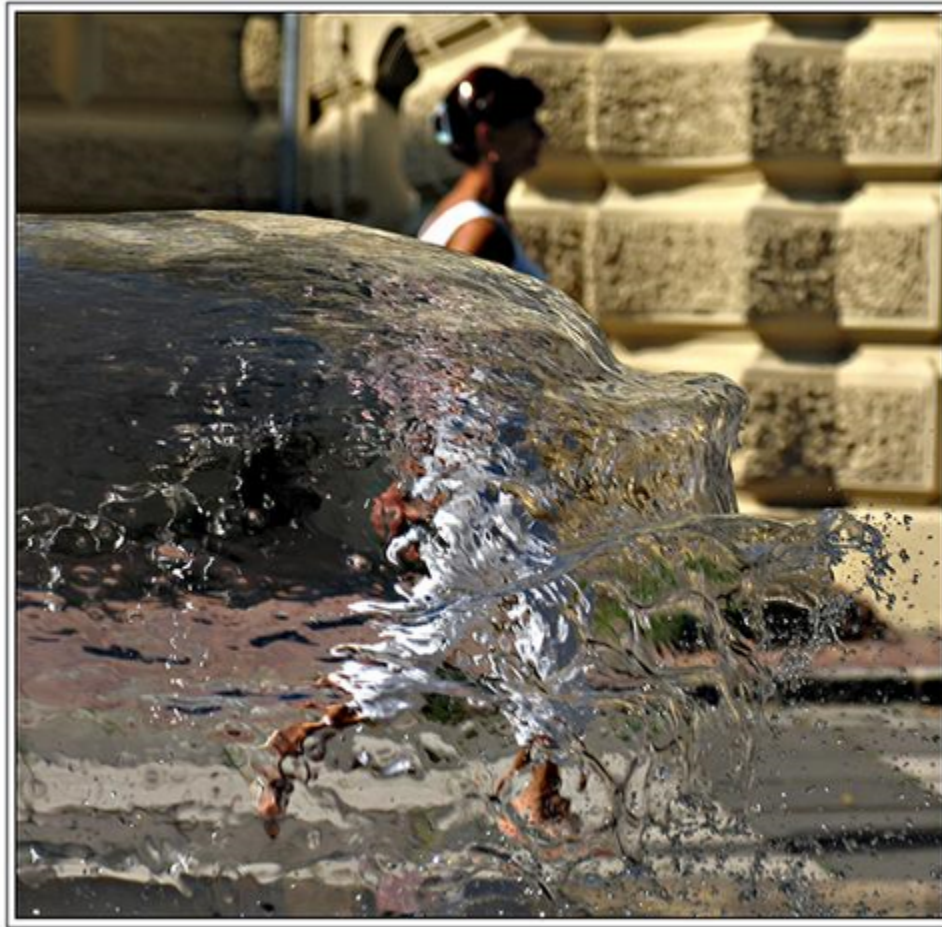


The Camera, Image Formation

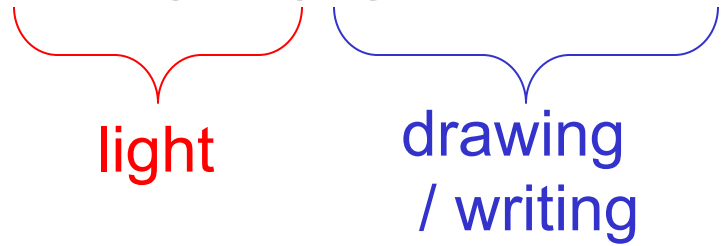


(c) Tomasz Pluciennik

CS180: Intro to Comp. Vision, and Comp. Photo
Efros & Ng, UC Berkeley, Fall 2026

Etymology

PHOTOGRAPHY

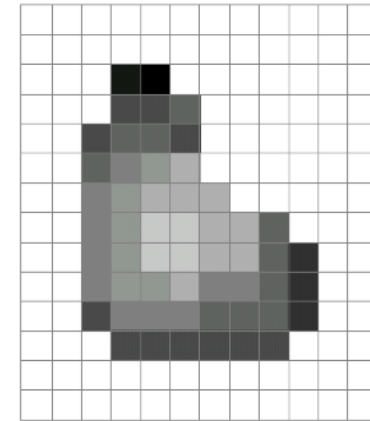
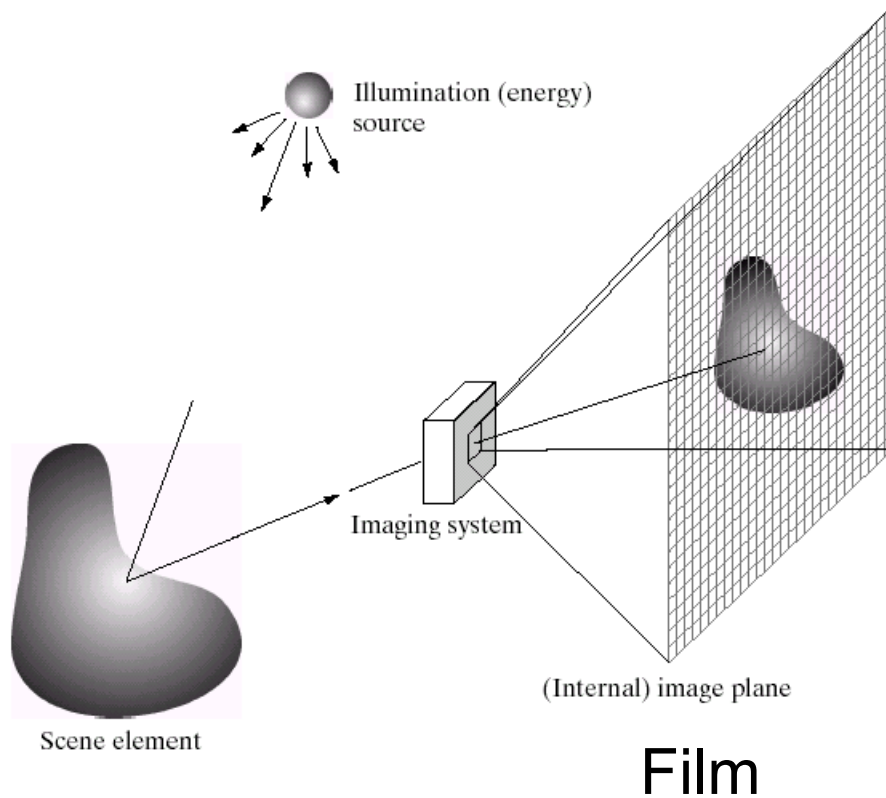


The word 'PHOTOGRAPHY' is shown in black capital letters. A red bracket underneath the first four letters ('PHOT') points to the word 'light' in red lowercase letters. A blue bracket underneath the remaining letters ('GRAPHY') points to the words 'drawing / writing' in blue lowercase letters.

