cameras is perspective!



Building a real camera

Camera Obscura

First published picture of camera obscura (1545)



Depth of the room is the image distance

Pinhole cameras everywhere

Tree shadow during a solar eclipse

Photo credit: Nils van der Burg http://www.physicstogo.org/index.cfm

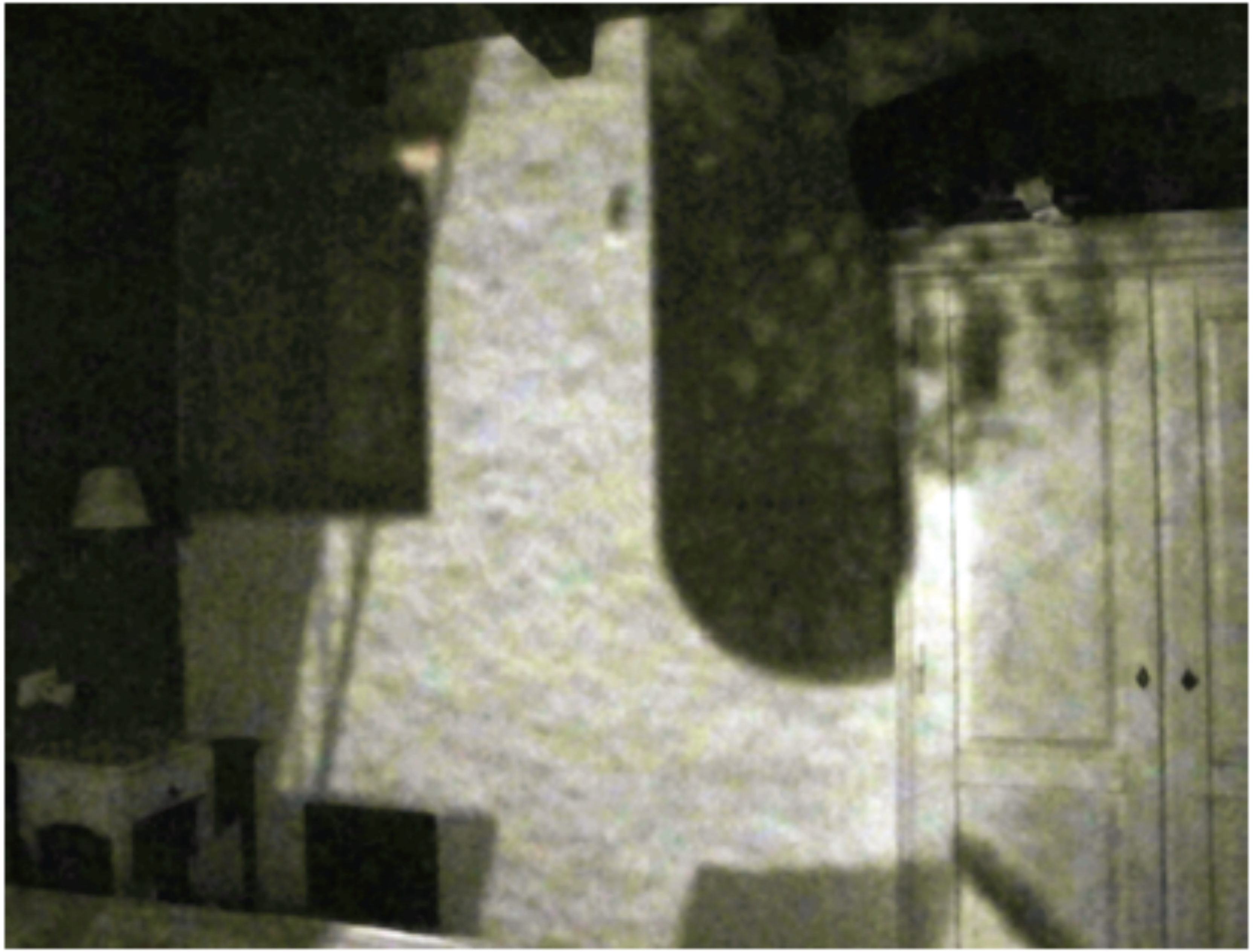
Slide by Steve

Accidental pinhole cameras

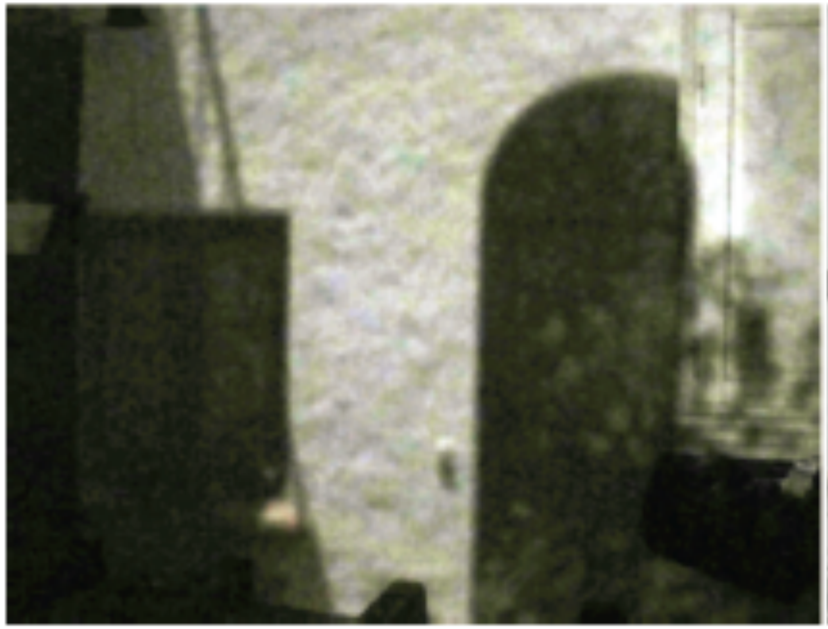
- **Accidental Pinholes produce images that are usually misinterpreted as shadows**

A. Torralba and W. Freeman, [Accidental Pinhole and Pinspeck Cameras](), CVPR 2012

Torralba and Freeman, CVPR’12



Window turned into a pinhole



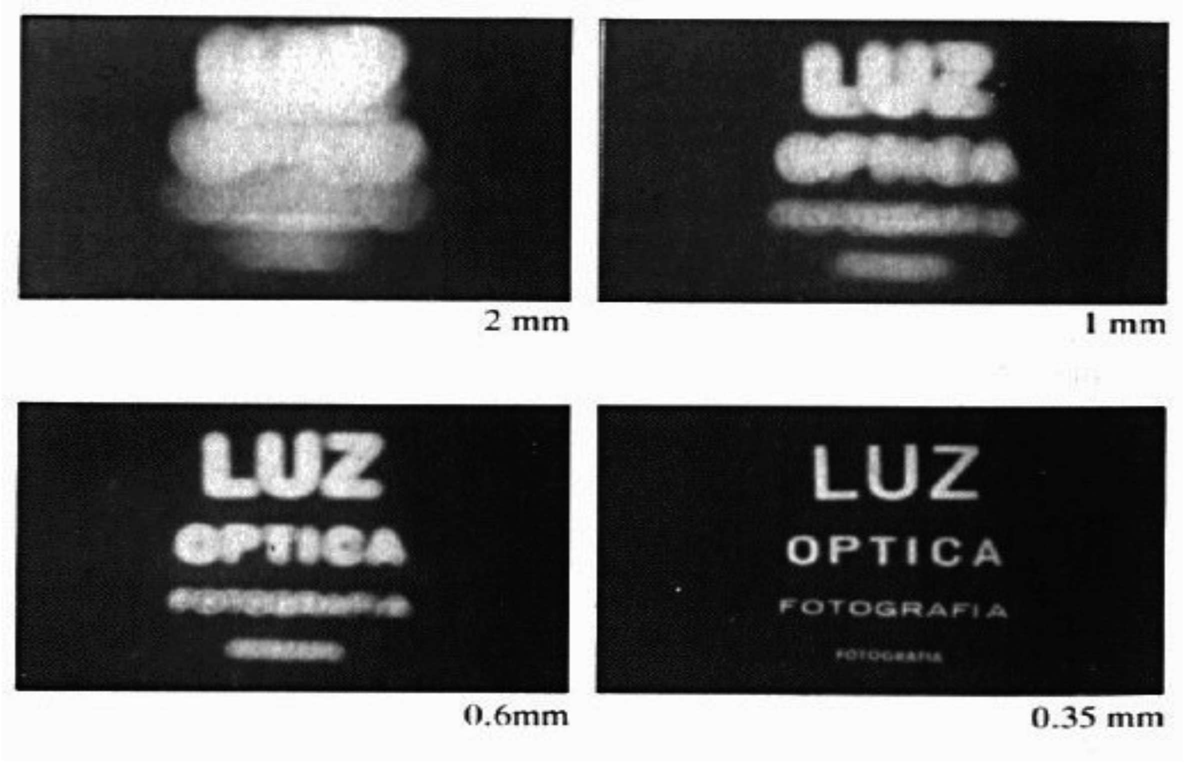
View outside

Home-made pinhole camera

➢ **Why is it so blurry?**

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

Shrinking the aperture



Shrinking the aperture

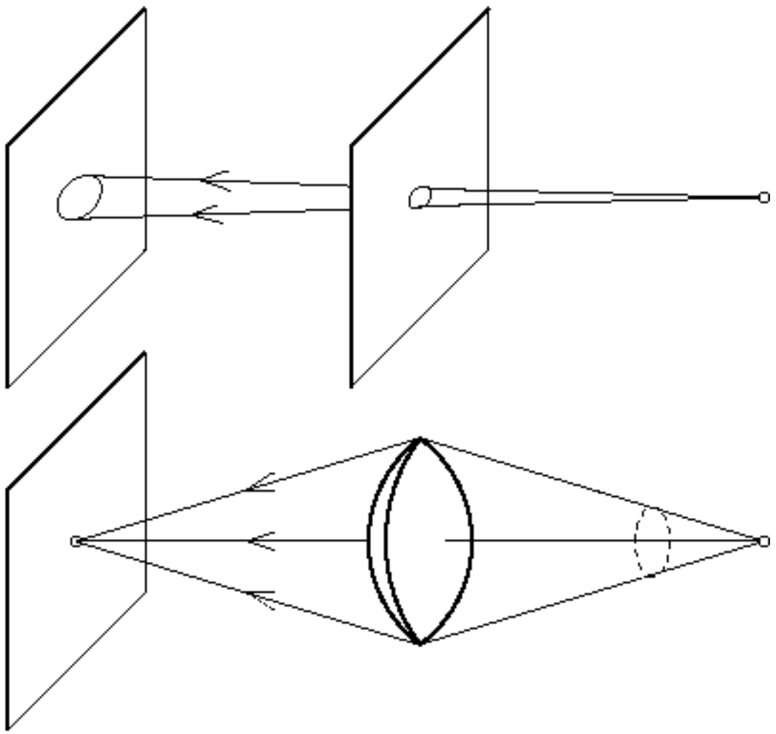
- Why not make the aperture as small as possible?
  - Problem 1: Less light gets through
    - We can increase the exposure, but causes motion blur
  - Problem 2: Diffraction effects

Slide by Steve Seitz

Shrinking the aperture

Use a lens

- Make the aperture larger, but use a lens to focus the light
- Refraction to the rescue



film/sensor

From Photography, London et al.

Assignment 1

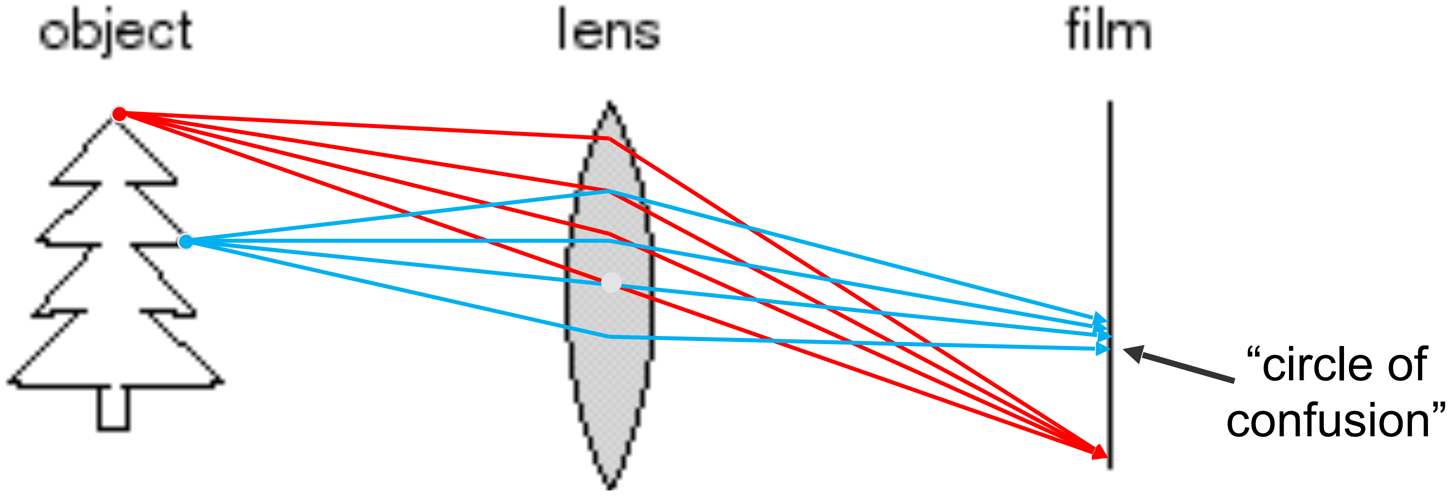
- ➢ **Building a pinhole camera using a cardboard box**
- ➢ **Requires a digital camera with the ability to capture long exposure images (15 – 30 seconds)**
- ➢ **There are apps that allow capturing images with long exposure**
- ➢ **Teams of up to 3**
- ➢ **Only one member submit the report via Canvas**
- ➢ **All team members receive the same grade**

Outline

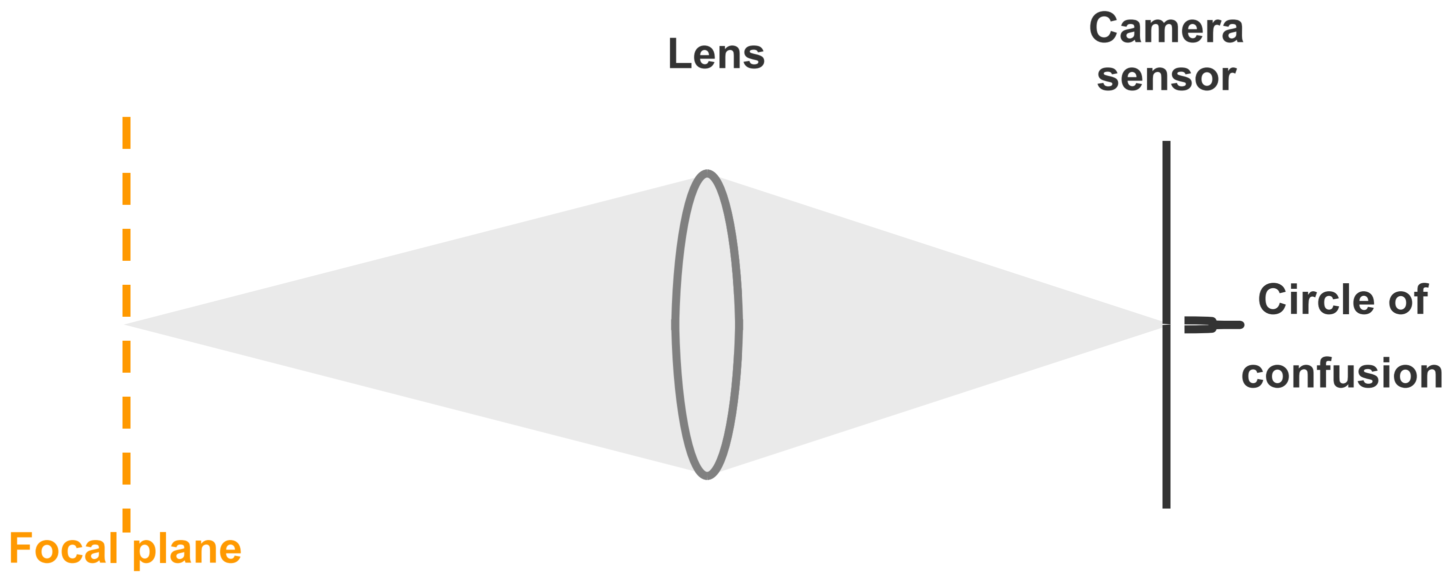
- ➢ **Pinhole camera**
- ➢ **Lens**
- ➢ **Depth of field**
- ➢ **Field of view**
- ➢ **Exposure**
- ➢ **Digital camera**

Focus and Defocus

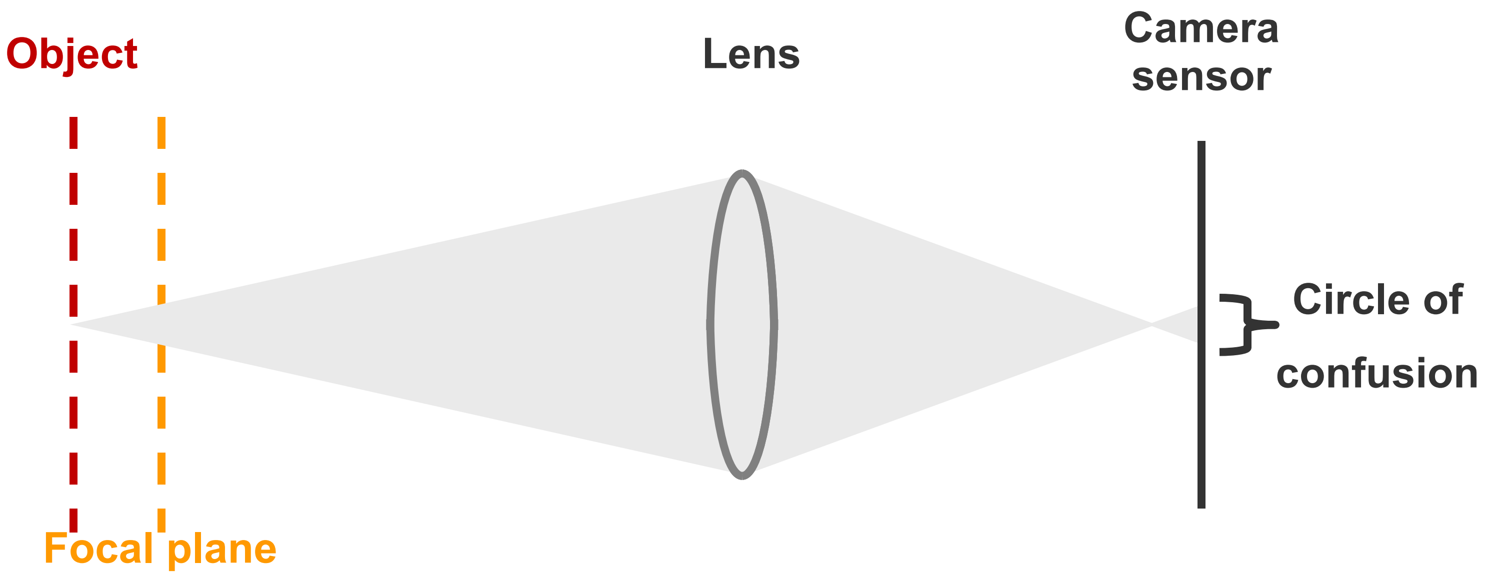
- A lens focuses light onto the film
  - A specific distance at which objects are "in focus"
  - Other points project to a "circle of confusion" in the image