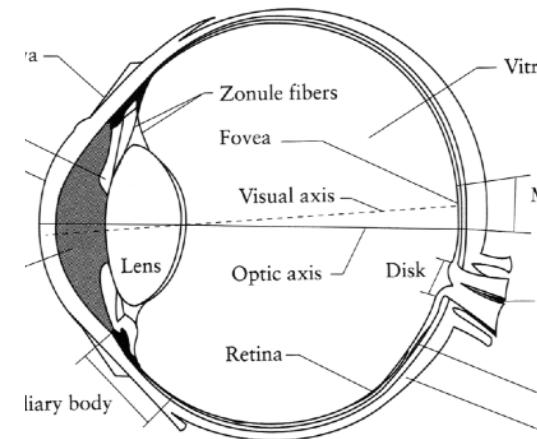
light

drawing
/ writing

Image Formation

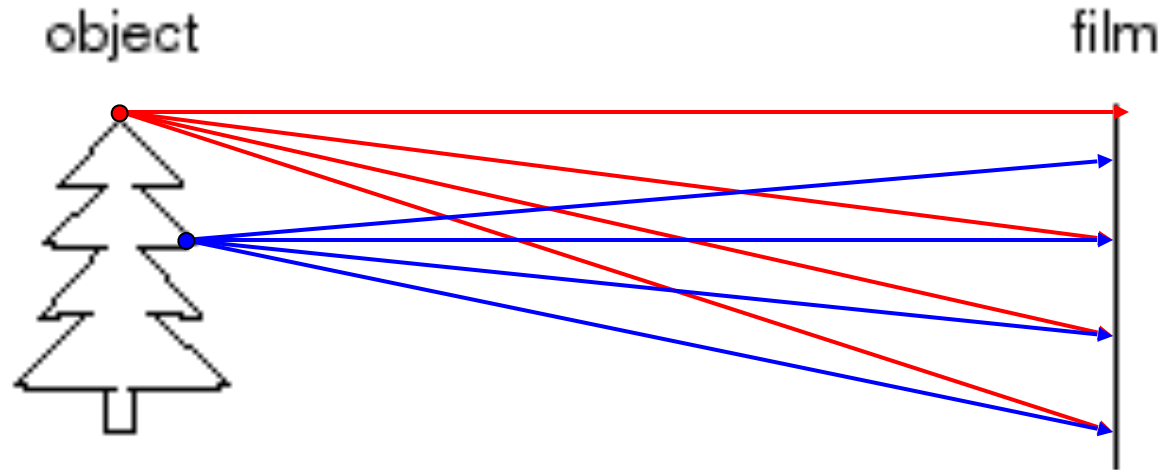


Digital Camera



The Eye

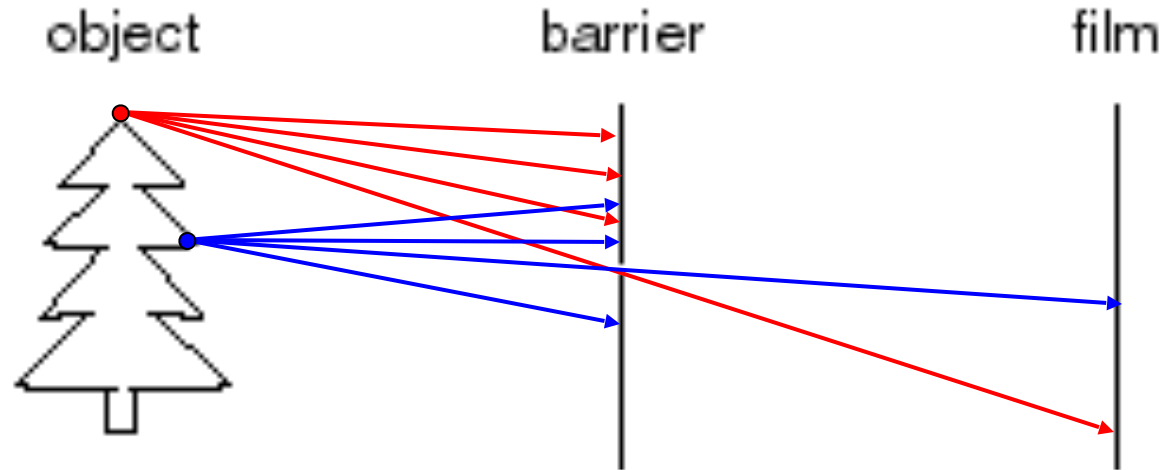
How Do We See the World?



Let's design a camera

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

Adding a Pinhole Aperture



Add a barrier to block off most of the rays

- This reduces blurring
- The opening is known as the **aperture**
- How does this transform the image?

DIY Pinhole Camera

Figure 5.4: A simple setting for creating images on a white piece of paper. In front of the white piece of paper we place another piece of black paper with a hole in the middle. The black paper projects a shadow on the white paper and, in the middle of the shadow, appears a picture of the scene in front of the hole. By making the hole large you will get a brighter, but blurrier image.



Accidental Pinhole Cameras



Tree shadow during a solar eclipse

photo credit: Nils van der Burg

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

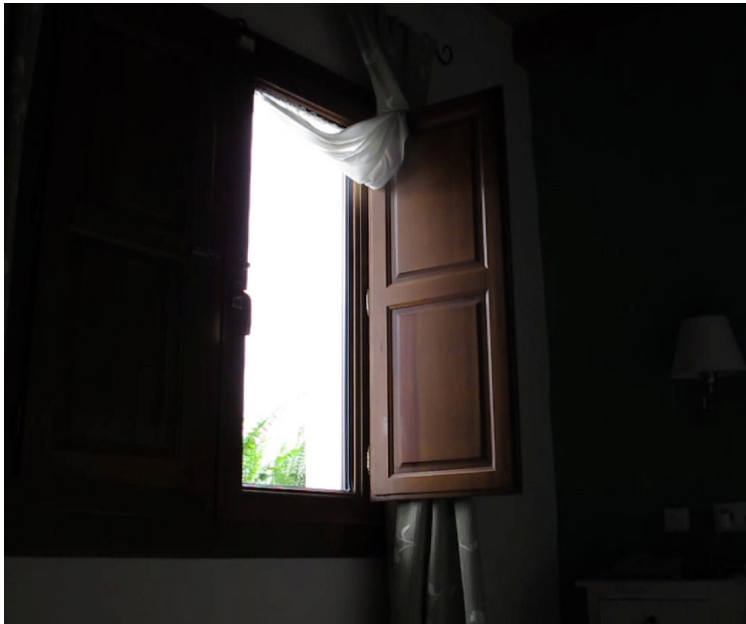
Accidental Pinhole Cameras



© Trina Singley

Slide by Steve Seitz

Accidental Pinhole Cameras

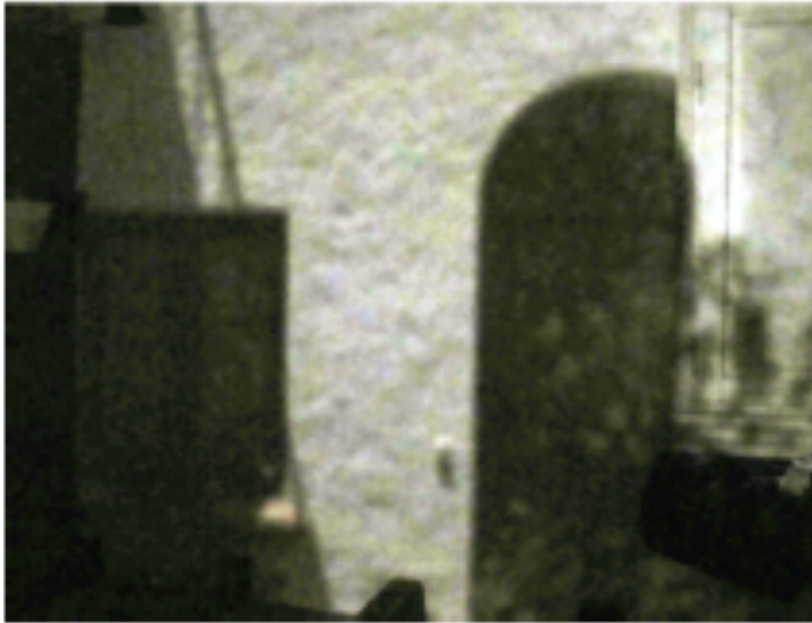


Accidental pinholes project images that are unnoticed or misinterpreted as shadows

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







Window closed into a pinhole
(image inverted)



View outside

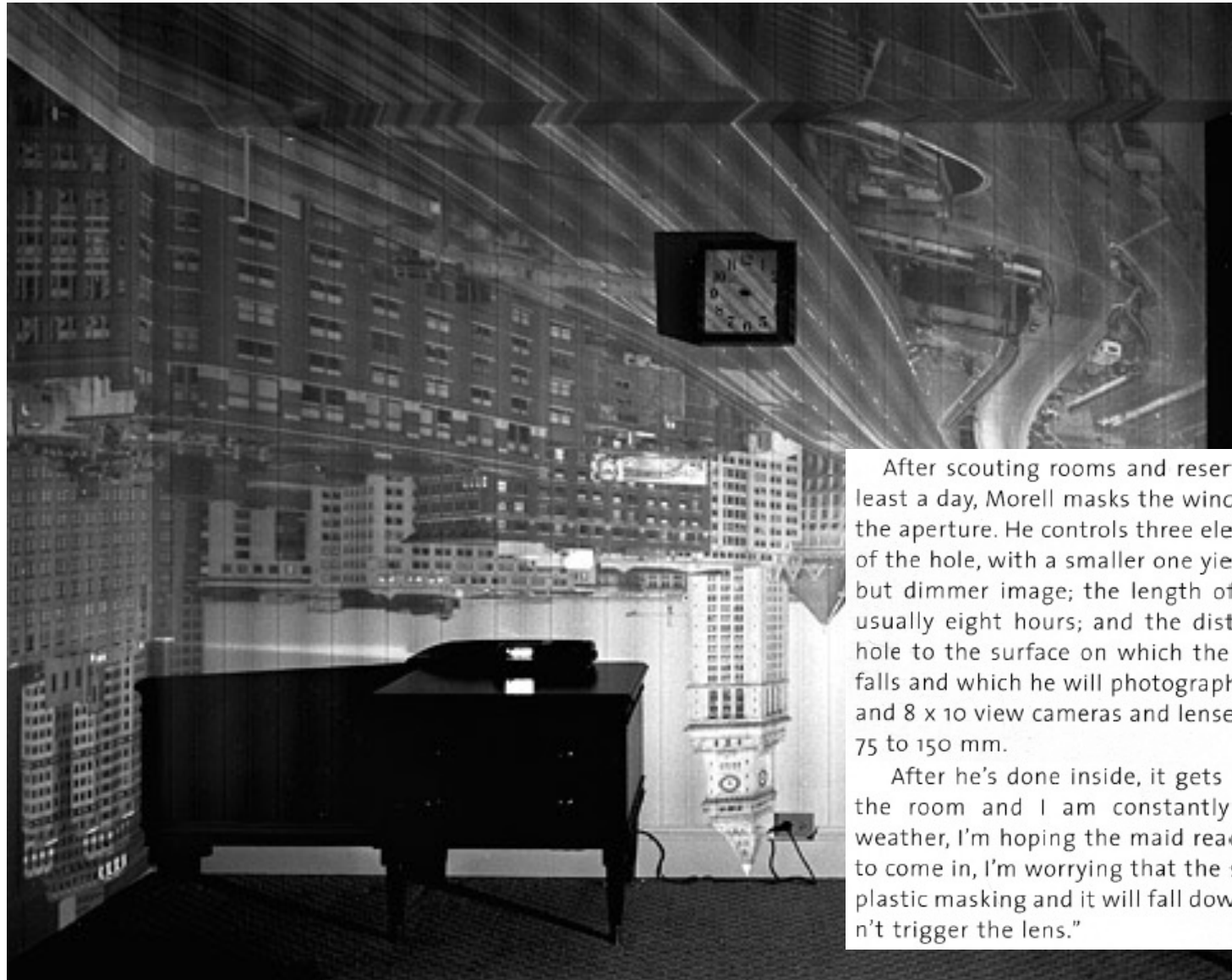
Accidental Pinhole Cameras



Accidental pinholes project images that are unnoticed or misinterpreted as shadows

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

8-Hour Exposure (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."

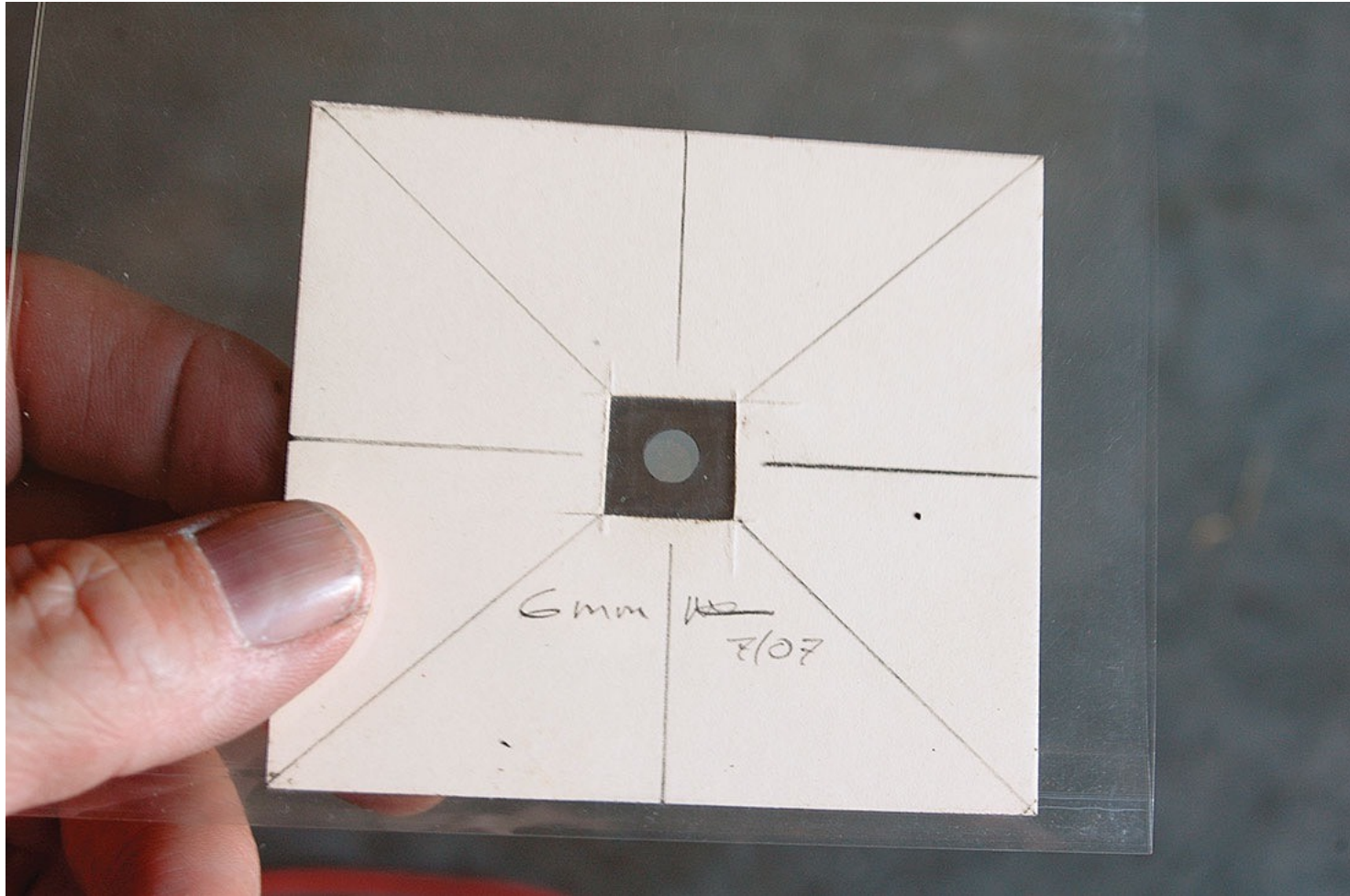


Largest Pinhole Photograph



“The Great Picture”