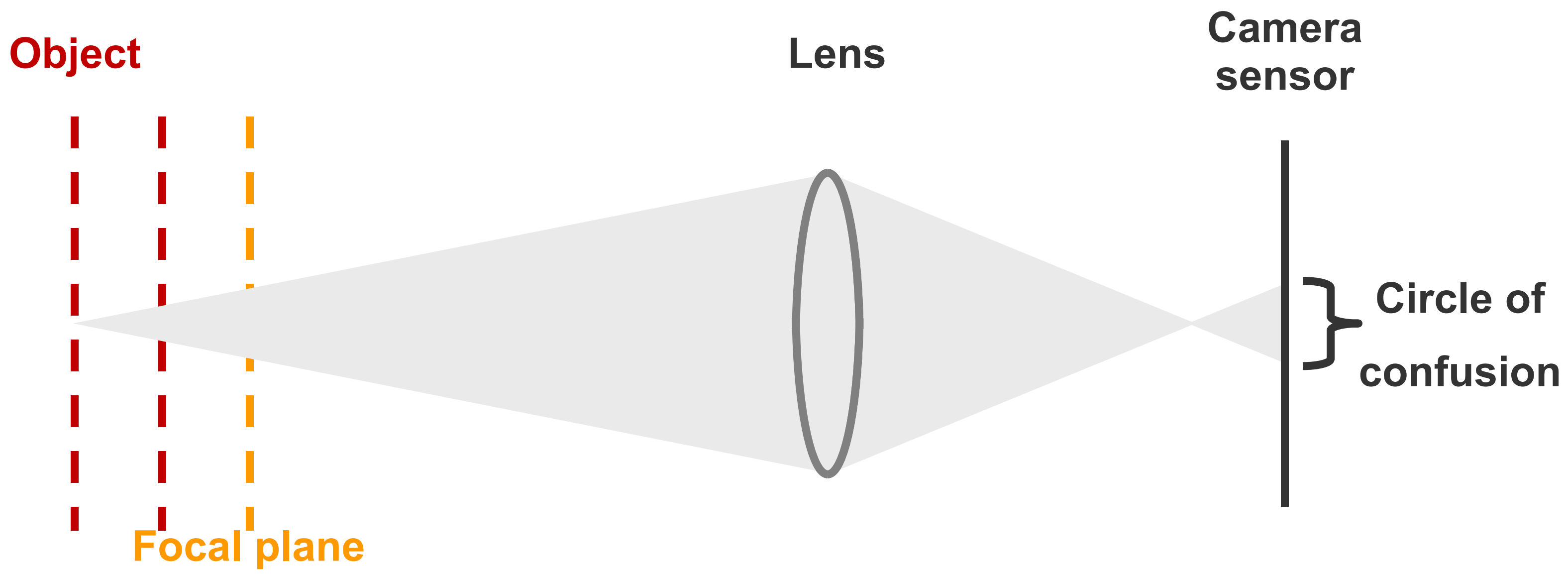
Lens and defocus



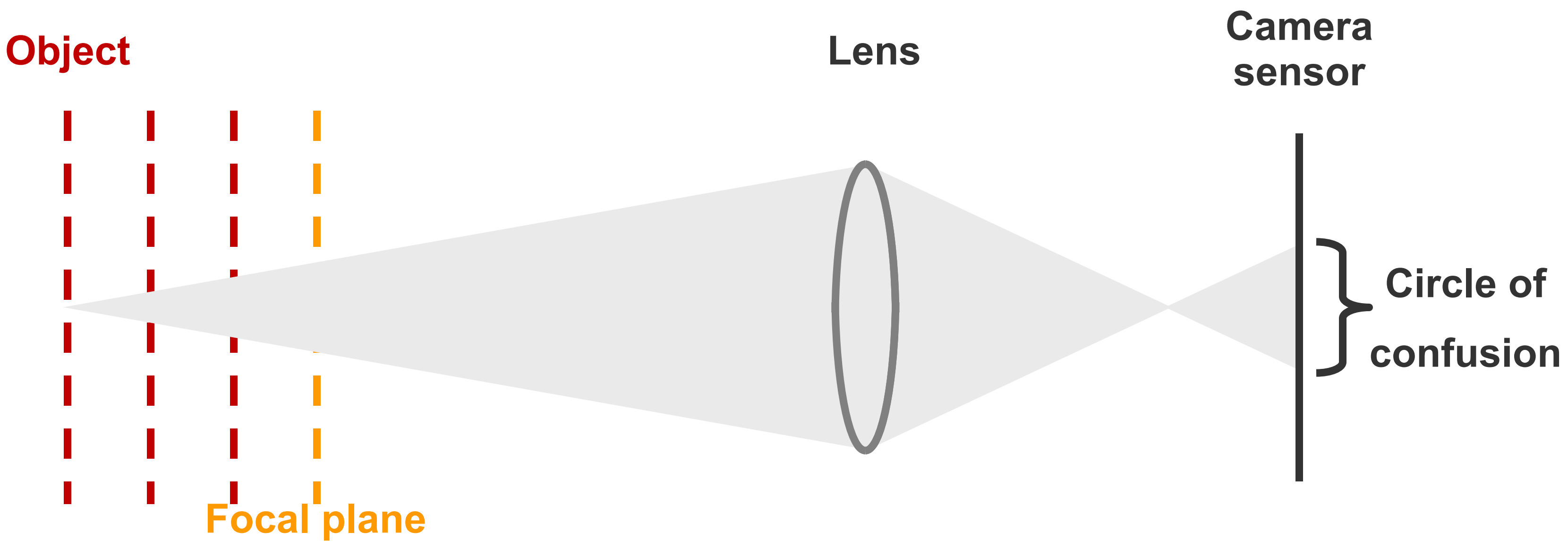
Lens and defocus



Lens and defocus

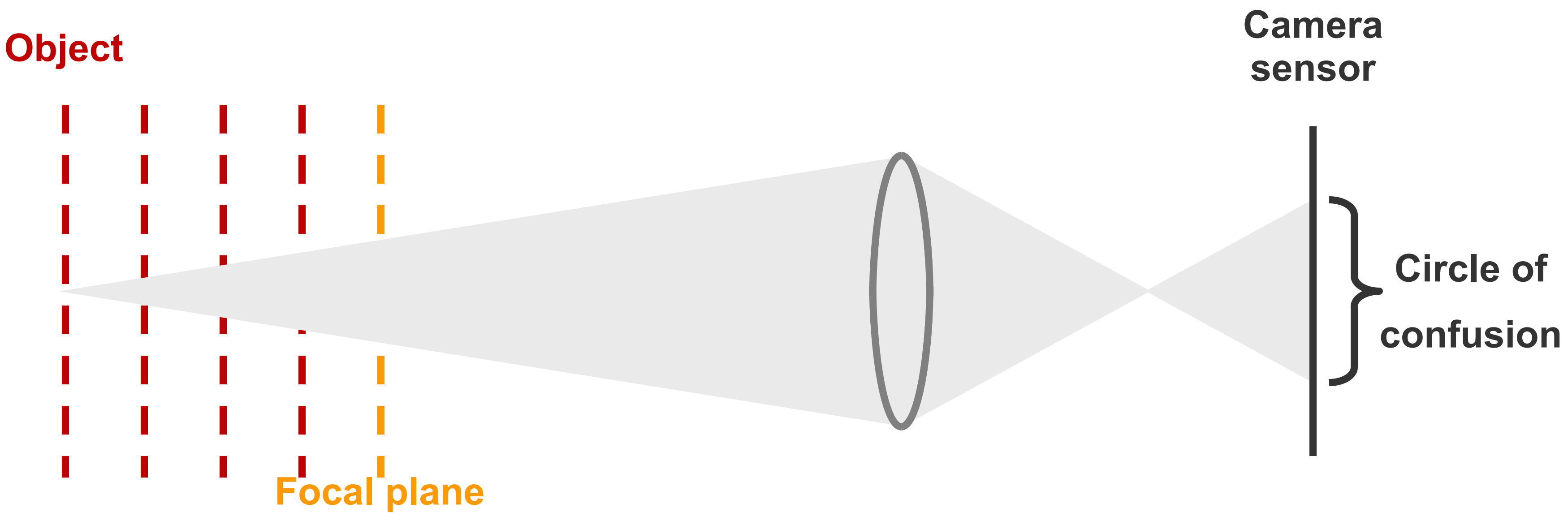


Lens and defocus



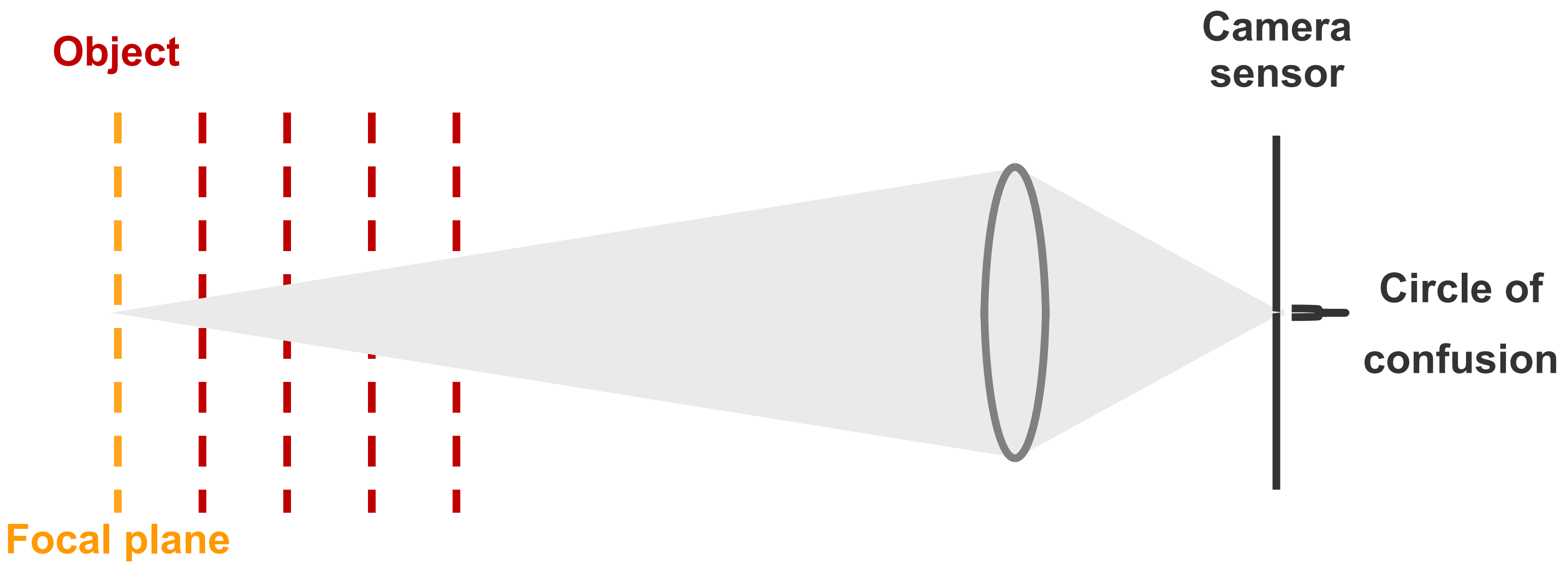
Lens and defocus

- What if we want to push the focal plane to where the object is?
  - Move the sensor closer to the lens



Lens and defocus

- What if we want to push the focal plane to where the object is?
  - Move the sensor closer to the lens
- What about focusing to infinity?
  - Move the sensor to the focal length



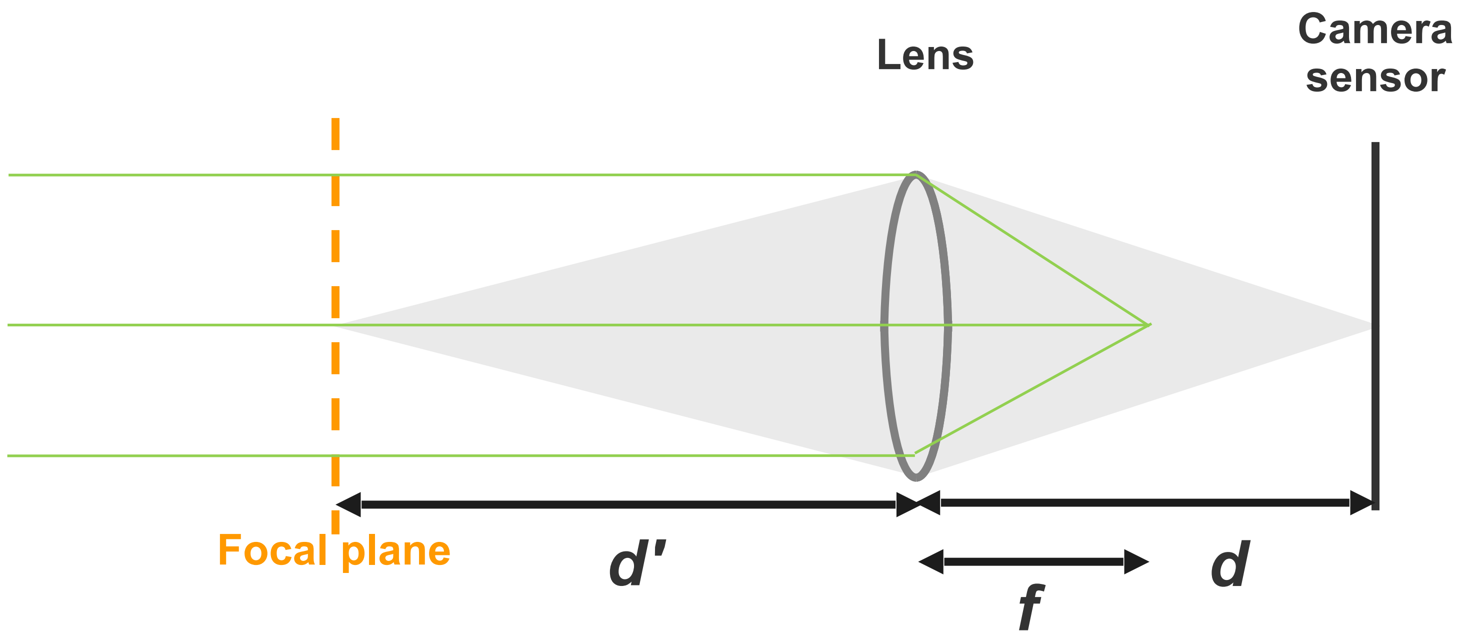
Focal Length

- ➢ The distance between sensor and lens when the camera is focused to infinity
- ➢ Focal length is the property of the lens

Terminology

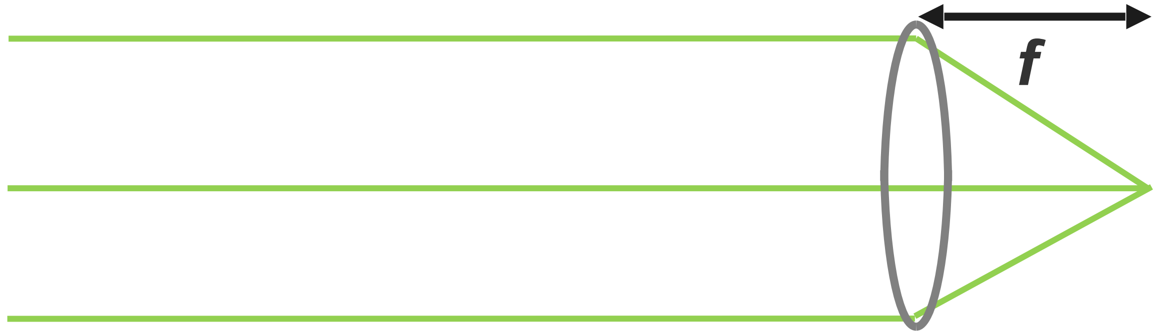
- Focal length (f)
- Image distance (d)
- Object distance (d’)

What is the relationship between them?

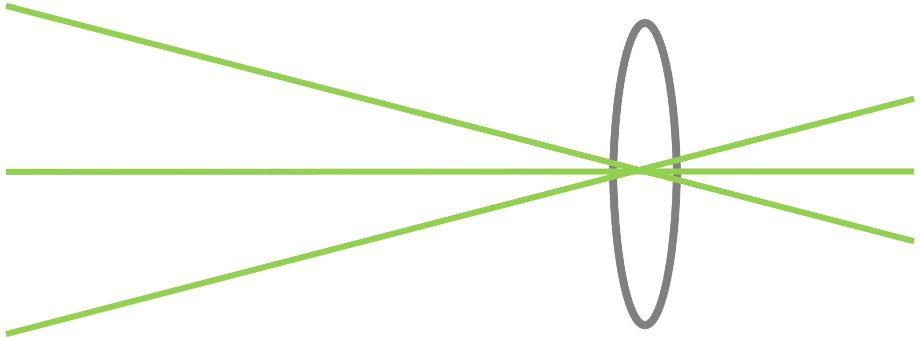


Thin lens optics

- ➢ **Thickness of the lens negligible compared to radii of the curvature**
- ➢ **Simplification of geometrical optics for well-behaved lenses**
- ➢ **All parallel rays converge to a point at the focal length f**

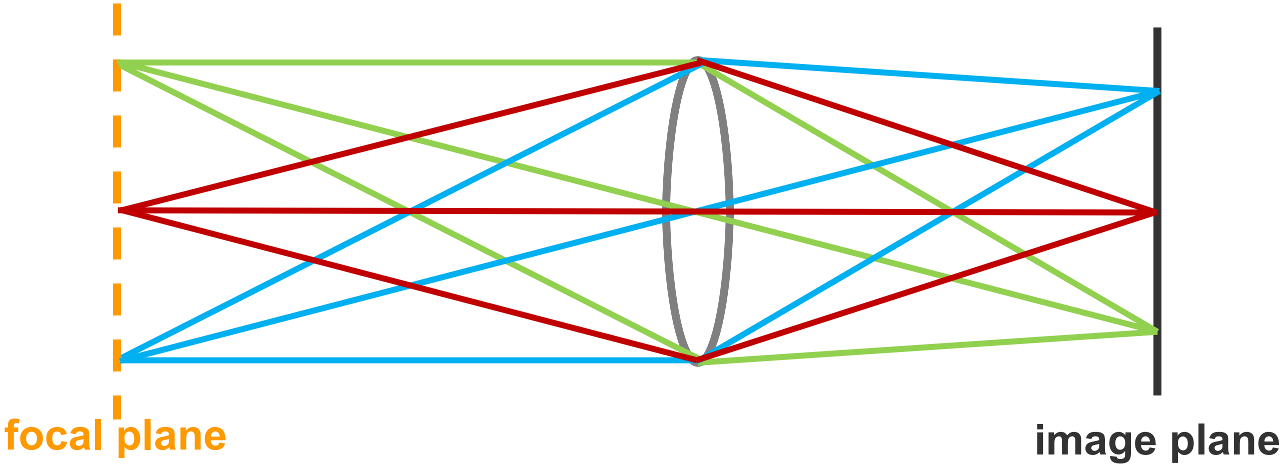


- ➢ **All rays going through the center are not deviated**



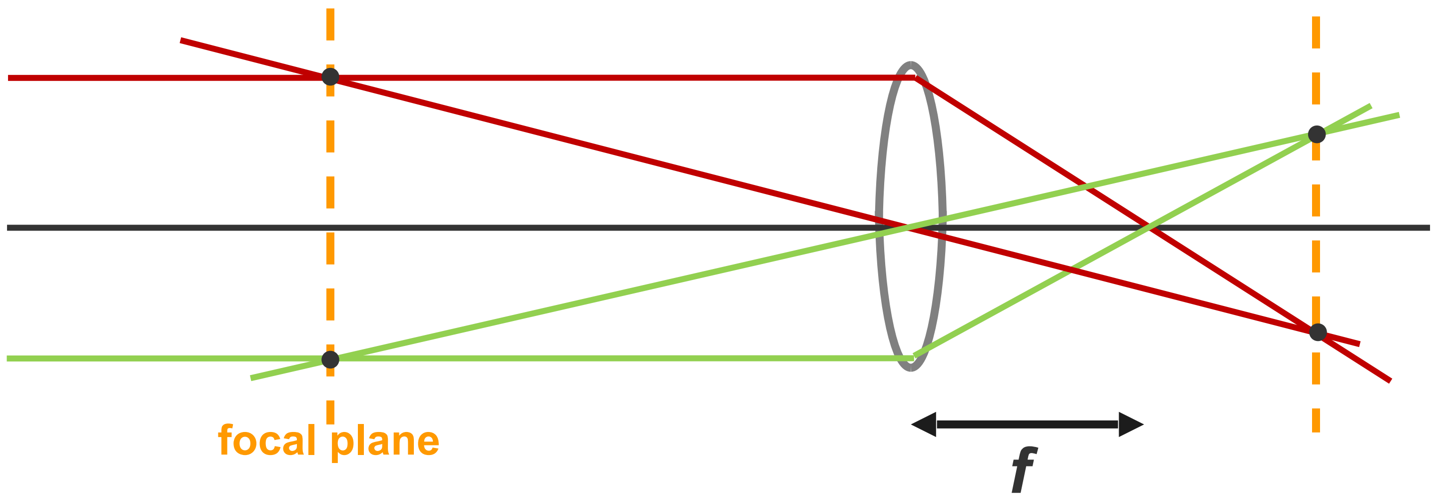
Focusing

- There is a focal plane for a given image plane
  - All rays coming from a point on the focal plane are focused to a point on the image plane