Largest Pinhole Photograph



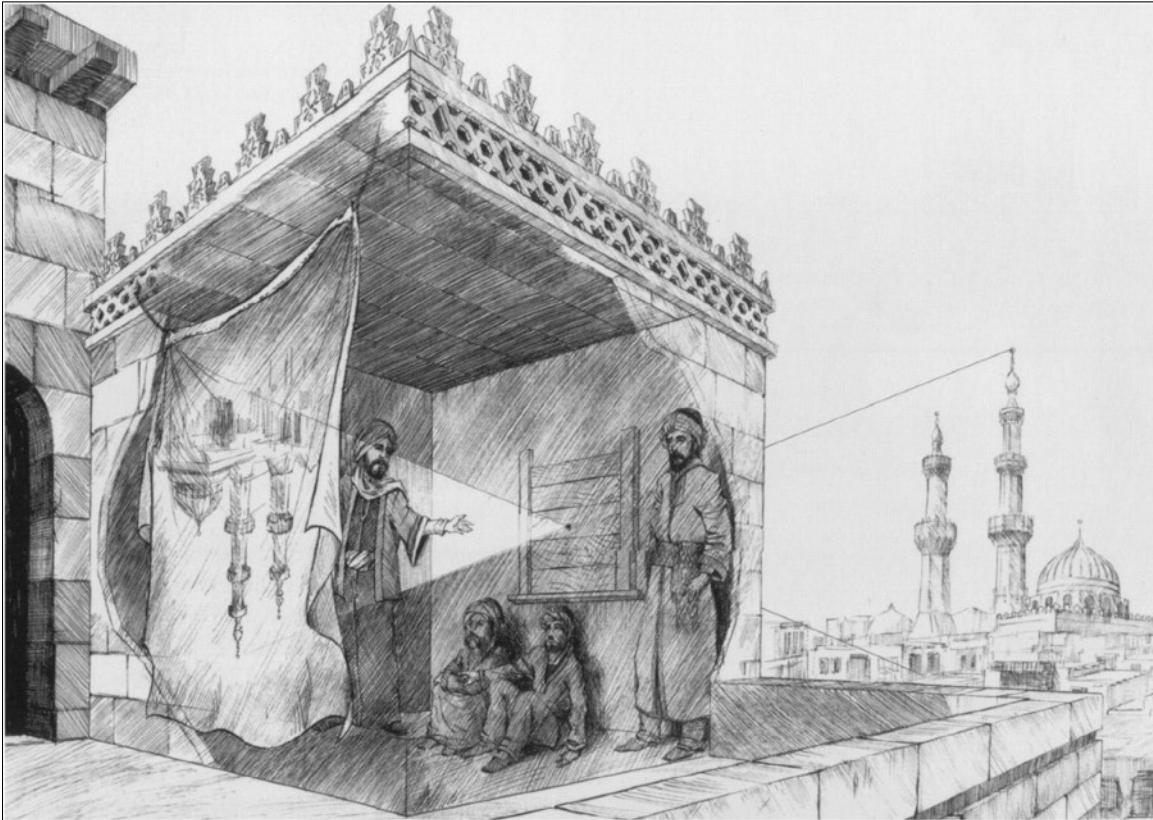
“The Great Picture”

Largest Pinhole Photograph



“The Great Picture”

Camera Obscura: the Pre-Camera

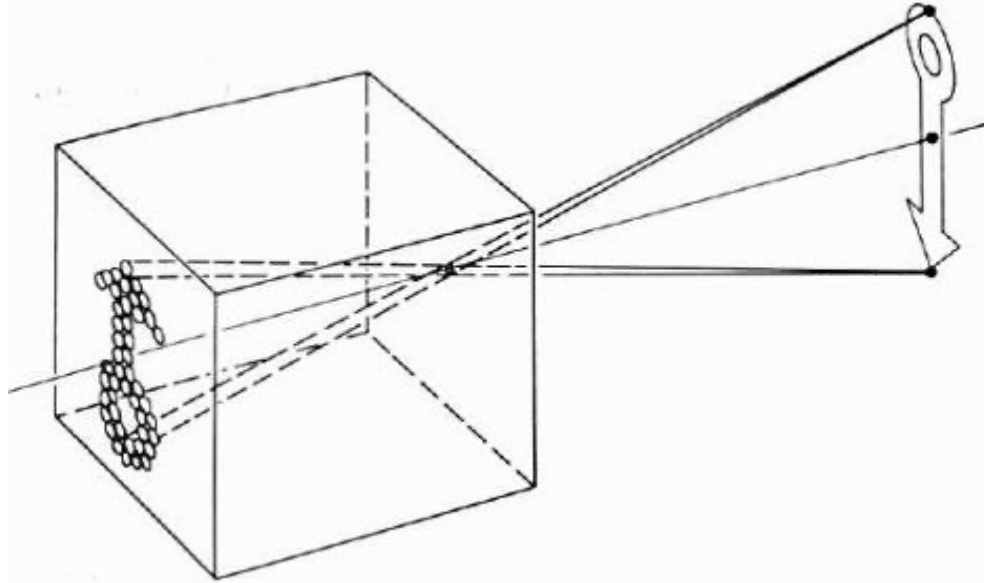


- First Idea: Mo-Ti, China (470-390 BC)
- First build: Al Hacen, Iraq/Egypt (965-1039 AD)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)



Camera Obscura near Cliff House, San Francisco

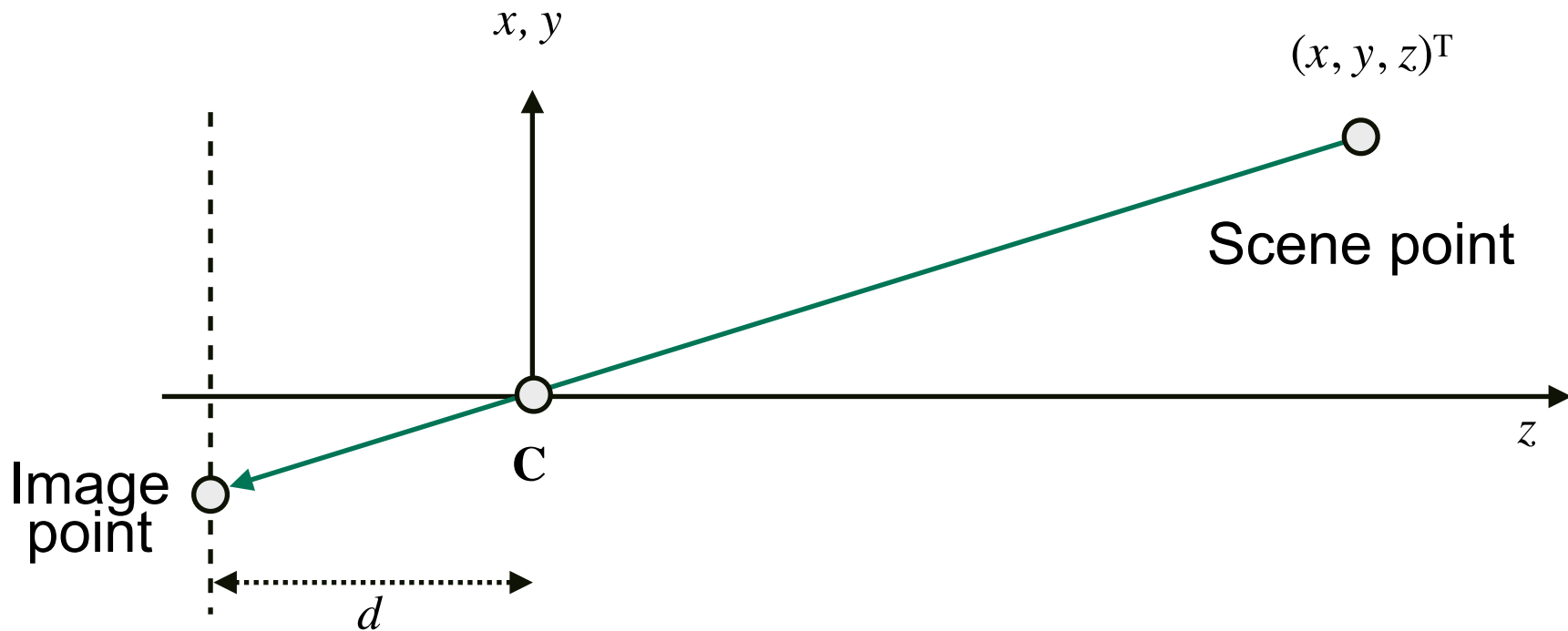
Pinhole Camera Model



Pinhole model:

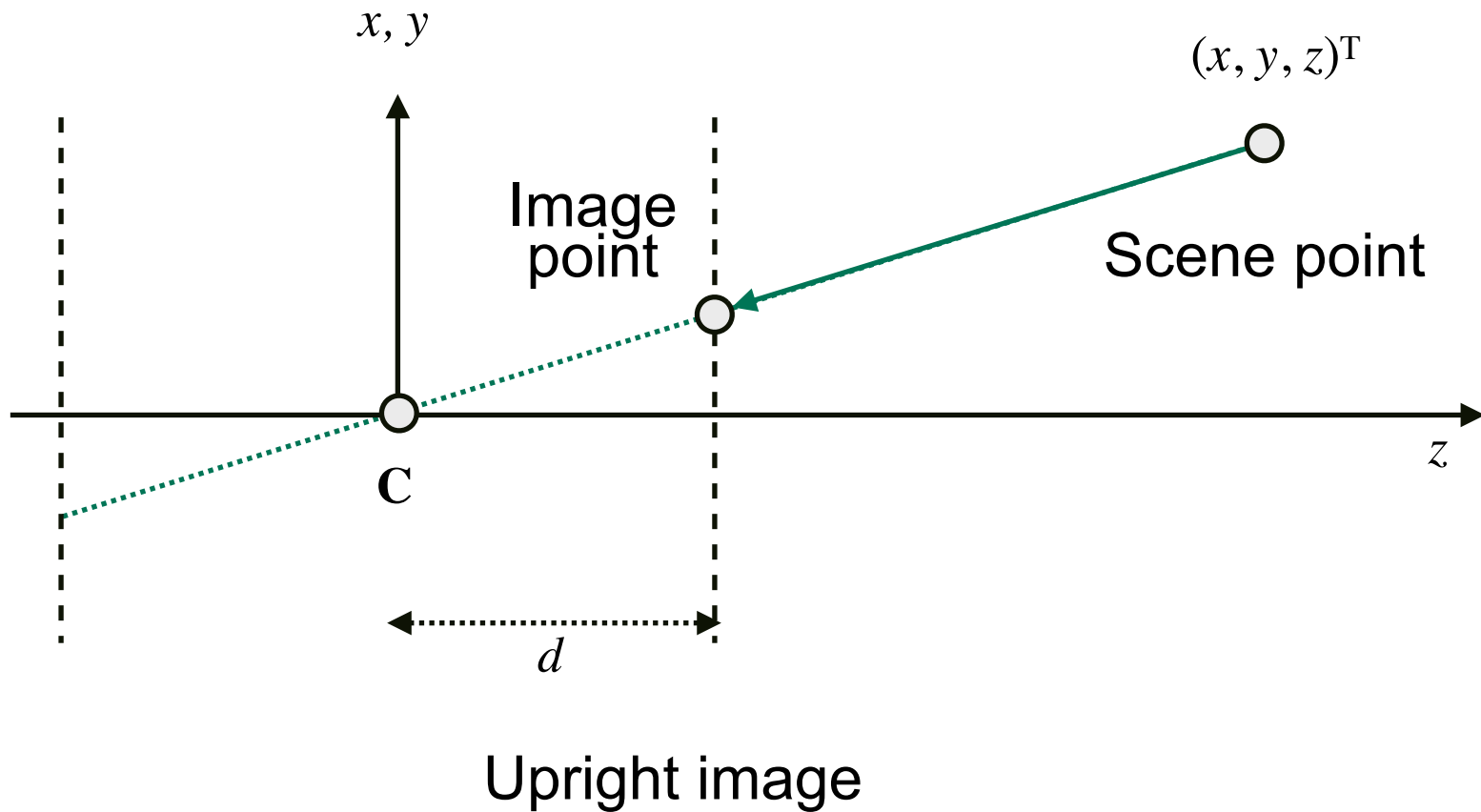
- Captures **pencil of rays** – all rays through a single point
- The point is called **Center of Projection (COP)**
- The image is formed on the **Image Plane**
- **Camera length** is the projection distance from COP to Image Plane (often referred to as the **effective focal length**)

Pinhole Camera Projective Transform



Inverted image (as in real pinhole camera)

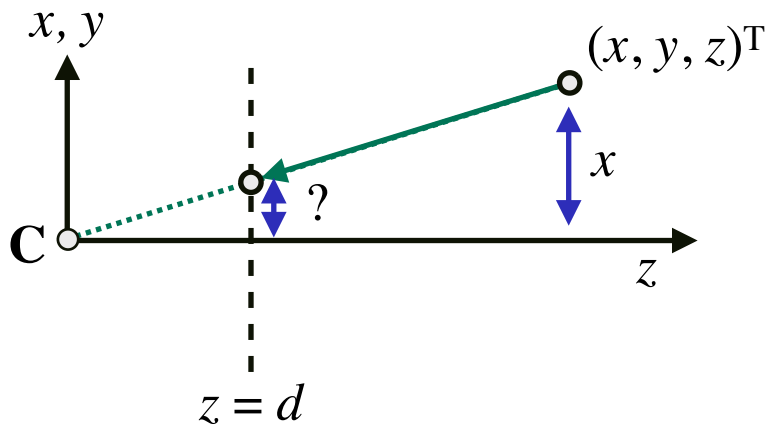
Pinhole Camera Projective Transform



Pinhole Camera Projective Transform

Standard perspective projection

- Center of projection: $(0, 0, 0)^T$
- Image plane at $z = d$



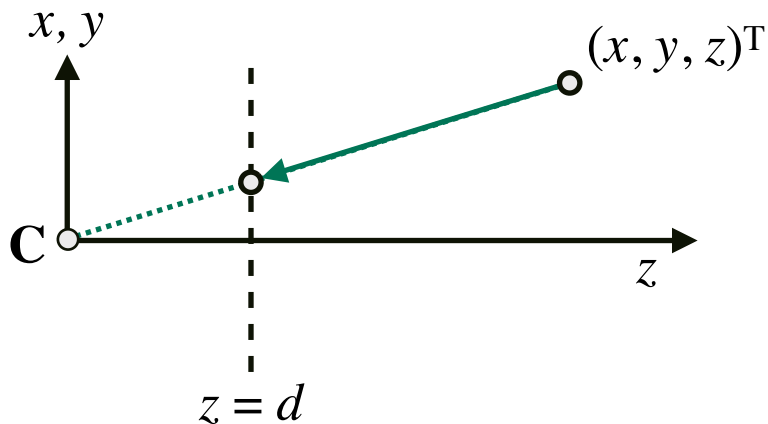
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} x \\ y \\ d \end{pmatrix}$$