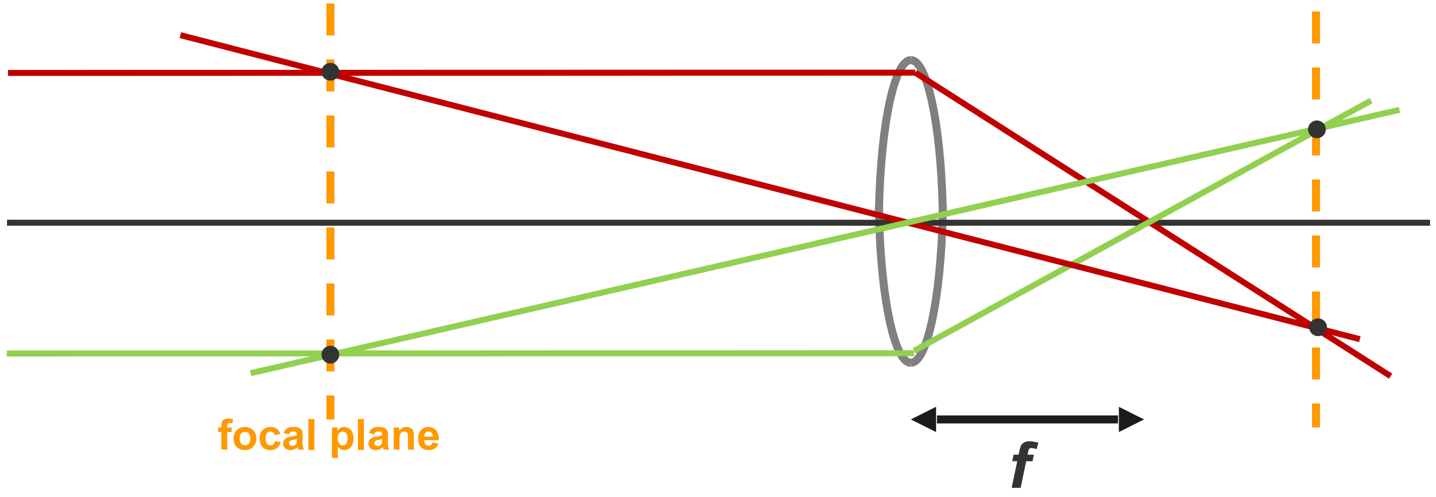


How to trace rays

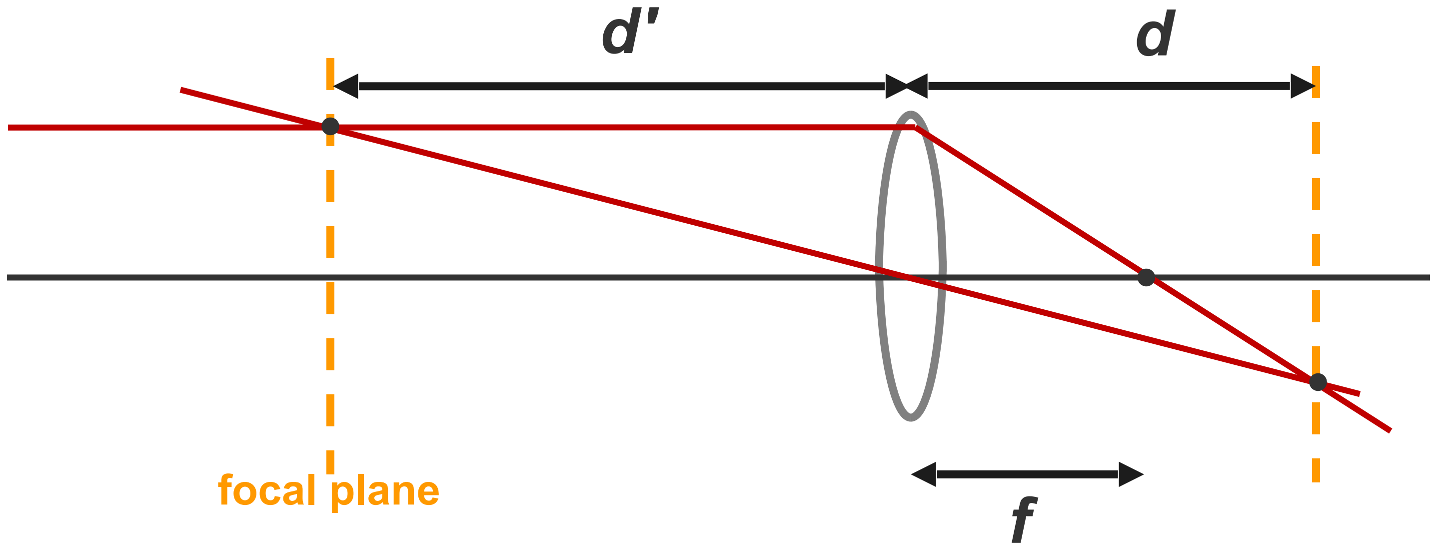
- ➢ Pick a focal plane
- ➢ Pick a focal length and trace the parallel lines
- ➢ Trace the rays through the center



Thin lens formula

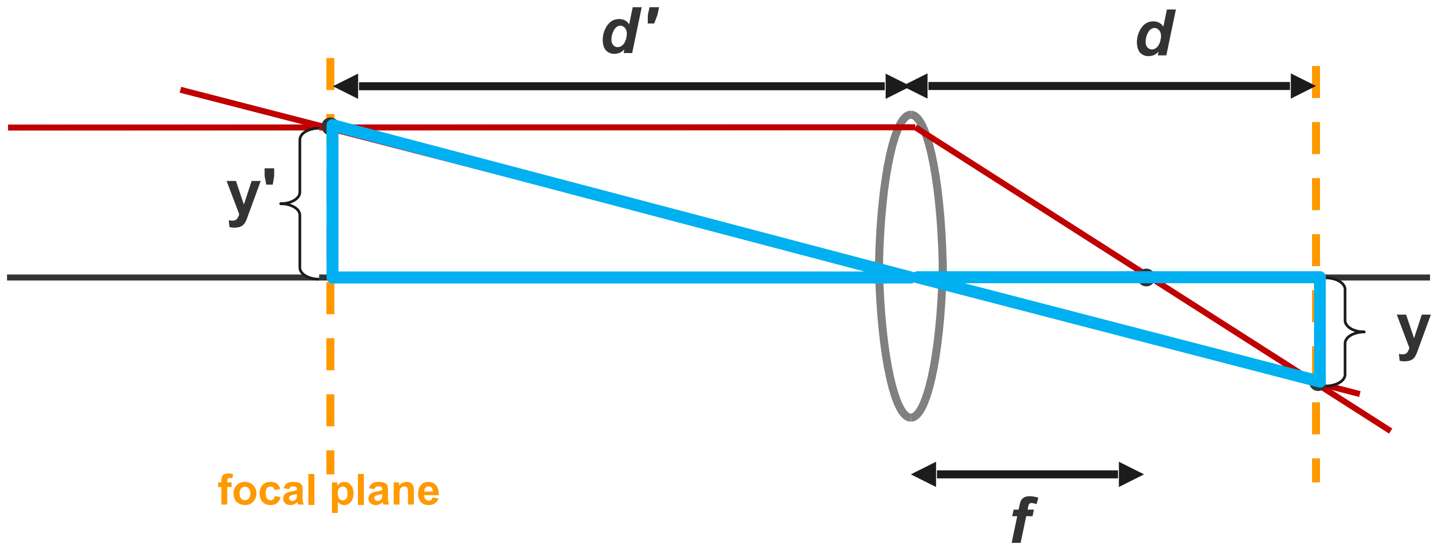


Thin lens formula



Thin lens formula

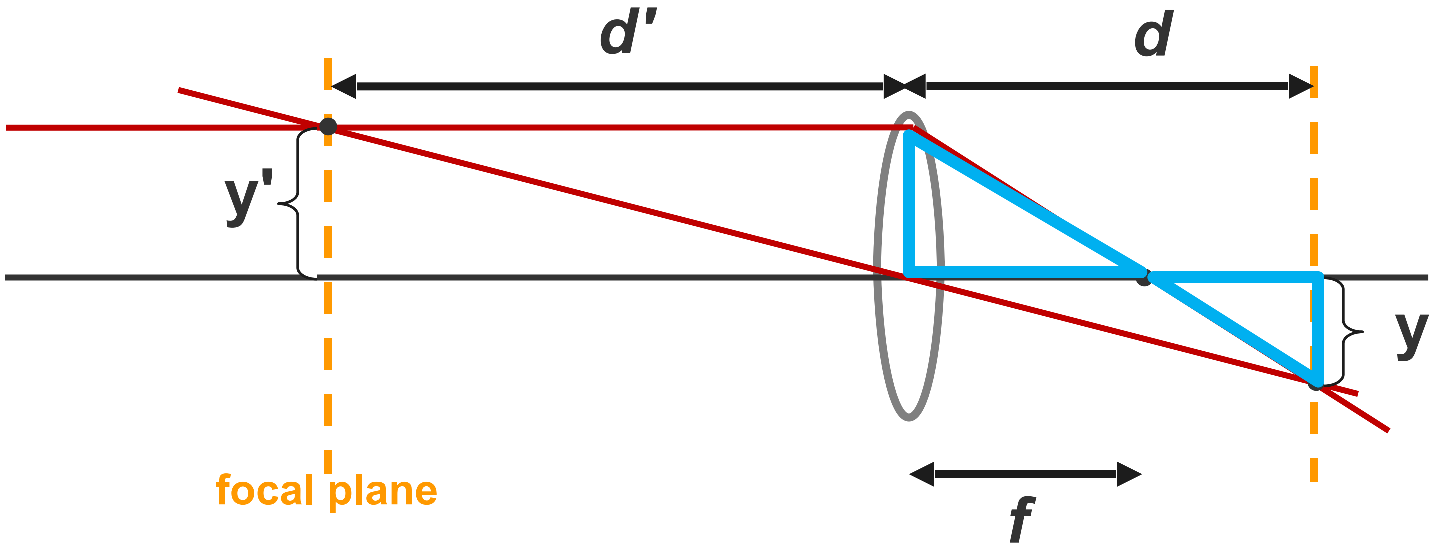
$$\frac{y'}{y} = \frac{d'}{d}$$



Thin lens formula

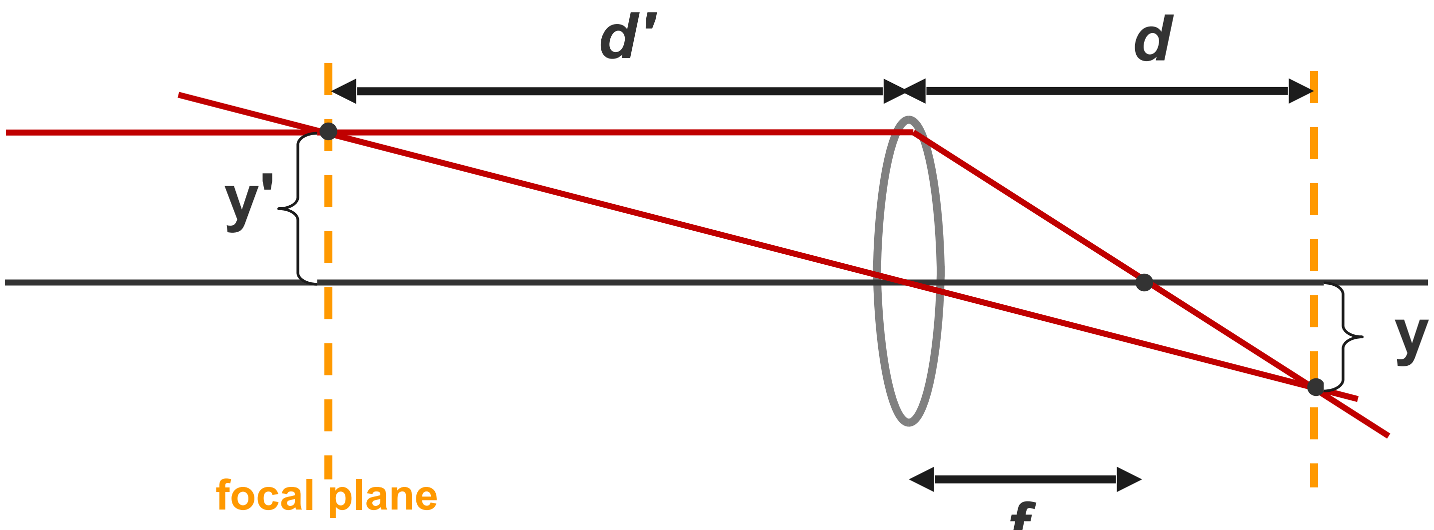
$$\frac{y'}{y} = \frac{d'}{d}$$

$$\frac{y'}{y} = \frac{f}{d - f}$$



Thin lens formula

$$\left.\begin{array}{l} \dfrac{y'}{y} = \dfrac{d'}{d} \\[2ex] \dfrac{y'}{y} = \dfrac{f}{d-f} \end{array}\right\} \quad \boxed{\frac{1}{d'} + \frac{1}{d} = \frac{1}{f}}$$



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- ➢ **Digital camera**

Depth of field

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

Depth of field

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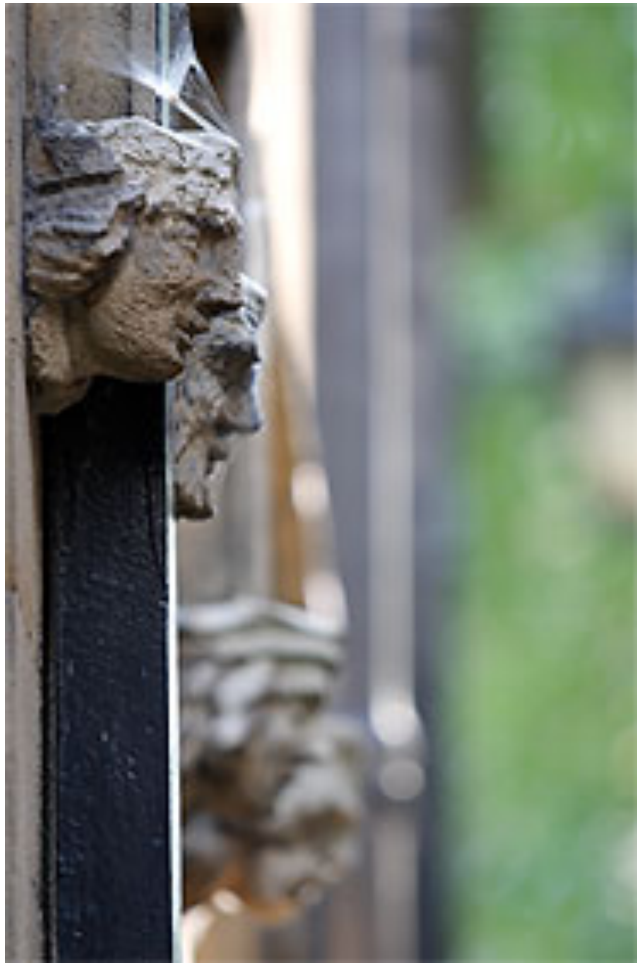
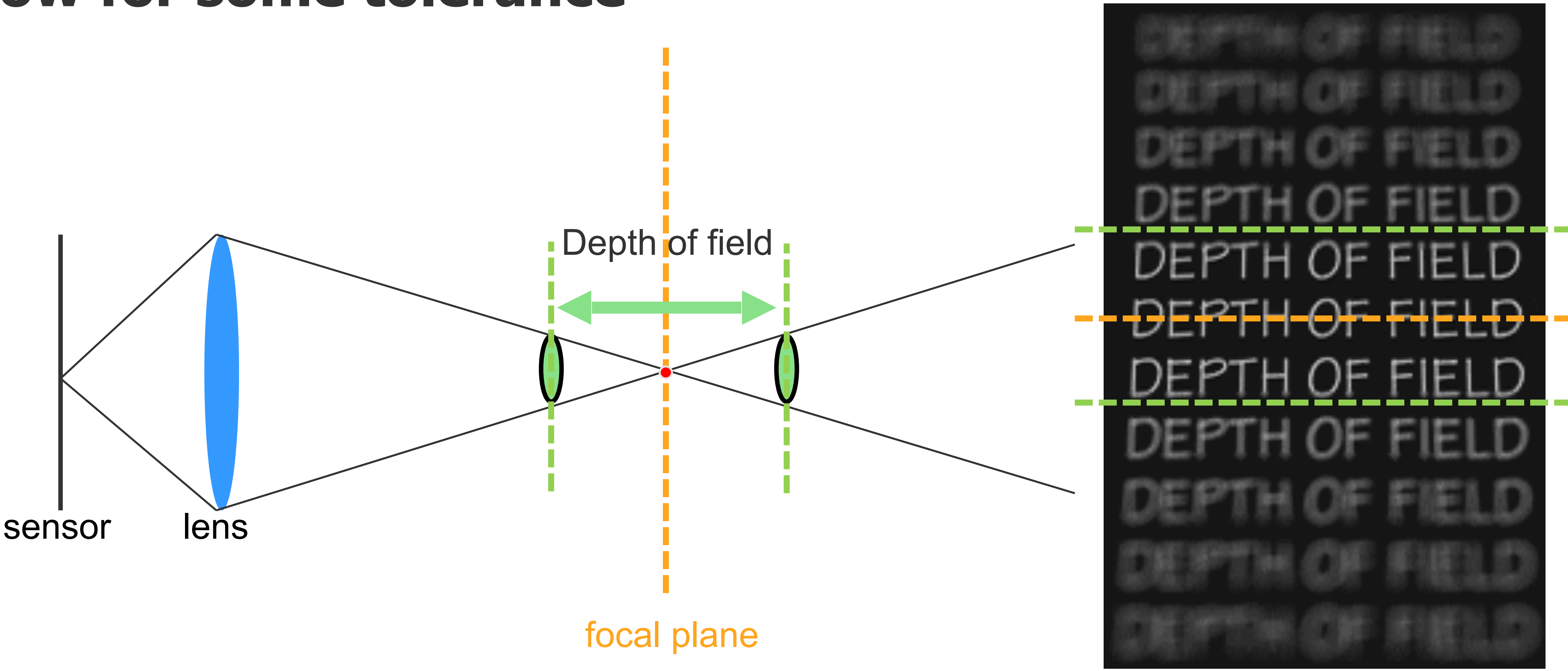
Depth of field