$$\frac{?}{d} = \frac{x}{z}$$

Pinhole Camera Projective Transform

Standard perspective projection

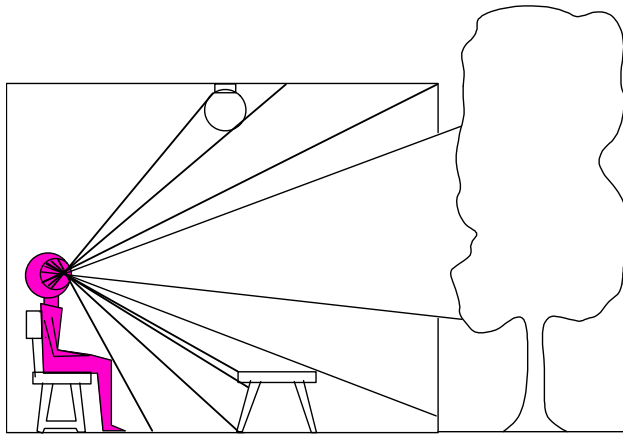
- Center of projection: $(0, 0, 0)^T$
- Image plane at $z = d$



$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} x \cdot d/z \\ y \cdot d/z \\ d \end{pmatrix} \cong \begin{pmatrix} x \cdot d/z \\ y \cdot d/z \end{pmatrix}$$

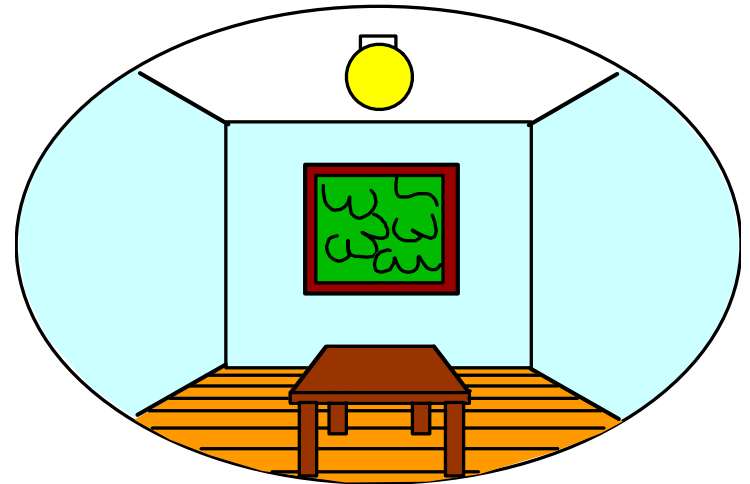
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

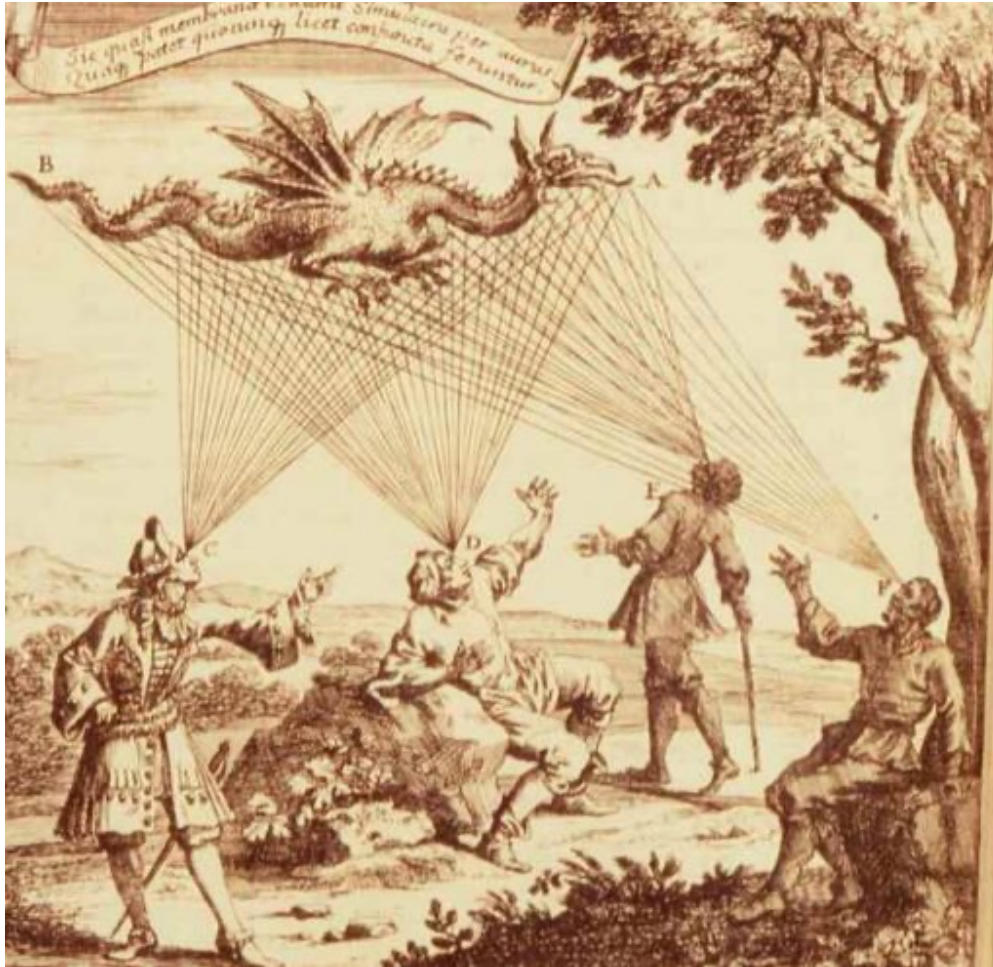
2D image



But there is a problem...

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} x \cdot d/z \\ y \cdot d/z \end{pmatrix}$$

Emission Theory of Vision



“For every complex problem there is an answer that is clear, simple, and wrong.”
-- H. L. Mencken

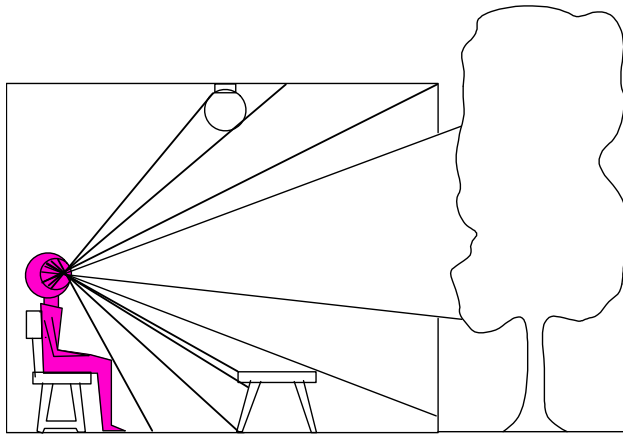
Supported by:

- Empedocles
- Plato
- Euclid (kinda)
- Ptolemy
- ...