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

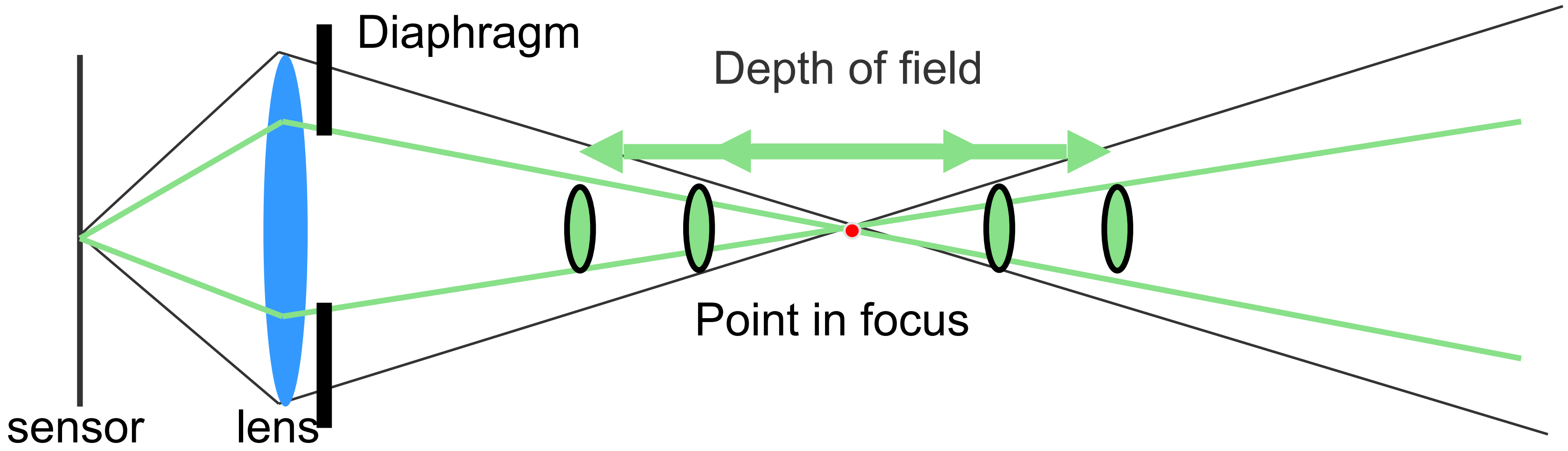
Depth of field

➢ **We allow for some tolerance**



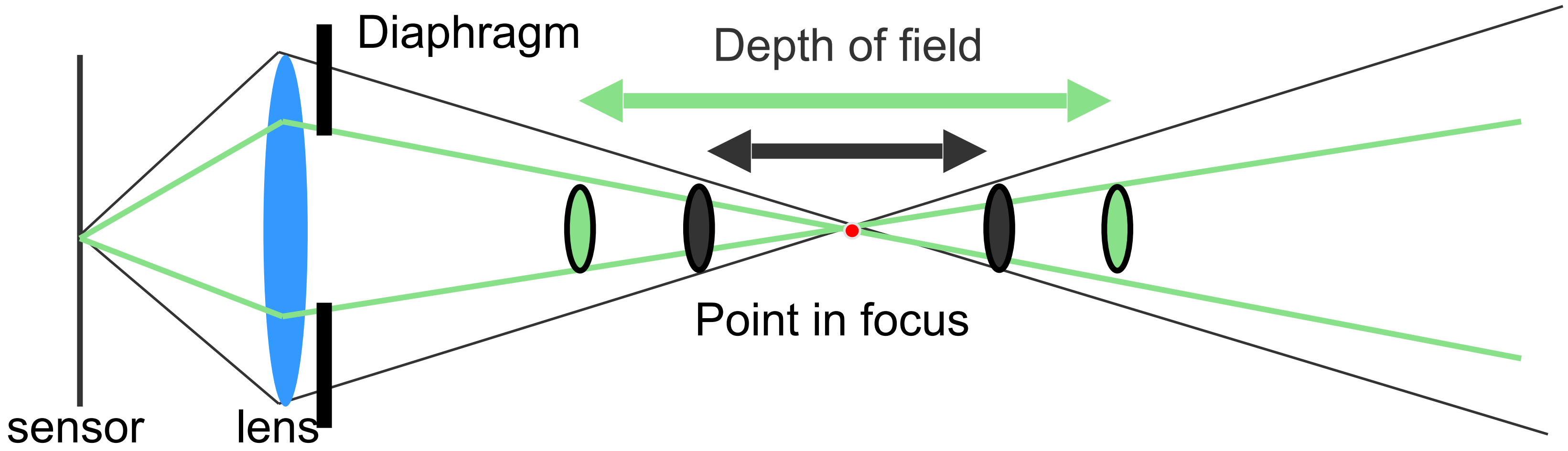
Controlling depth of field

- How can we increase the depth of field?
  - By reducing the size of the aperture

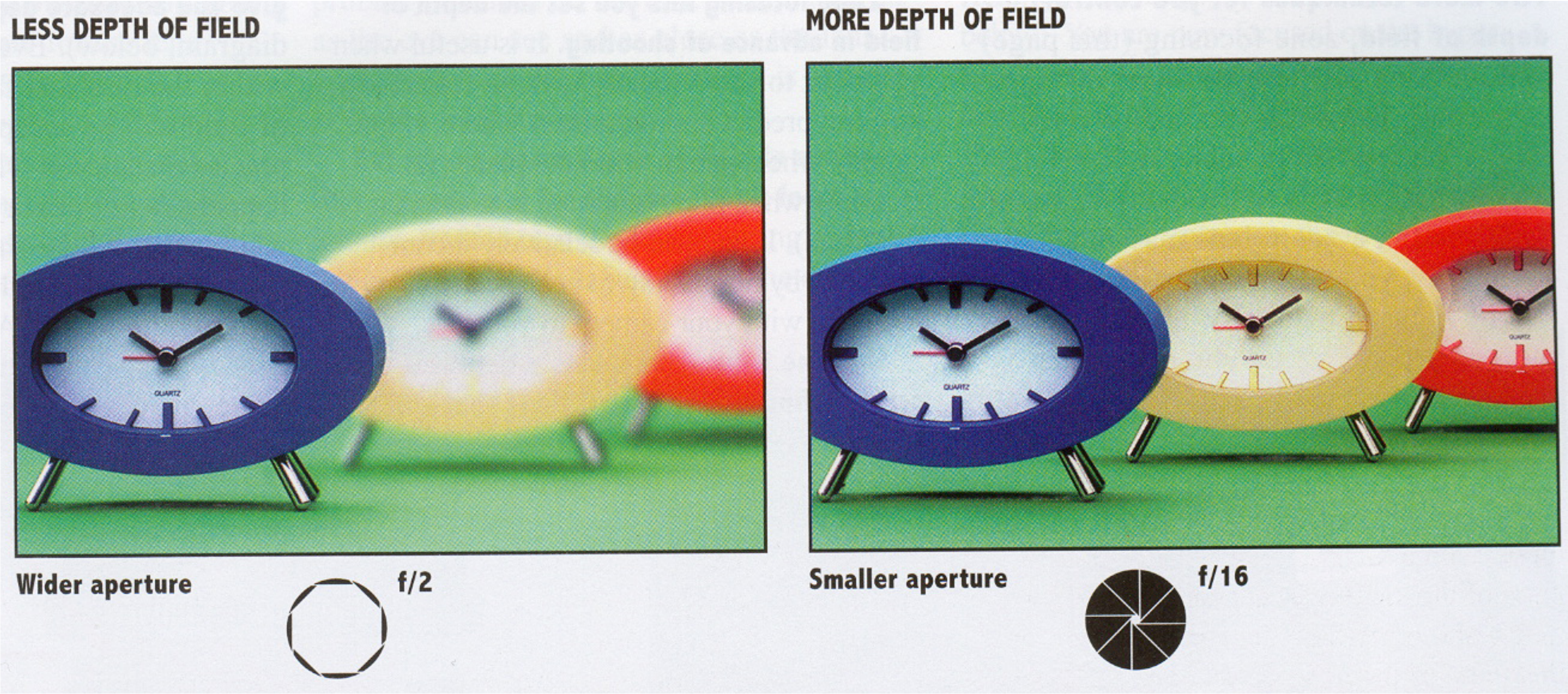


Controlling depth of field

- How can we increase the depth of field?
  - By reducing the size of the aperture
- If we decrease the aperture diameter by a factor of 2
  - The DoF increases by a factor of 2 (similar triangles)



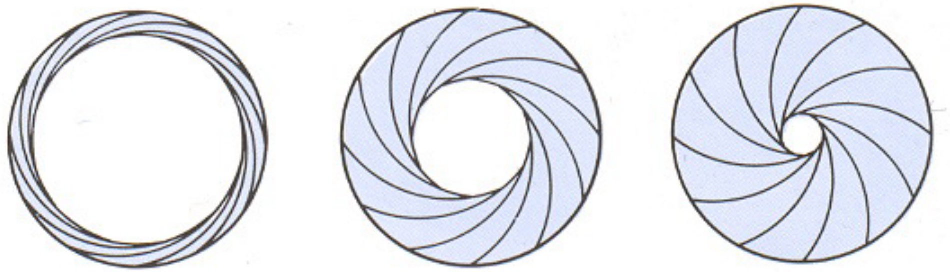
Depth of field



From Photography, London et al.

Aperture

- Diameter of the lens opening (controlled by diaphragm)
- Expressed as a fraction of focal length, in f-number
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- Small f number = big aperture



Full aperture   Medium aperture   Stopped down

Focal length

$$D = \frac{f}{N}$$

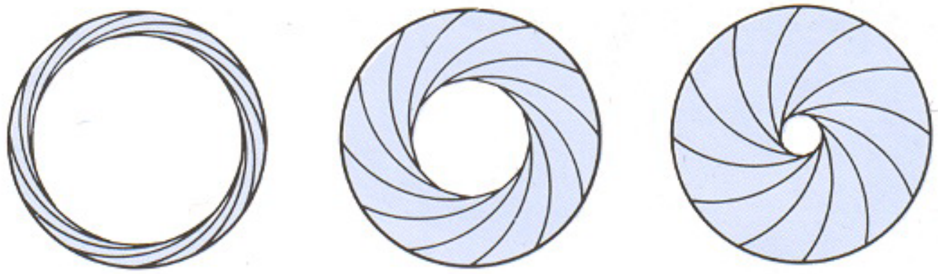
Aperture diameter

F-number

Aperture

- What happens to the area of the aperture when going from f/2.0 to f/4.0?
  - Divided by 4
- Typical f numbers are

  f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32
  - See the pattern?



Full aperture Medium aperture Stopped down

Focal length

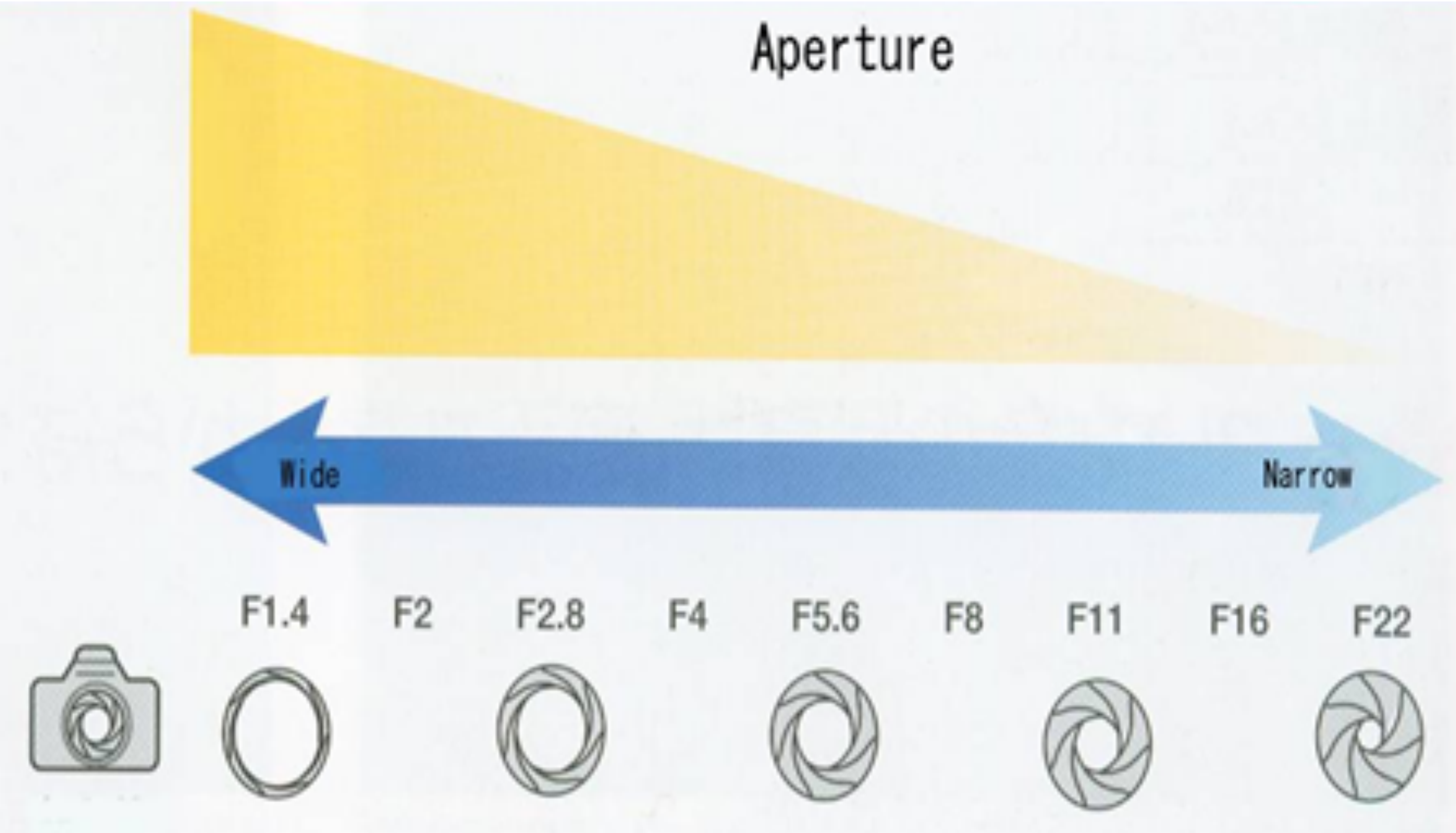
$$D = \frac{f}{N}$$

Aperture diameter

F-number

$$\text{Area} = \pi \left(\frac{f}{2N}\right)^2$$

F-number: focal length/aperture diameter

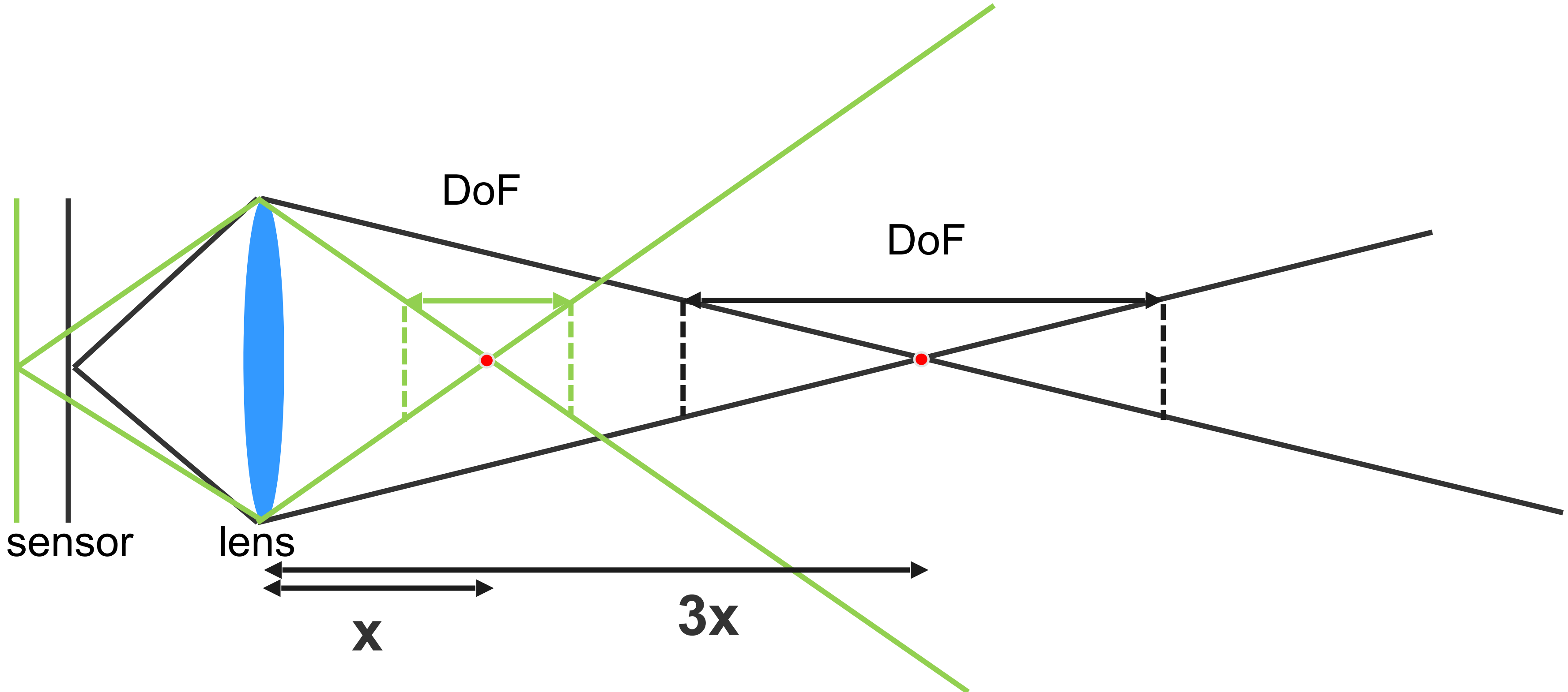


Varying the aperture

Wide apeture = small DOF   Narrow apeture = large DOF

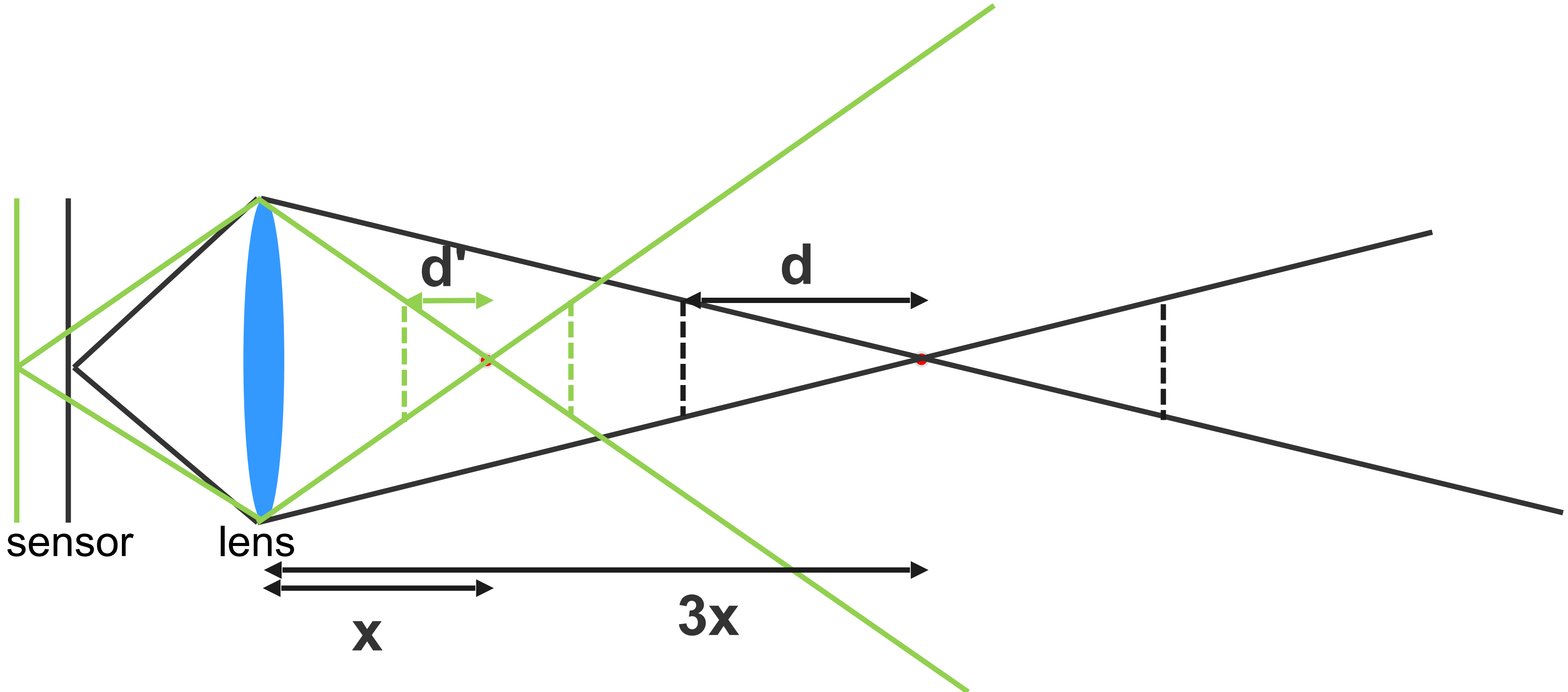
Depth of field & focusing distance

➢ **What happens when we divide focusing distance by three?**



Depth of field & focusing distance

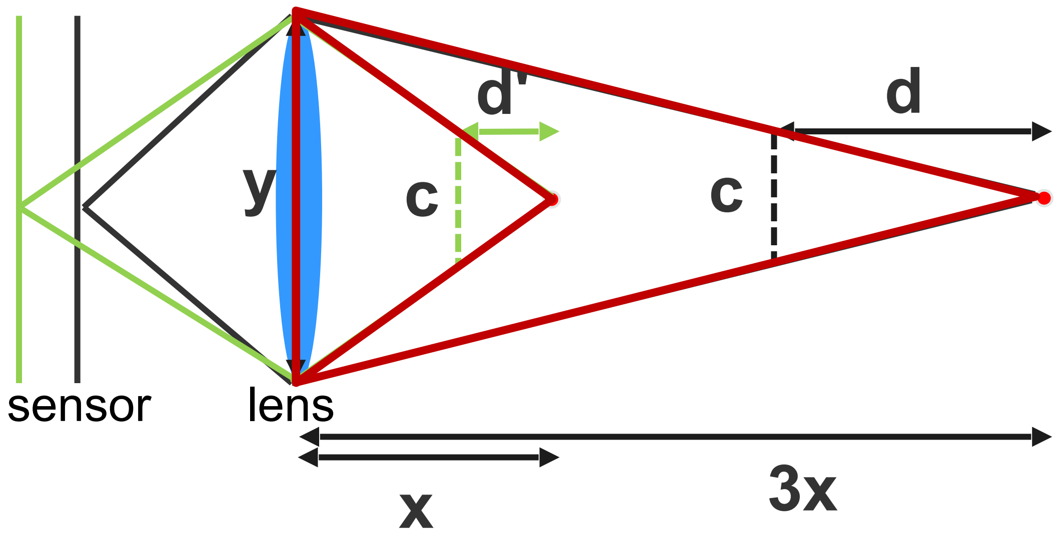
- What happens when we divide focusing distance by three?



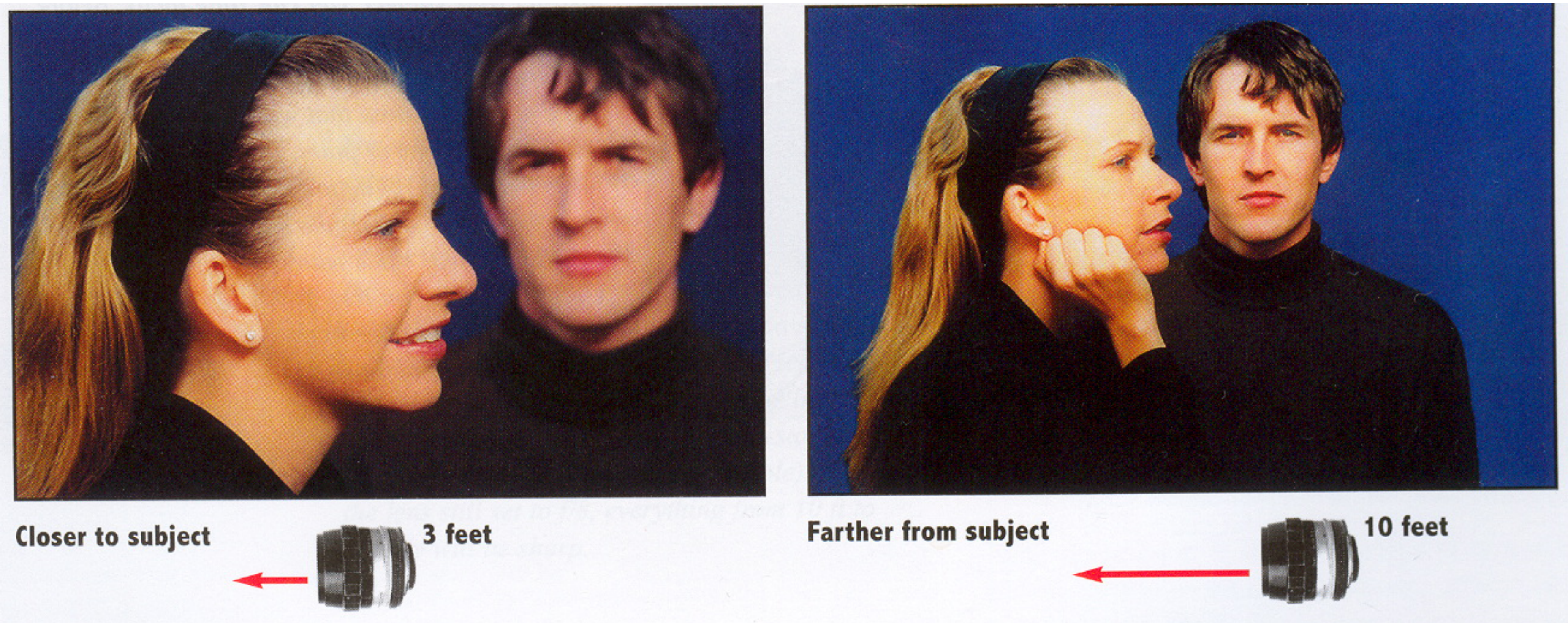
Depth of field & focusing distance

- What happens when we divide focusing distance by three?
  - Similar triangles => divided by three as well

$$\frac{y}{c} = \frac{x}{d'} \qquad \frac{y}{c} = \frac{3x}{d} \quad \Longrightarrow \quad d = 3d'$$

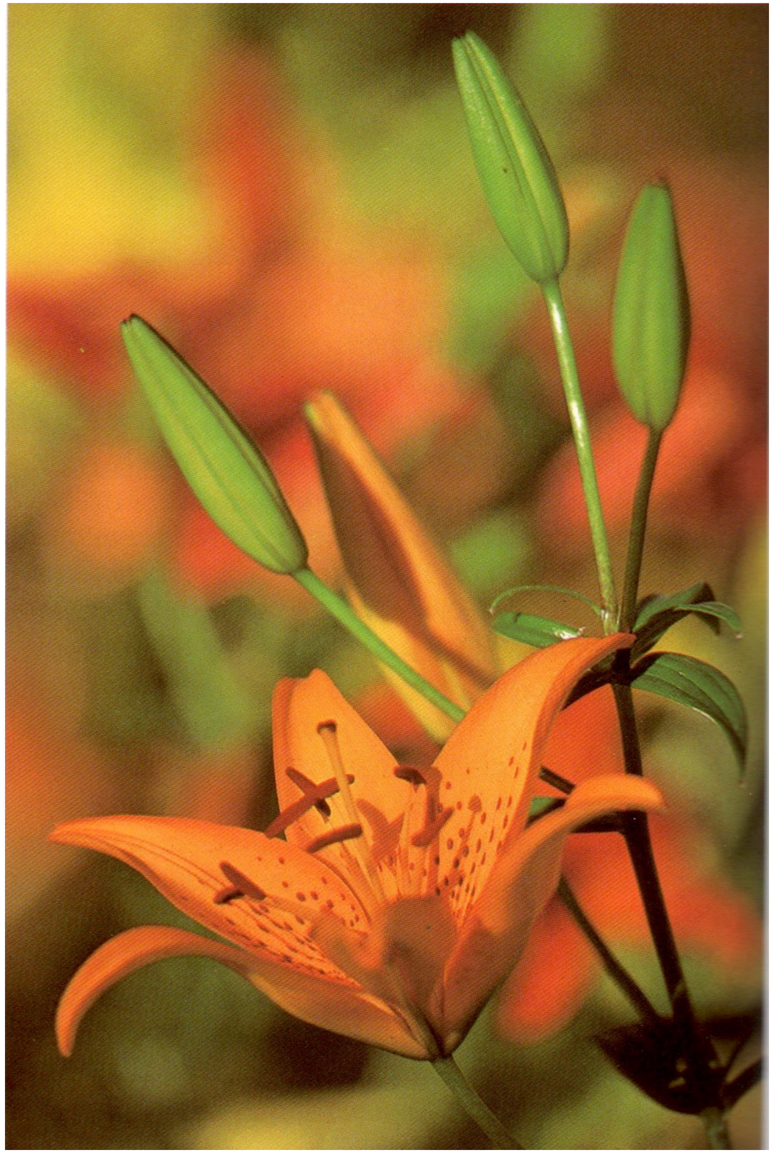


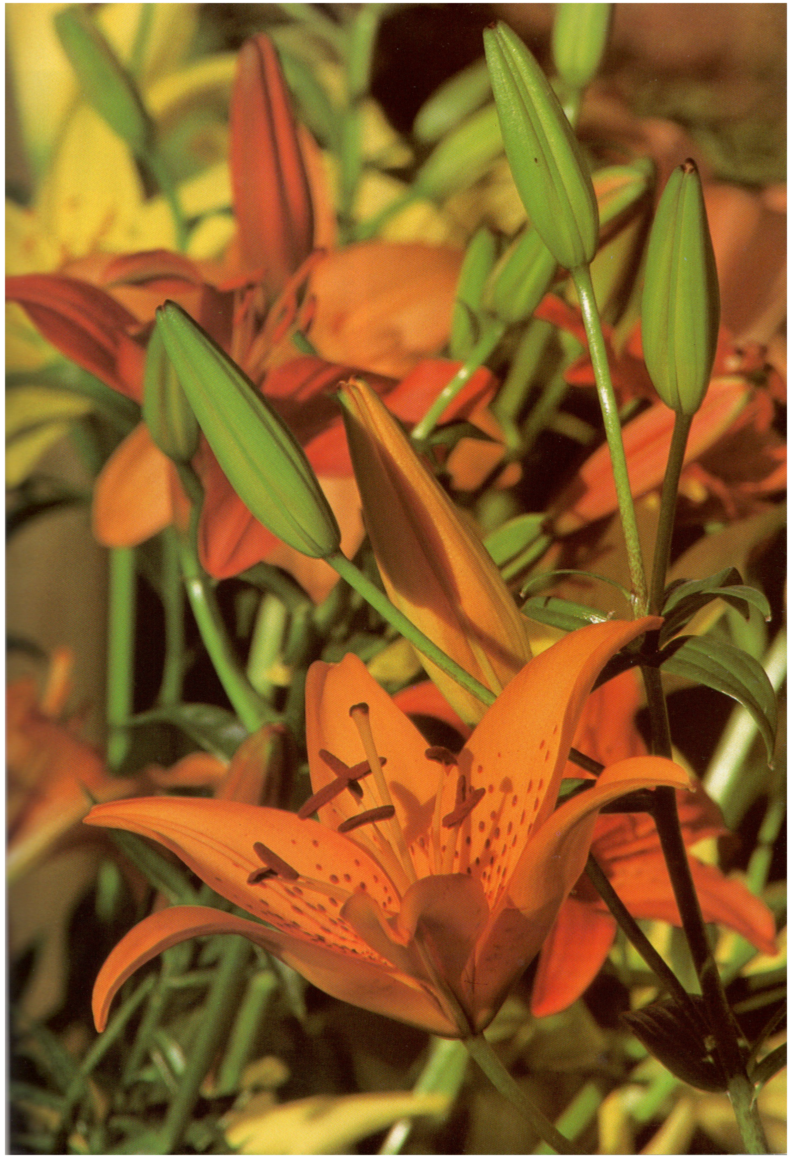
Depth of field & focusing distance



From Photography, London et al.

Nice Depth of Field effect





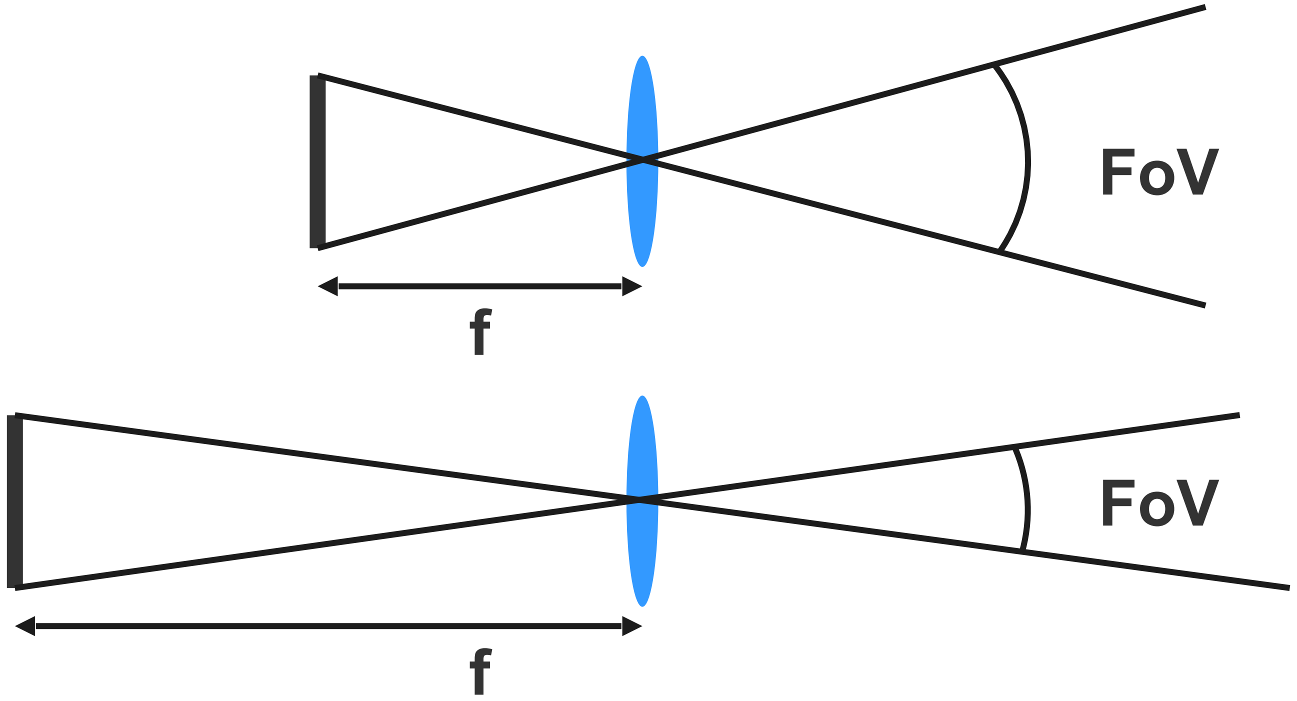
From Peterson, Understanding Exposure

Outline

- ➢ **Pinhole camera**
- ➢ **Lens**
- ➢ **Depth of field**
- ➢ **Field of view**
- ➢ **Exposure**
- ➢ **Digital camera**

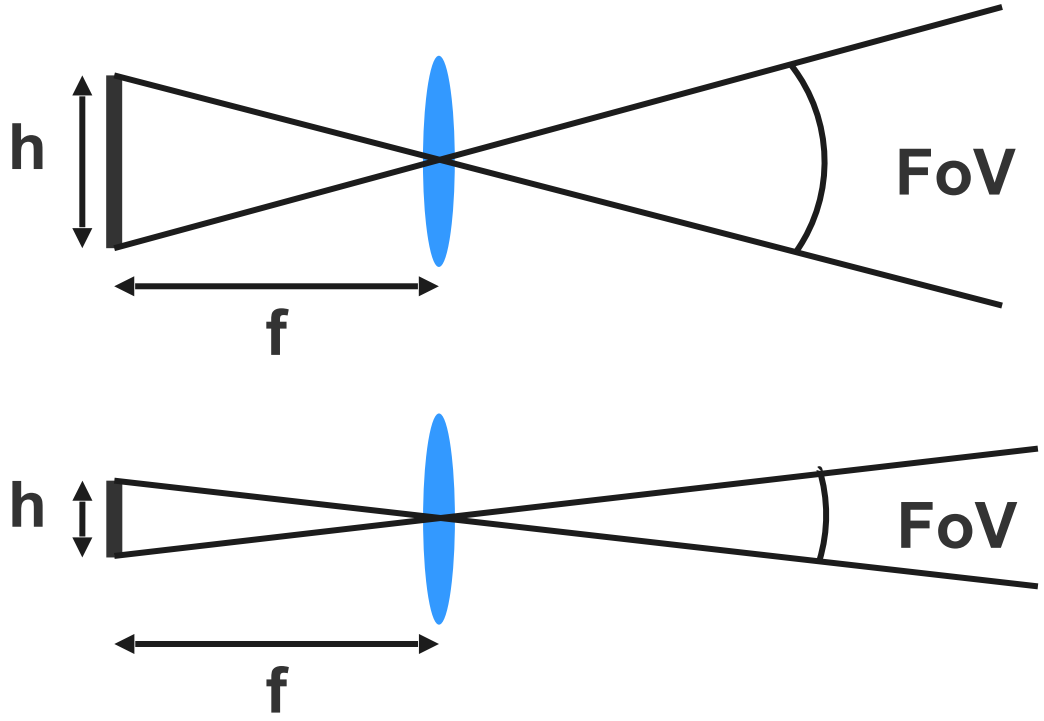
Field of View

- The angle through which the camera can see the world
- What happens if we increase the focal length?
  - FoV decreases



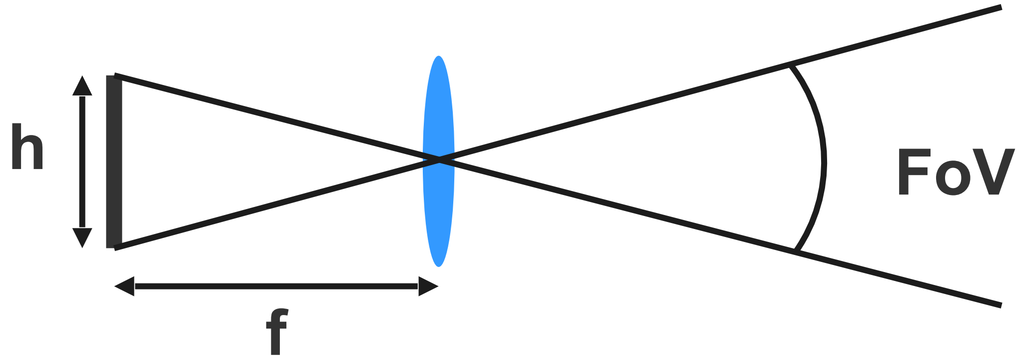
Field of View

- The angle through which the camera can see the world
- What if we decrease the sensor size
  - FoV decreases

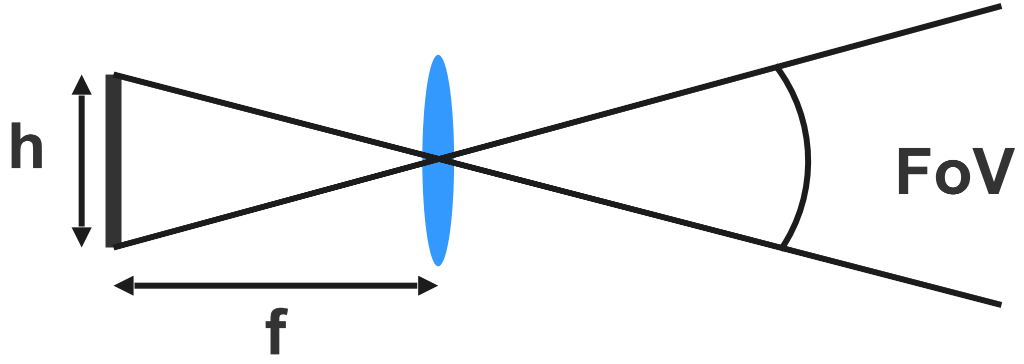


Field of View

- Depends on two factors
  - Inversely proportional to focal length
  - Directly proportional to sensor size