Eyes send out “feeling rays” into the world

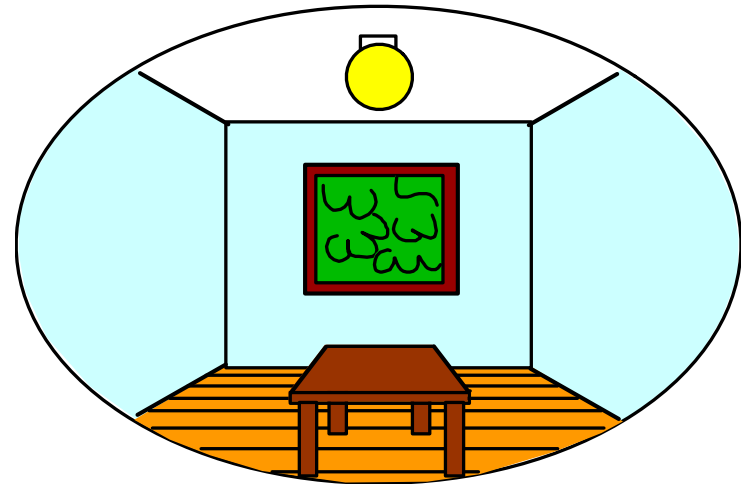
How we See the World

3D world



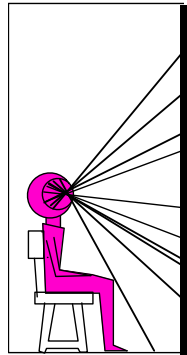
Point of observation

2D image



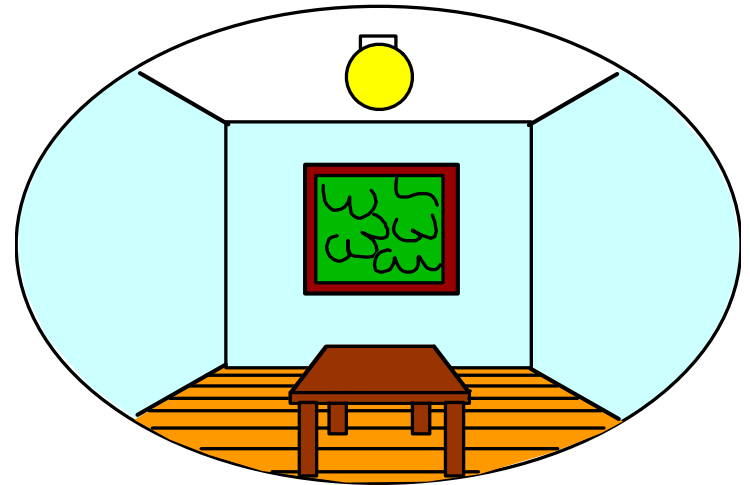
How we See the World

3D world



Painted
backdrop

2D image



Fooling the Eye



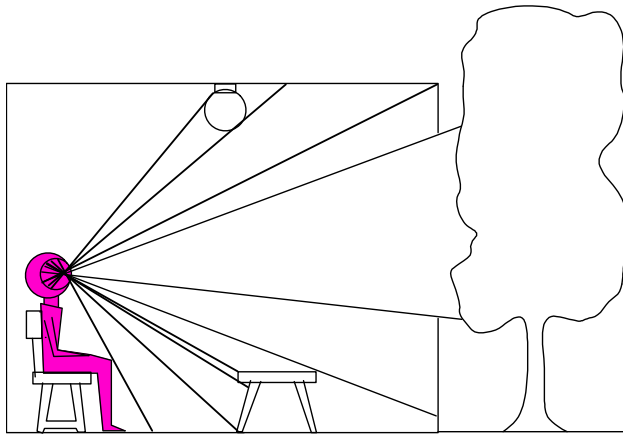
Fooling the Eye



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

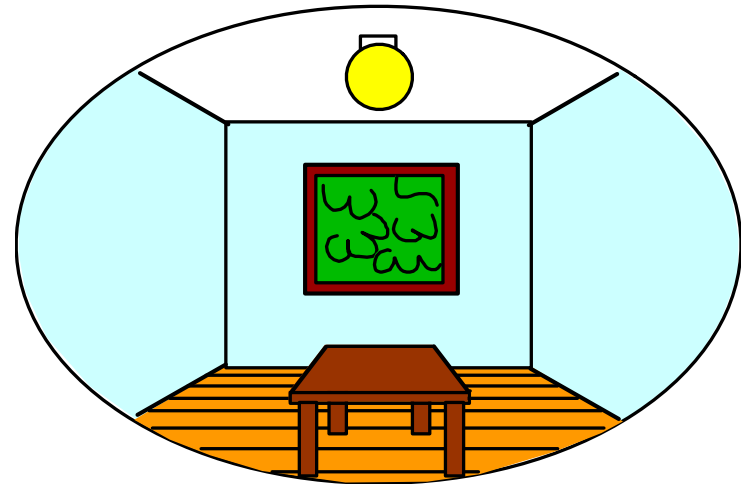
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

2D image

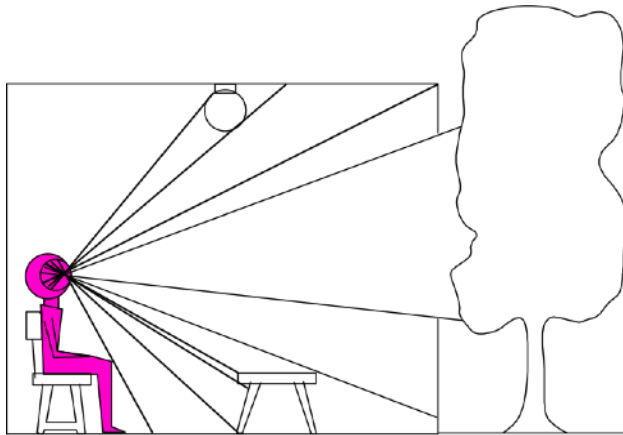


Why did evolution opt for such strange solution?

- Nice to have a passive, long-range sensor
- Can get 3D with stereo or by moving around, plus experience

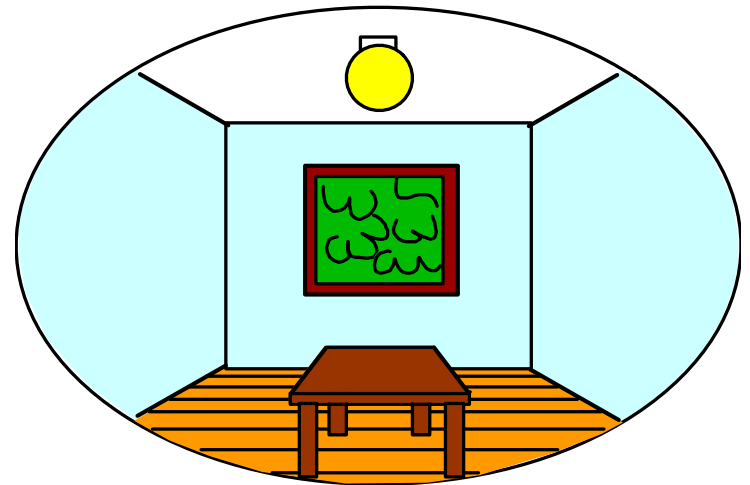
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