Field of View

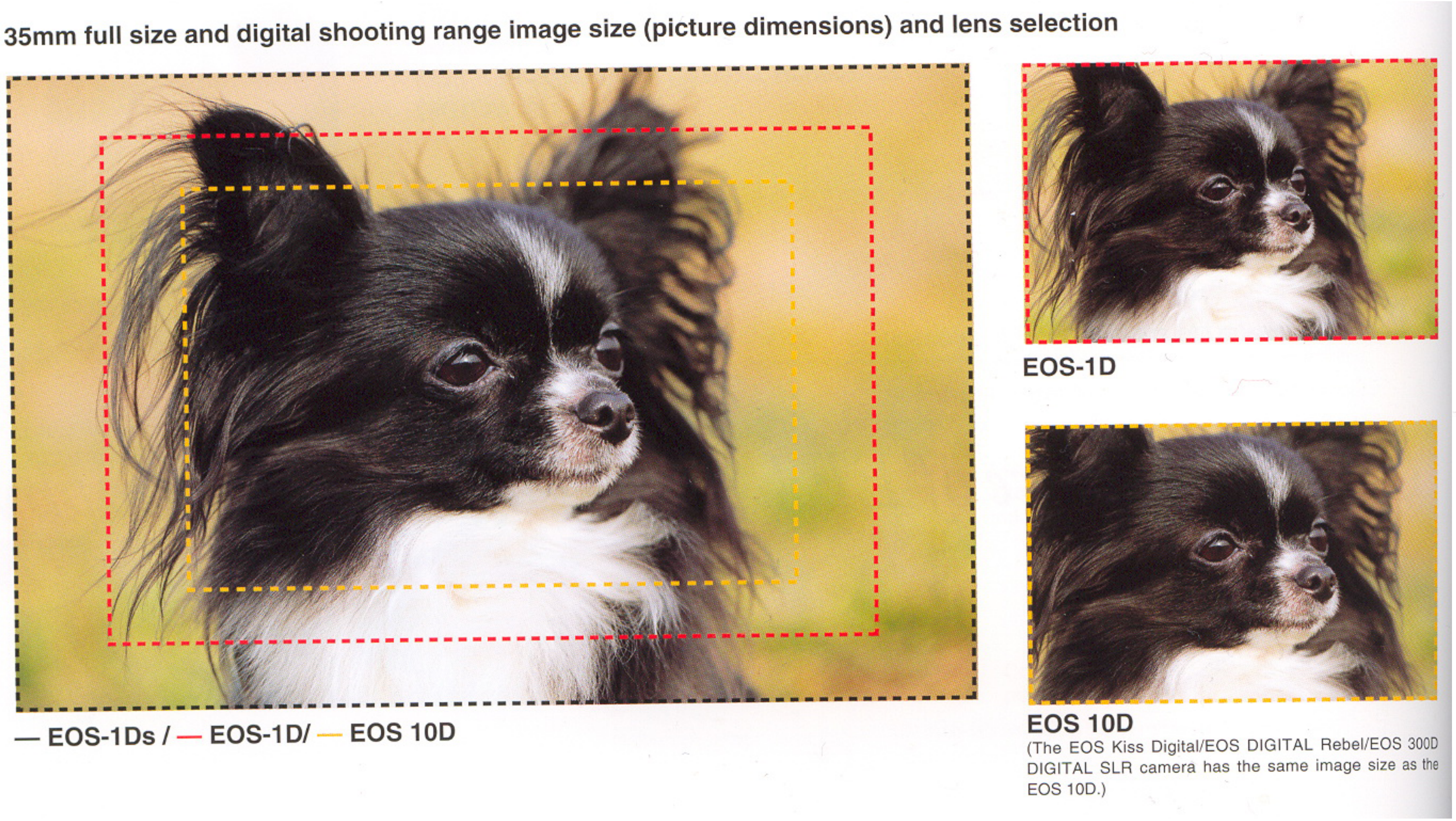


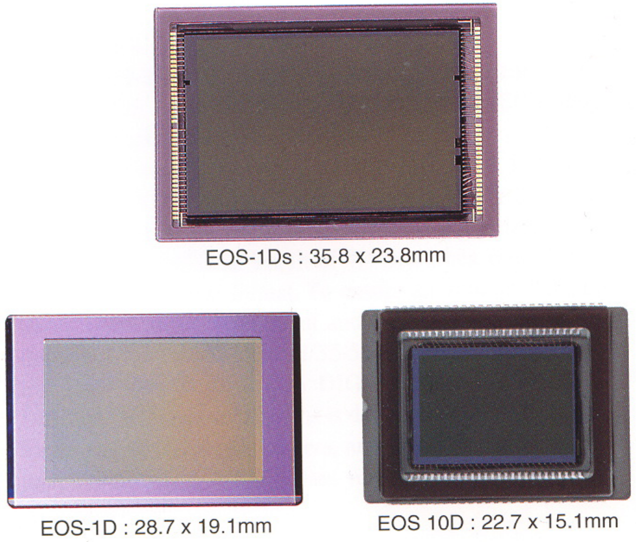
$$\mathrm{FoV} = 2\arctan\left(\frac{h}{2f}\right)$$

Effect of sensor size

Sensor size

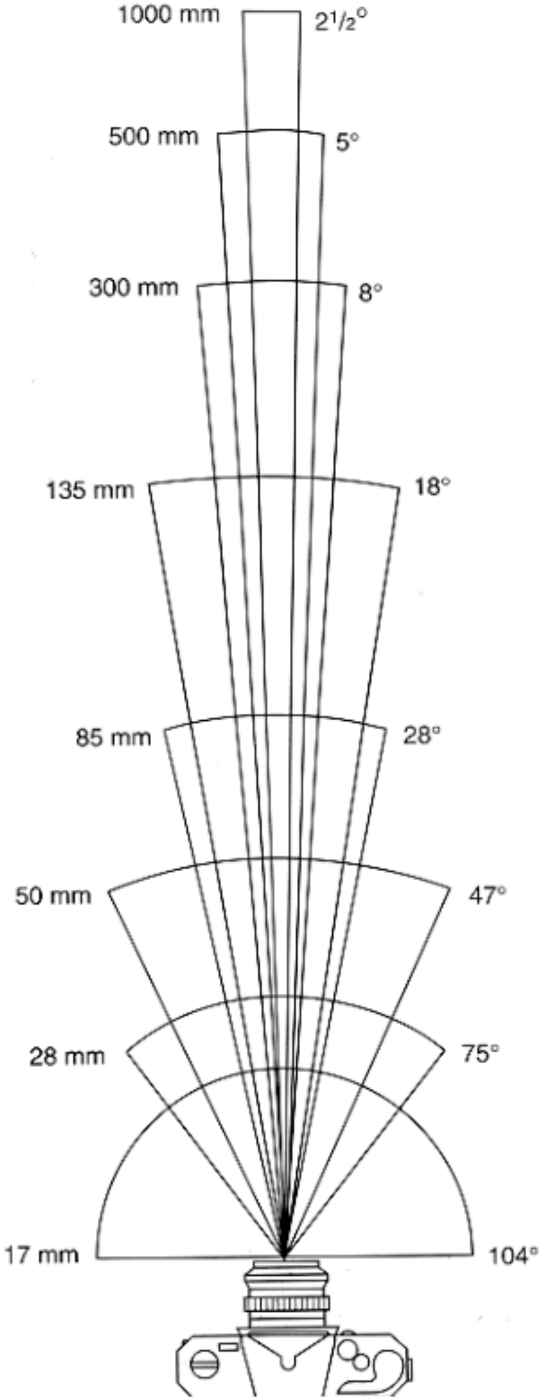
- ➢ **Similar to cropping**





source: canon red book

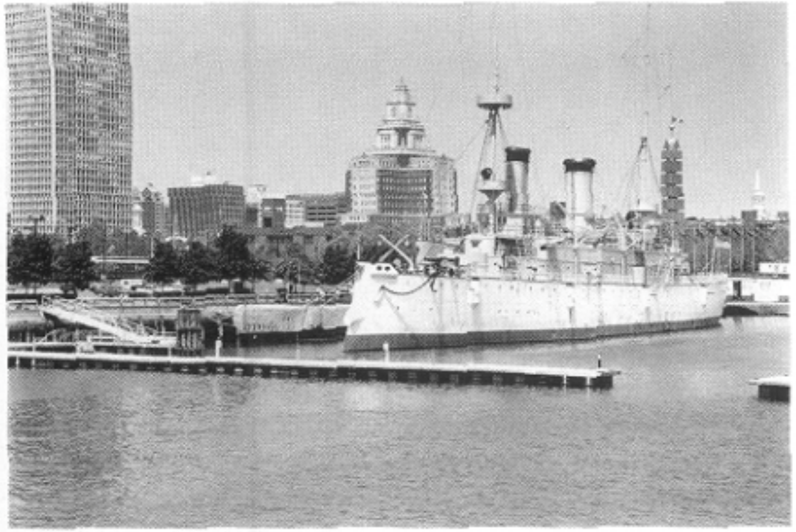
Effect of focal length



17mm

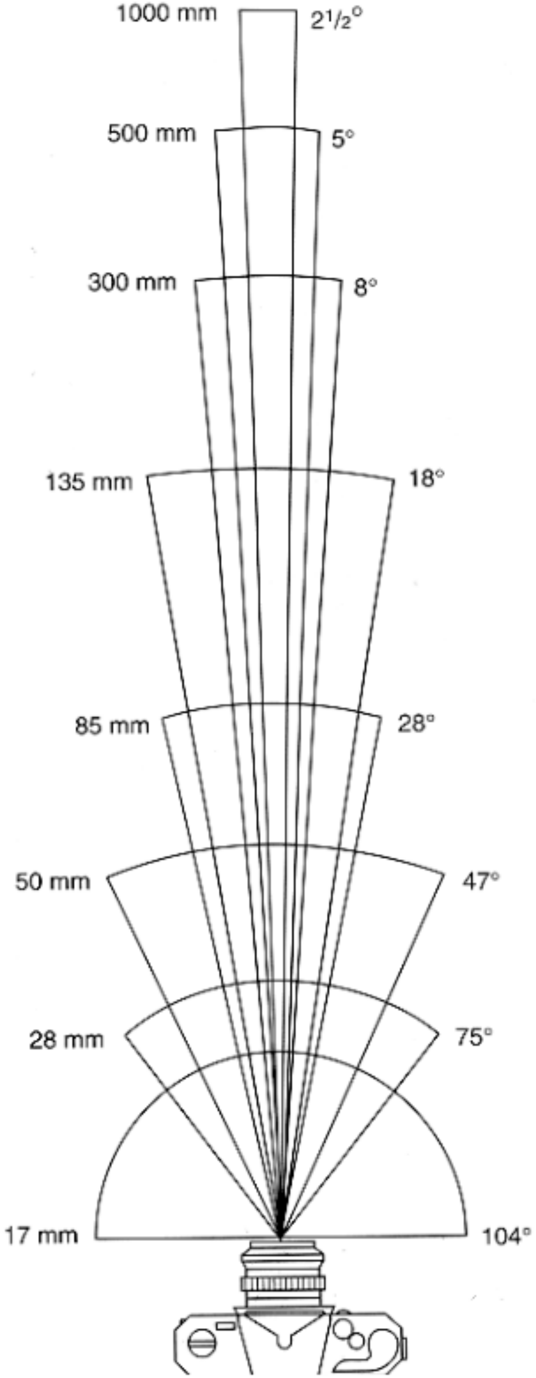
28mm

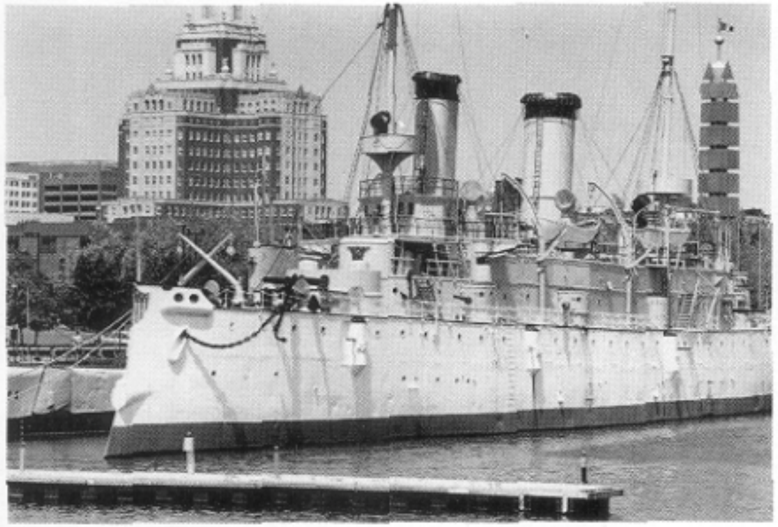
50mm



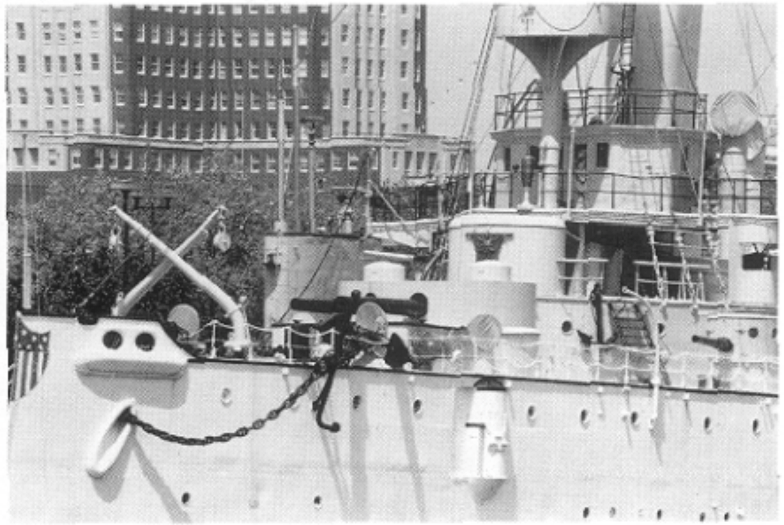
85mm

From London and Upton

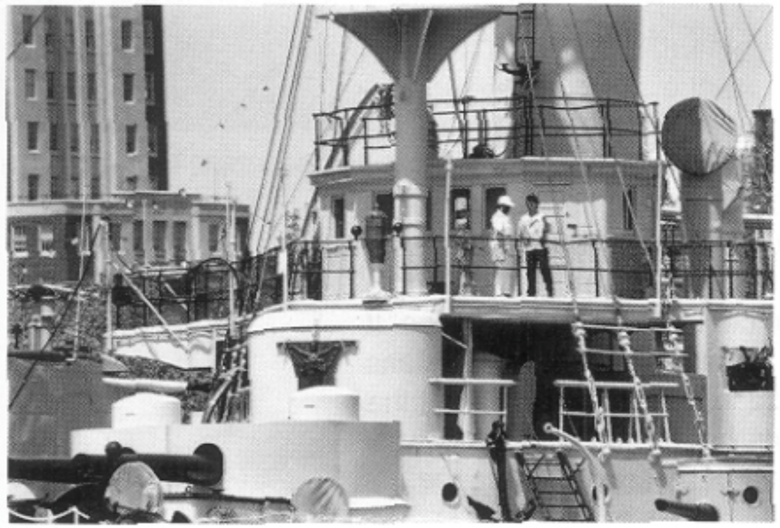




135mm



300mm



500mm

From London and Upton

Expensive toys…

Sigma 200-500mm F2.8 EX DG lens

What does 1600mm lens look like?

http://www.digitalpixels.net/varia/the-web/sigma-200-500mm-f28-ex-dg-lens-on-the-field/

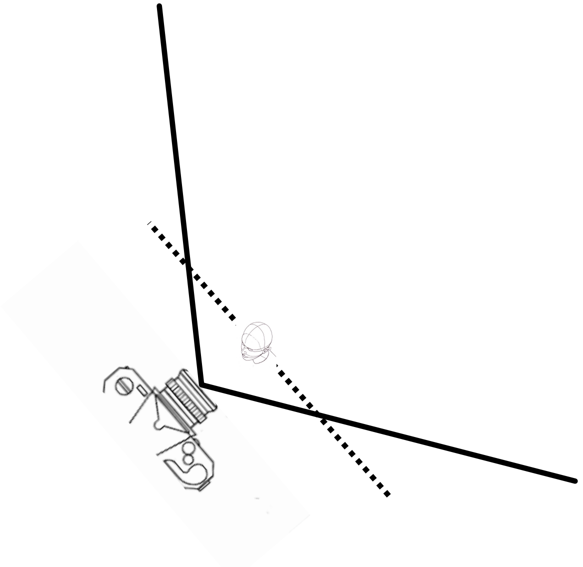
http://dancarrphotography.com/blog/wp-content/uploads/2011/05/Canon_super_tele_comparison.jpg

Focal length and perspective

- Increase the focal length
- Move away from the subject
- Subject remains the same size
- Background moves closer

From Canon EF Lens Work III

Perspective Composition

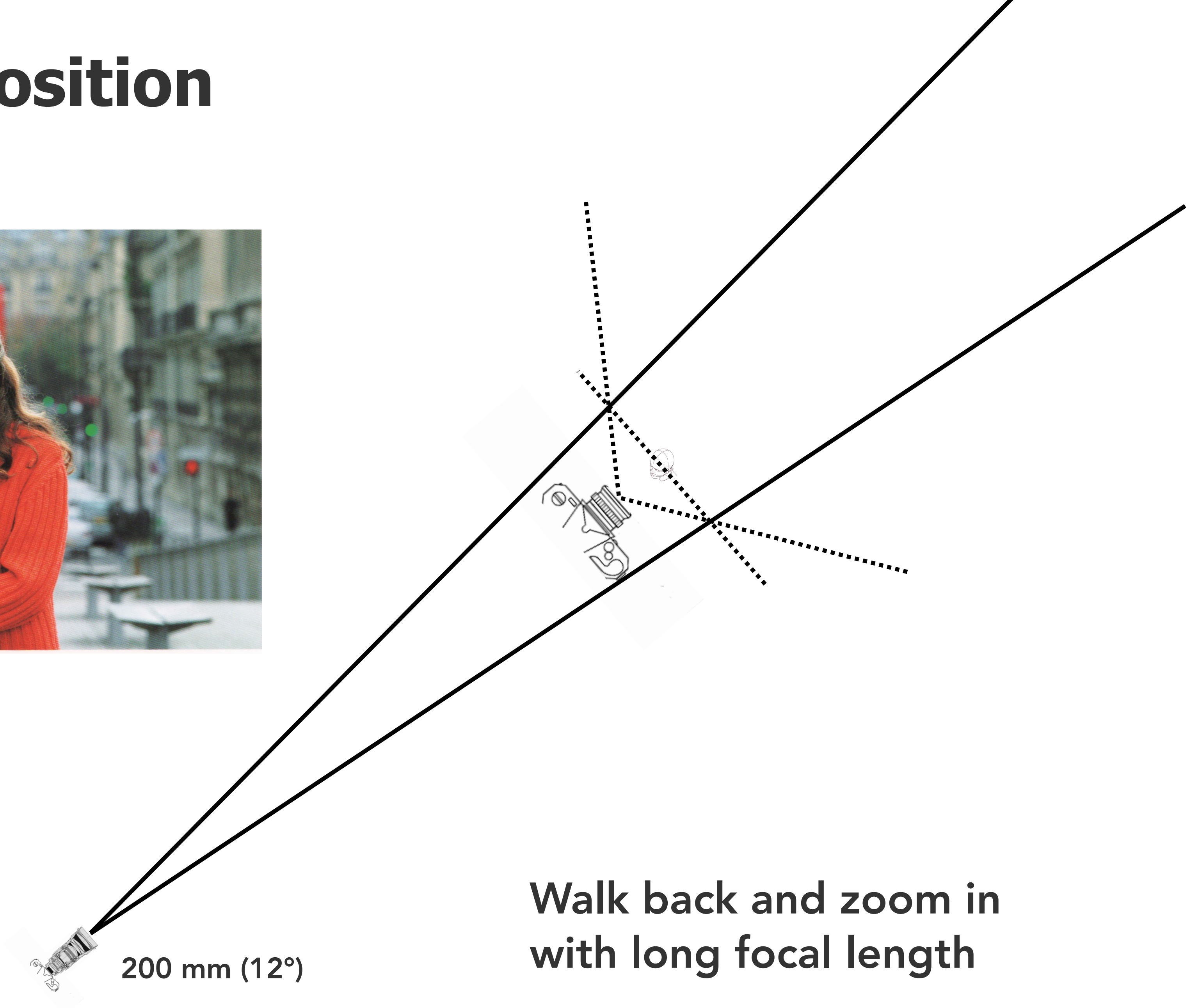


16 mm (110°)

Up close and zoomed wide
With short focal length

From Ren Ng

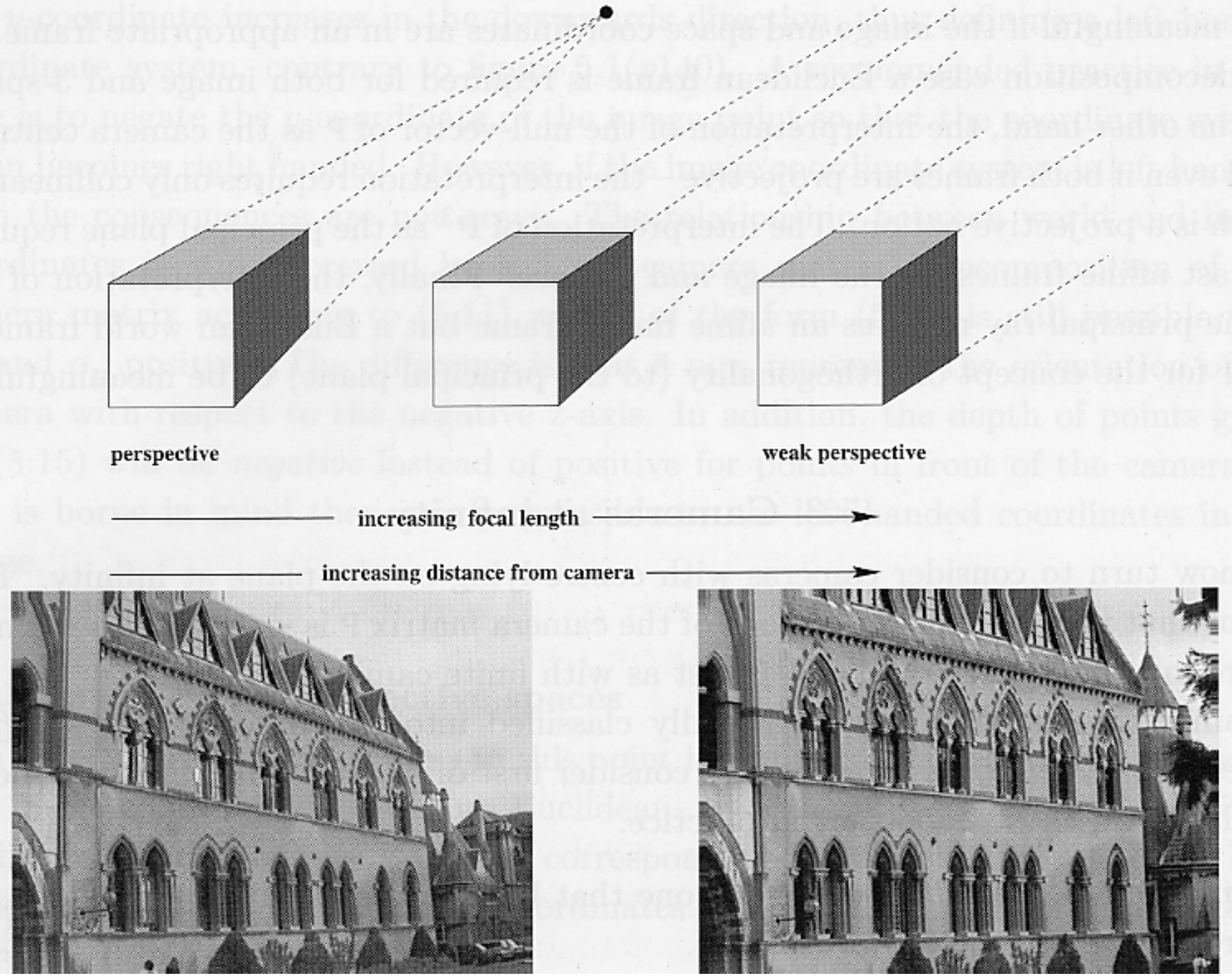
Perspective Composition



200 mm (12°)

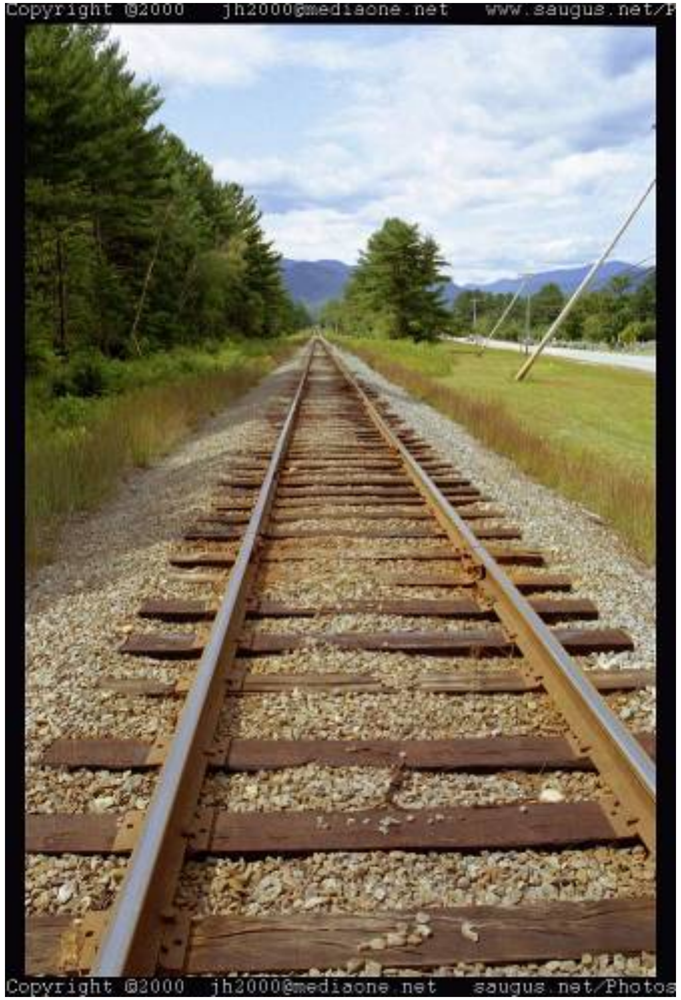
Walk back and zoom in with long focal length

From Ren Ng



From Zisserman & Hartley

Funny things happen…



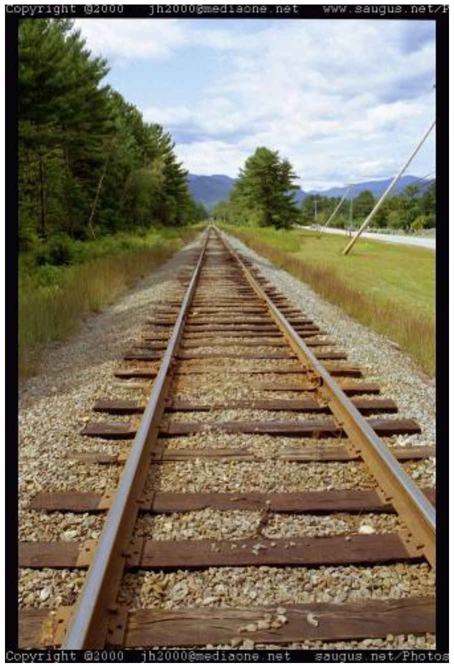
Modeling projection (perspective)

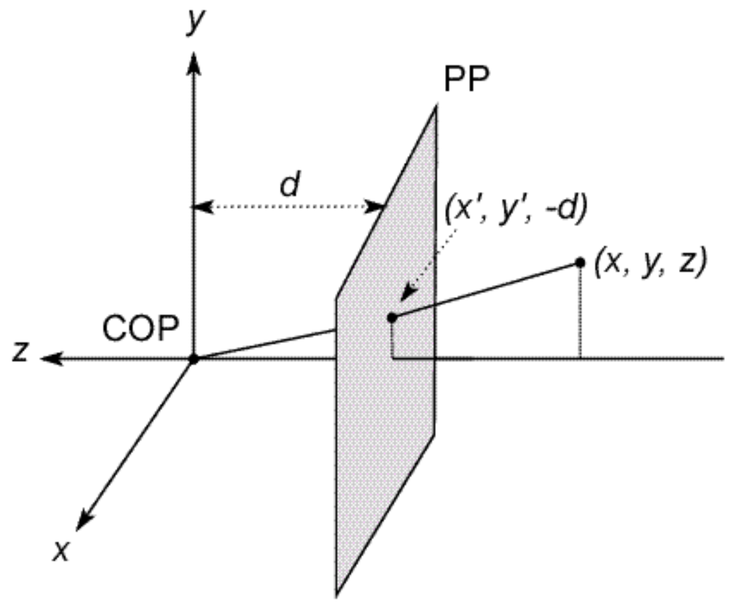
- **Projection equations**
  - **Compute intersection with PP of ray from (x,y,z) to COP**
  - **Derived using similar triangles**

$$(x, y, z) \rightarrow (-d\frac{x}{z},\ \ -d\frac{y}{z},\ \ -d)$$

  - **We get the projection by ignoring the last coordinate:**

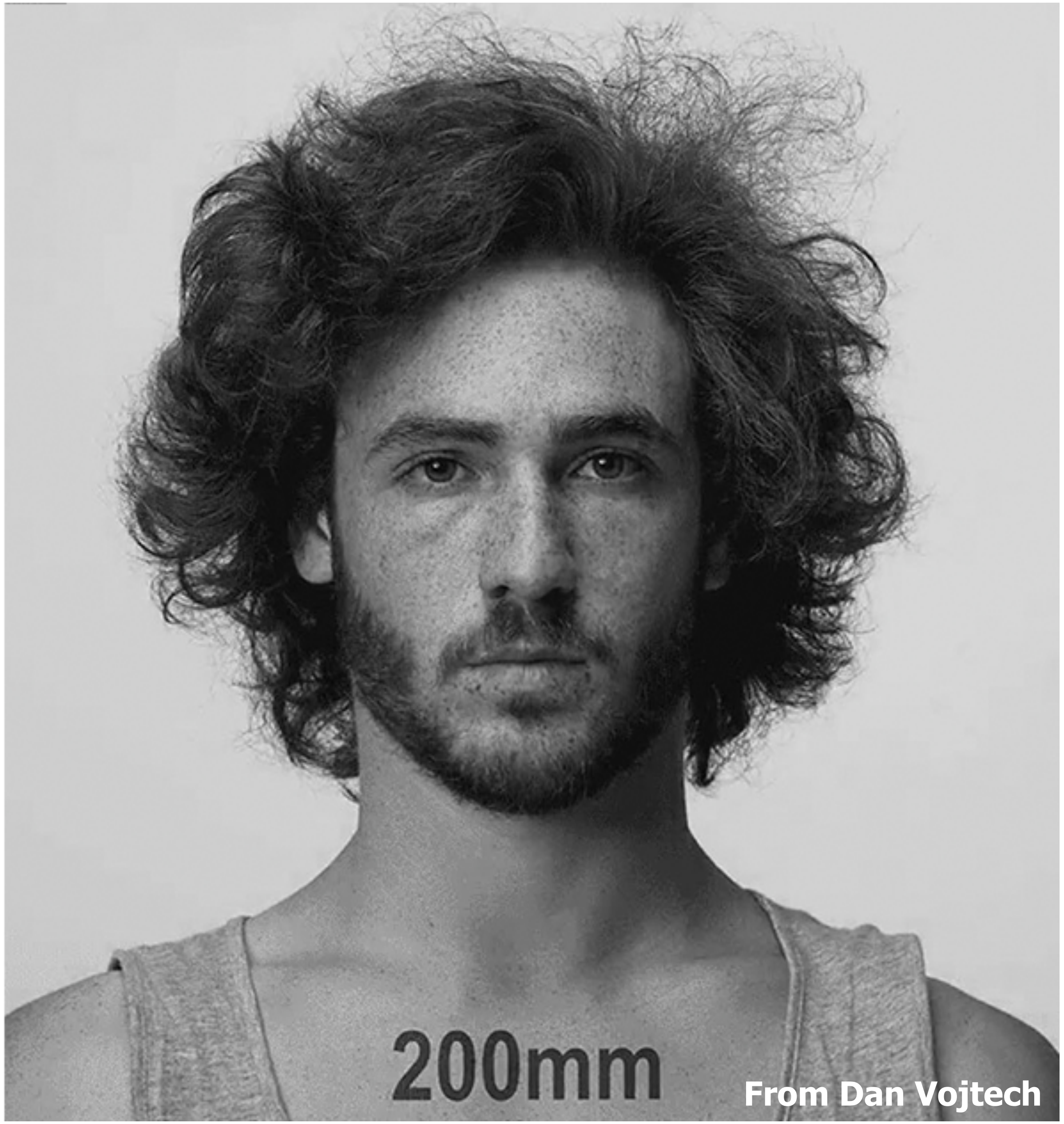
$$(x, y, z) \rightarrow (-d\frac{x}{z},\ \ -d\frac{y}{z})$$





Slide by Steve

Field of View / Focal Length



Fun with Focal Length (Jim Sherwood)

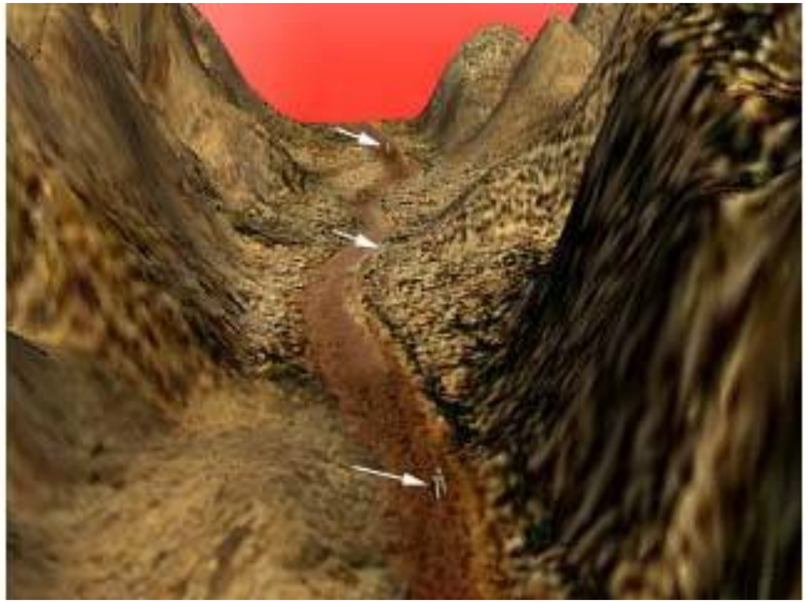


Figure 5.1

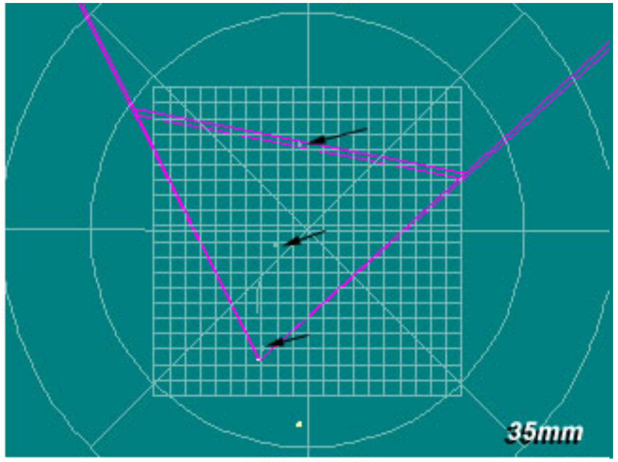
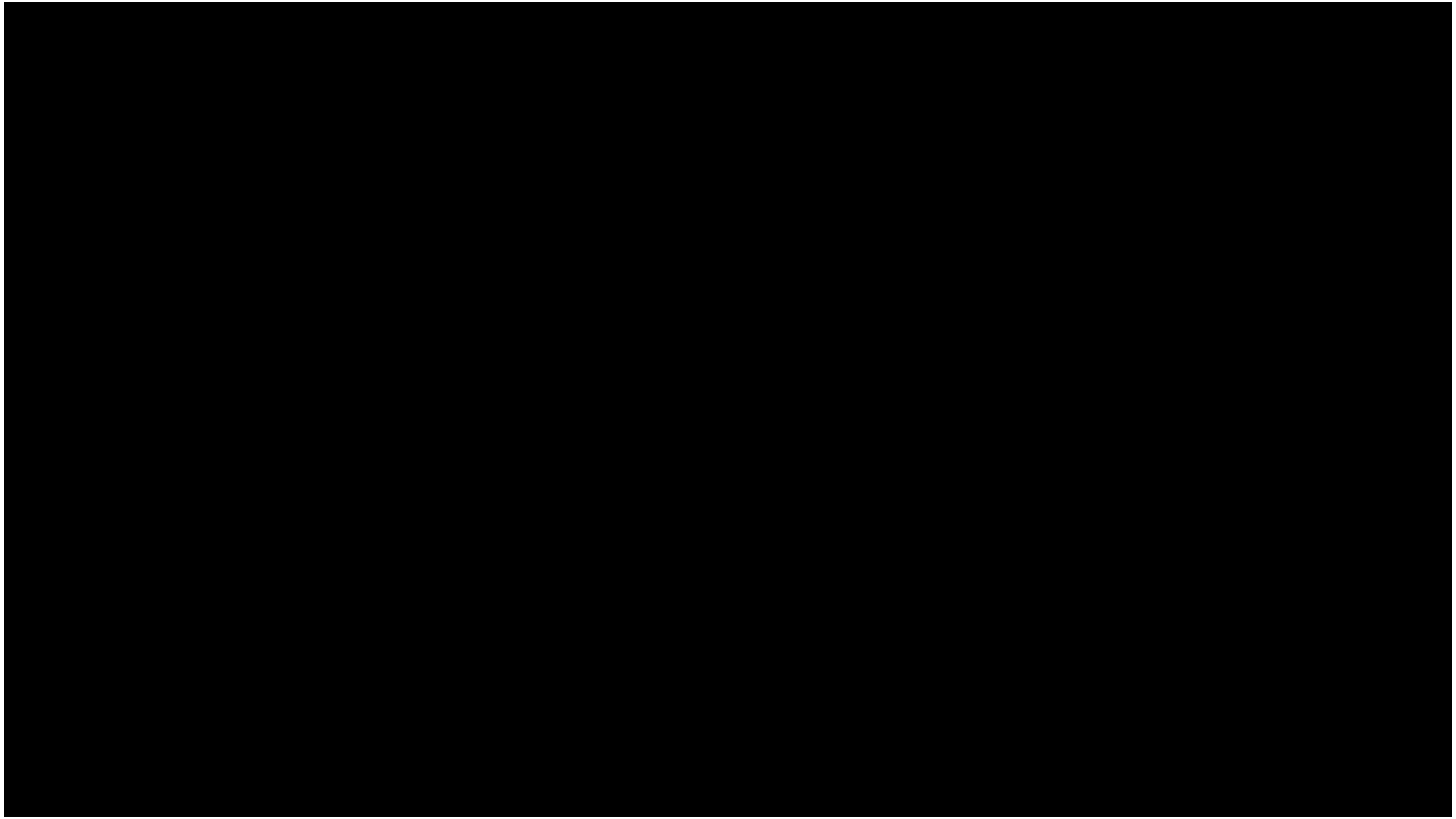


Figure 5.2

Dolly Zoom (“Vertigo Shot”)



Outline

- ➢ Pinhole camera
- ➢ Lens
- ➢ Depth of field
- ➢ Field of view
- ➢ Exposure
- ➢ Digital camera

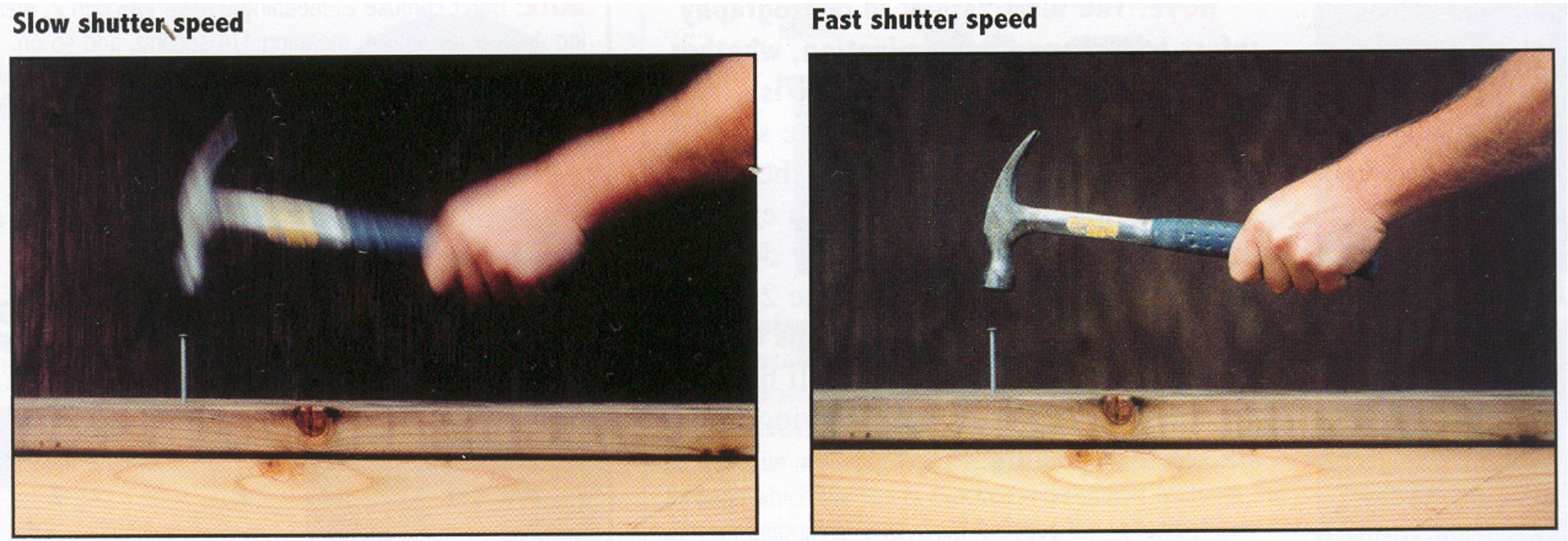
Exposure

- The amount of light to sensor/film
- Two main parameters:
  - Shutter speed
  - Aperture (area of lens)

Shutter speed

- Controls how long the film/sensor is exposed
- Pretty much linear effect on exposure
- Usually in fraction of a second:
  - 1/30, 1/60, 1/125, 1/250, 1/500
  - Get the pattern ?

Main effect of shutter speed (motion blur)



From Photography, London et al.

Shutter speed

- Controls how long the film/sensor is exposed
- Pretty much linear effect on exposure
- Usually in fraction of a second:
  - 1/30, 1/60, 1/125, 1/250, 1/500
  - Get the pattern ?
- On a normal lens, normal humans can hand-hold down to 1/60
  - In general, the rule of thumb says that the limit is the inverse of focal length, e.g., 1/500 for a 500mm

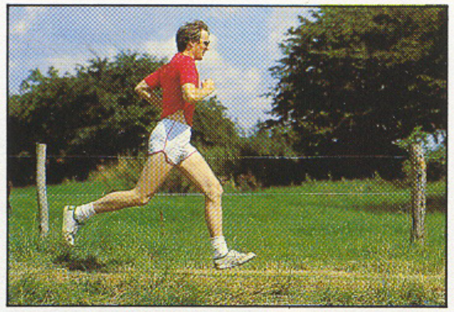
Effect of shutter speed

➢ **Freezing motion**

Walking people

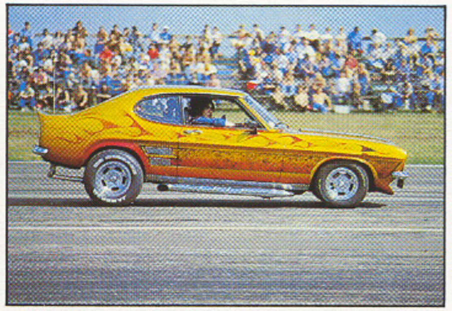
1/125

Running people



1/250

Car



1/500

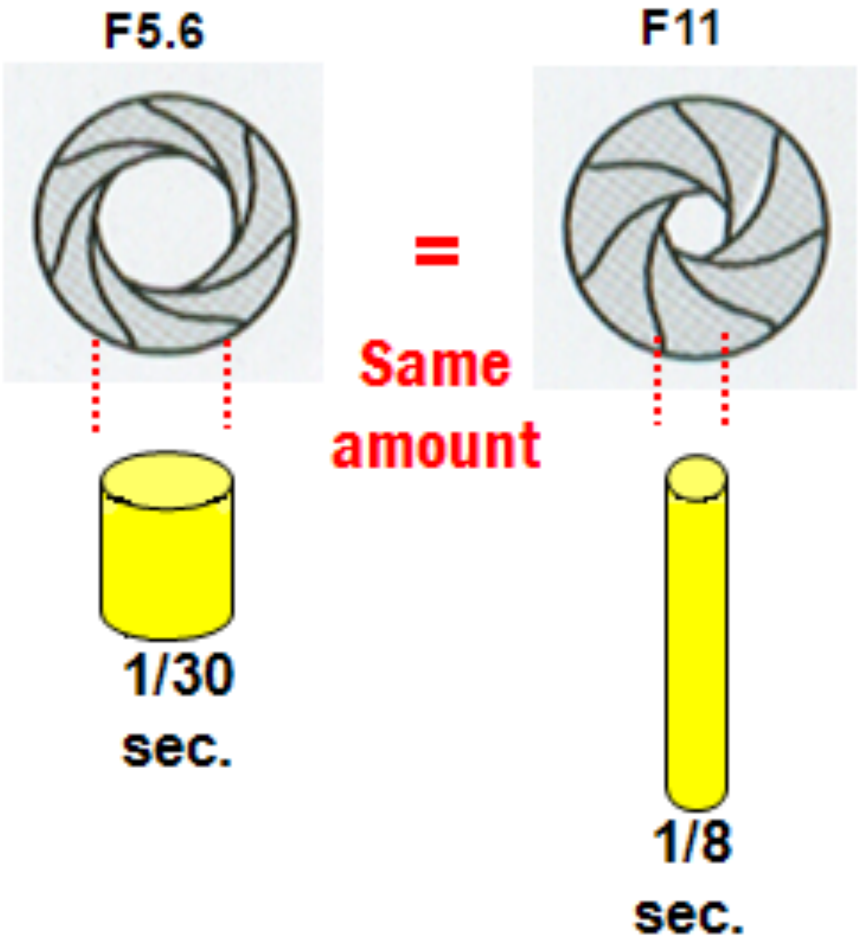
Fast train

1/1000

Exposure

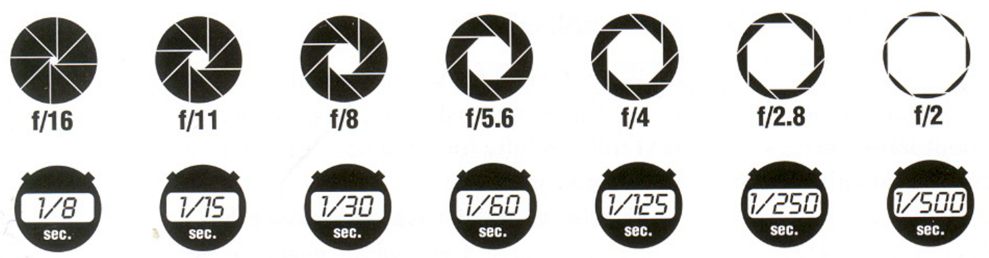
- Get the right amount of light to sensor/film
- Two main parameters:
  - Shutter speed
  - Aperture (area of lens)
- Exposure ~ shutter time x lens area

Exposure: shutter speed vs. aperture



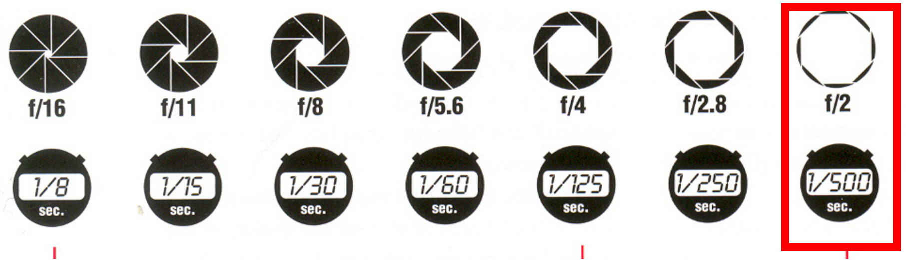
Reciprocity

- Assume we know how much light we need
- We have several choices for shutter speed/aperture pairs

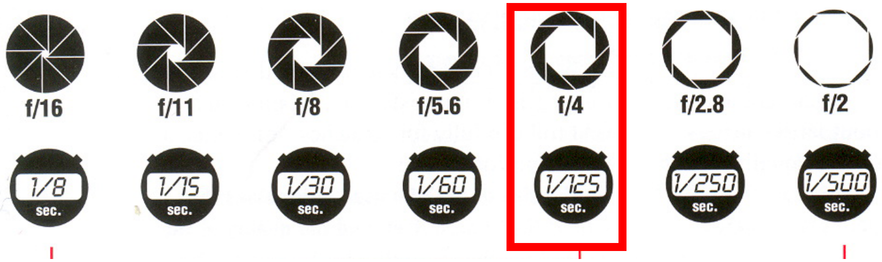


- What will guide our choice of a shutter speed?
  - Freeze motion vs. motion blur, camera shake
- What will guide our choice of an aperture?
  - Depth of field, diffraction limit
- Often, we must compromise
  - Open more to enable faster speed (but shallow DoF)

Large aperture (shallow depth of field), fast shutter speed (motion sharp). *A fa shutter speed (1/500 sec) stops the motion of the pigeons so completely that the flapping wings are frozen. But the wide aperture (f/2) needed gives so little depti of field that the background is now out of focus.*



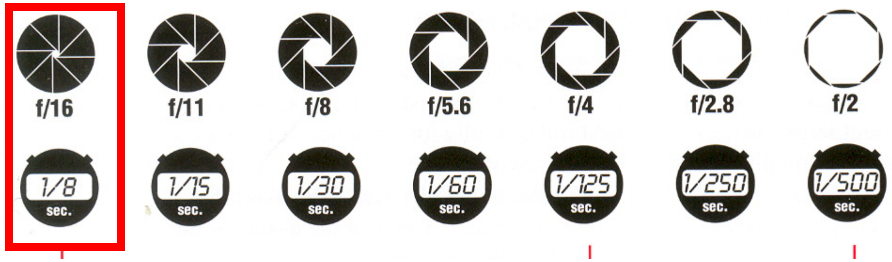
From Photography, London et al.



Medium aperture (moderate depth of field), medium shutter speed (some motion sharp). *A medium aperture (f/4) and shutter speed (1/125 sec) sacrifice some background detail to produce recognizable images of the birds. But the exposure is still too long to show the motion of the birds' wings sharply.*

From Photography, London et al.

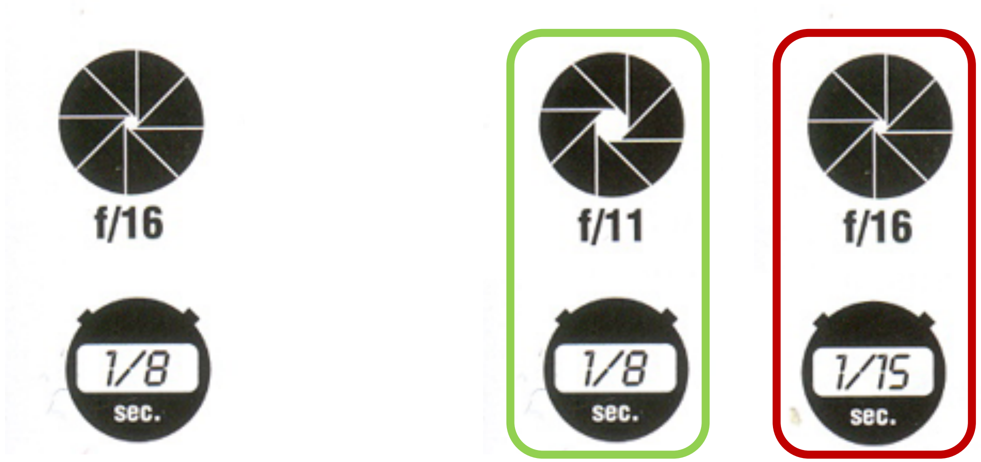
Small aperture (deep depth of field), slow shutter speed (motion blurred). In this scene, a small aperture (f/16) produced great depth of field; the nearest paving stones as well as the farthest trees are sharp. But to admit enough light, a slow shutter speed (1/8 sec) was needed; it was too slow to show moving pigeons sharp. It also meant that a tripod had to be used to hold the camera steady.



From Photography, London et al.

Exposure

- A stop is doubling or halving of the amount of light
  - Can be controlled by both aperture and shutter speed
- To increase the exposure by 1 stop
  - Increase the aperture by a factor of 2
  - Increase the shutter time by a factor of 2



More fun

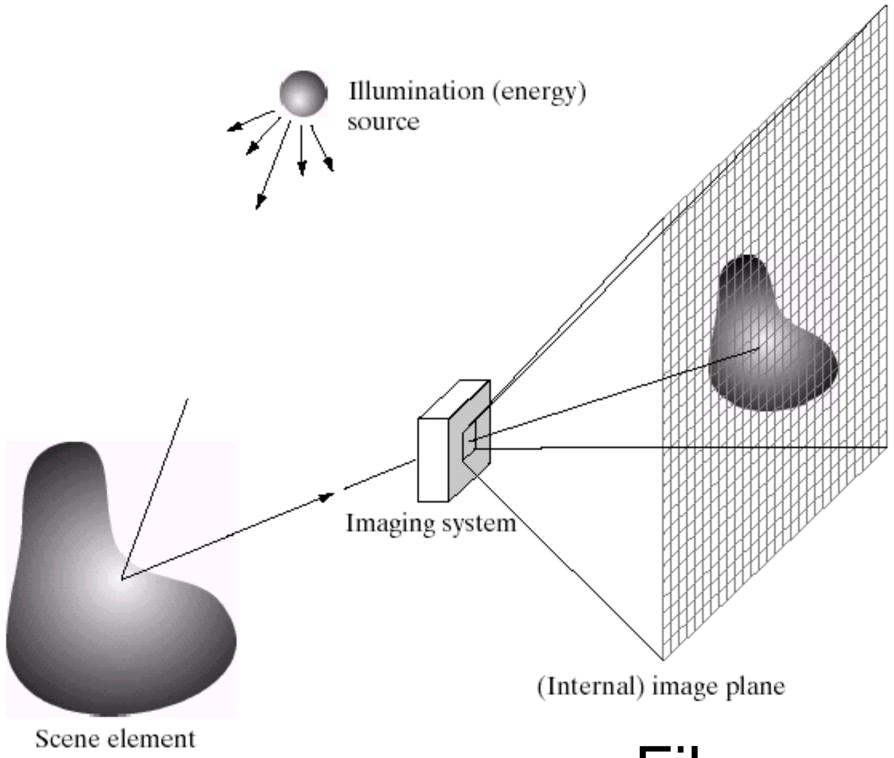
http://vimeo.com/14958082

Pixelstick

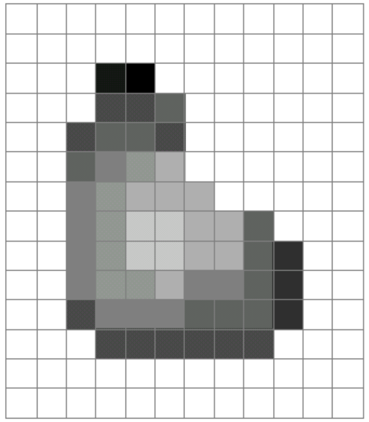
Outline

- ➢ **Pinhole camera**
- ➢ **Lens**
- ➢ **Depth of field**
- ➢ **Field of view**
- ➢ **Exposure**
- ➢ **Digital camera**

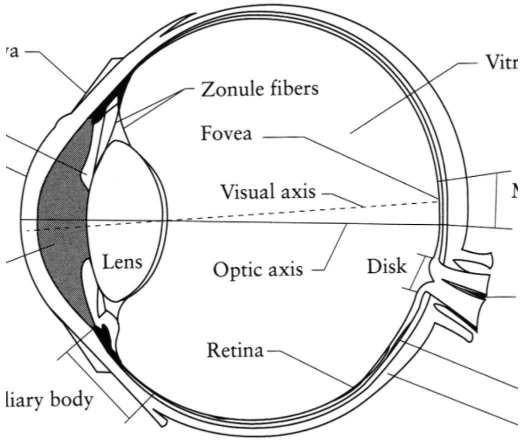
Image Formation



Film



Digital Camera



The Eye

Digital camera

- 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)
    - CMOS

Slide by Steve

Sampling and Quantization

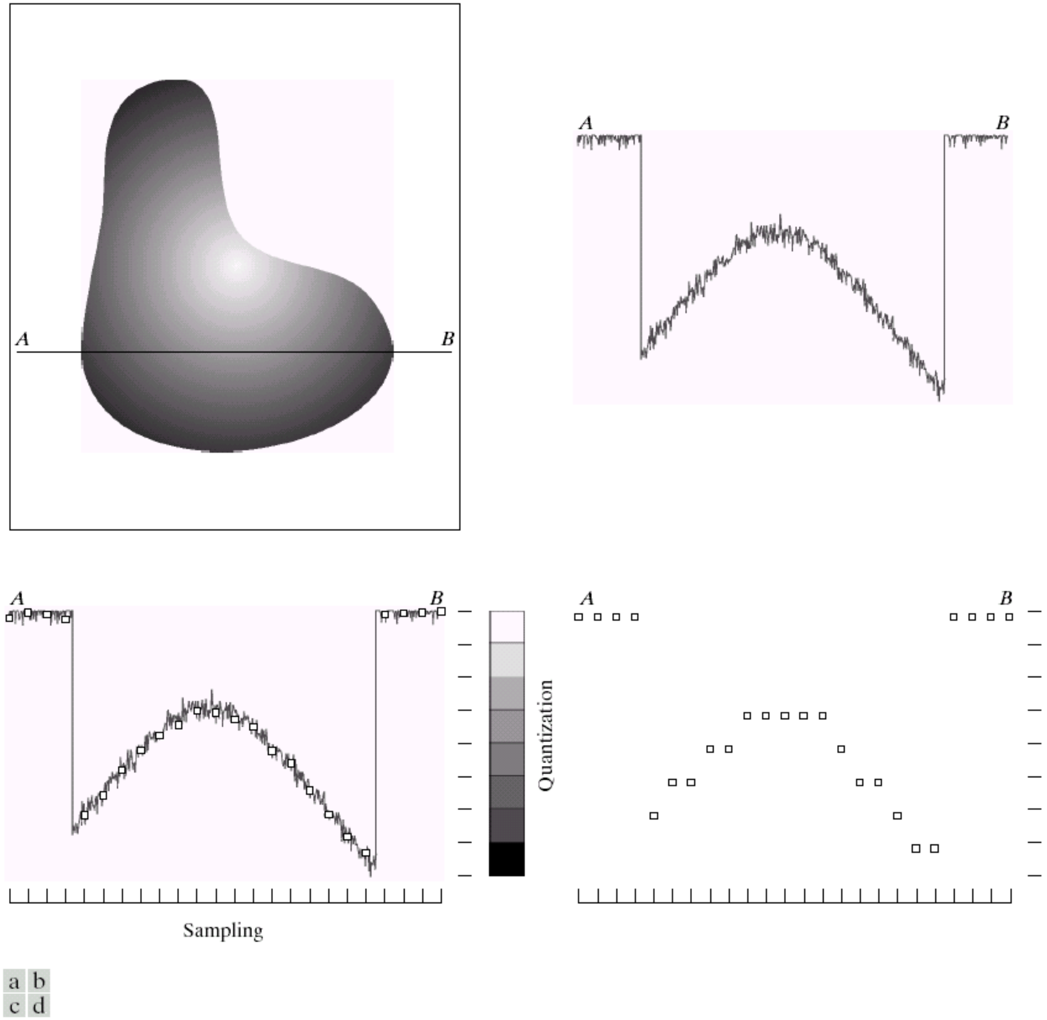
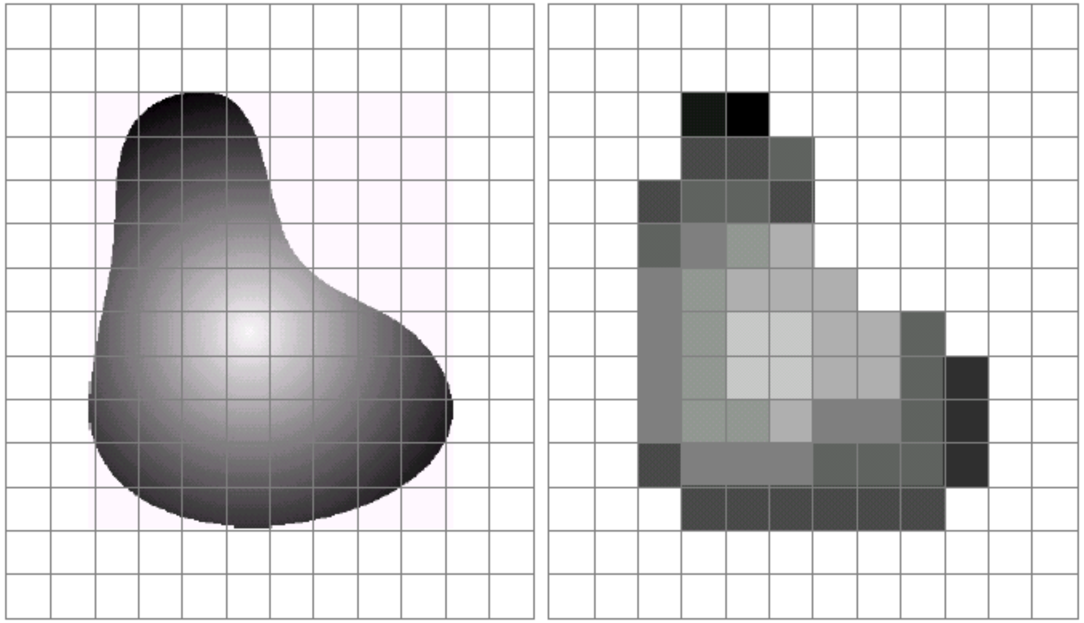


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

Sensor Array



a b

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

Global vs rolling shutter

- **Global: Taking a snapshot of the scene at a single instant**
- **Rolling: Scanning across the scene vertically or horizontally**

Rolling shutter (focal plane shutter)

From the Slow Mo Guys https://youtu.be/CmjeCchGRQo

Other shutter systems

- Also have leaf shutters
  - Circular iris that closes

London

- Global electronic shutter
  - Different circuit design that exposes all pixels with the same time duration
- Mixtures of physical and electronic shutter
  - E.g., electronic starts exposure, physical shutter ends exposure

From Ren Ng

Rolling shutter

Credit: smarter everyday

Rolling shutter

Credit: smarter everyday