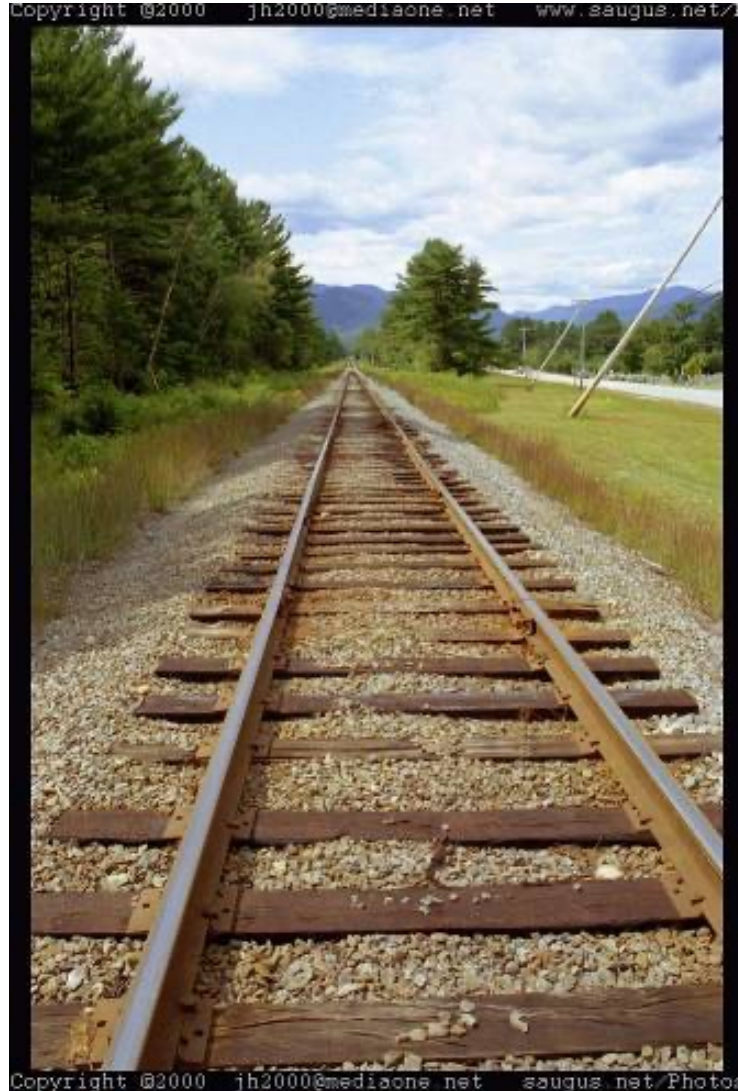
2D image



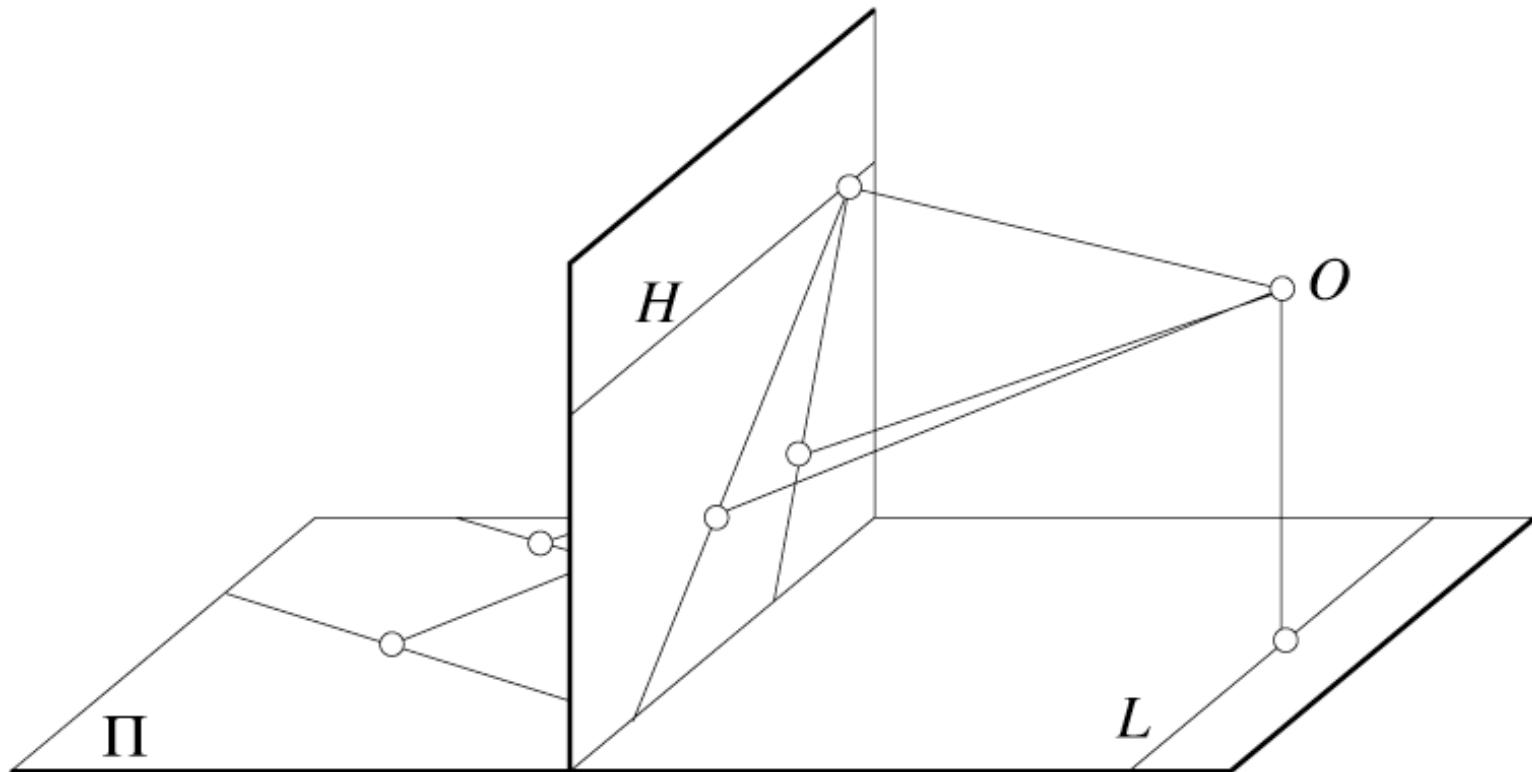
What have we lost?

- Angles
- Distances (lengths)

Funny Things Happen...



Parallel Lines Aren't...



Exciting New Study!



Sailors Take Warning



A.V. CLUB



VIDEO

POLITICS

SPORTS

BUSINESS

SCIENCE/TECH

ENTERTAINMENT

LOCAL

Q search

RECENT NEWS

Ariel Castro Failed By System

New Skin Cream To Do Something

Assad Unable To Convince Putin
That He Used Chemical Weapons
On Syrians

Royal Baby Already Making New
Friends

College-Aged Female Finds
Unlikely Kindred Spirit In Audrey
Hepburn

Personal Trainer Has Desk

Bruce Springsteen On Fence About
Playing Assad's Birthday Gig

Study: People Far Away From You Not Actually Smaller

NEWS • Science & Technology • ISSUE 49•34 • Aug 22, 2013



Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.



10.2K

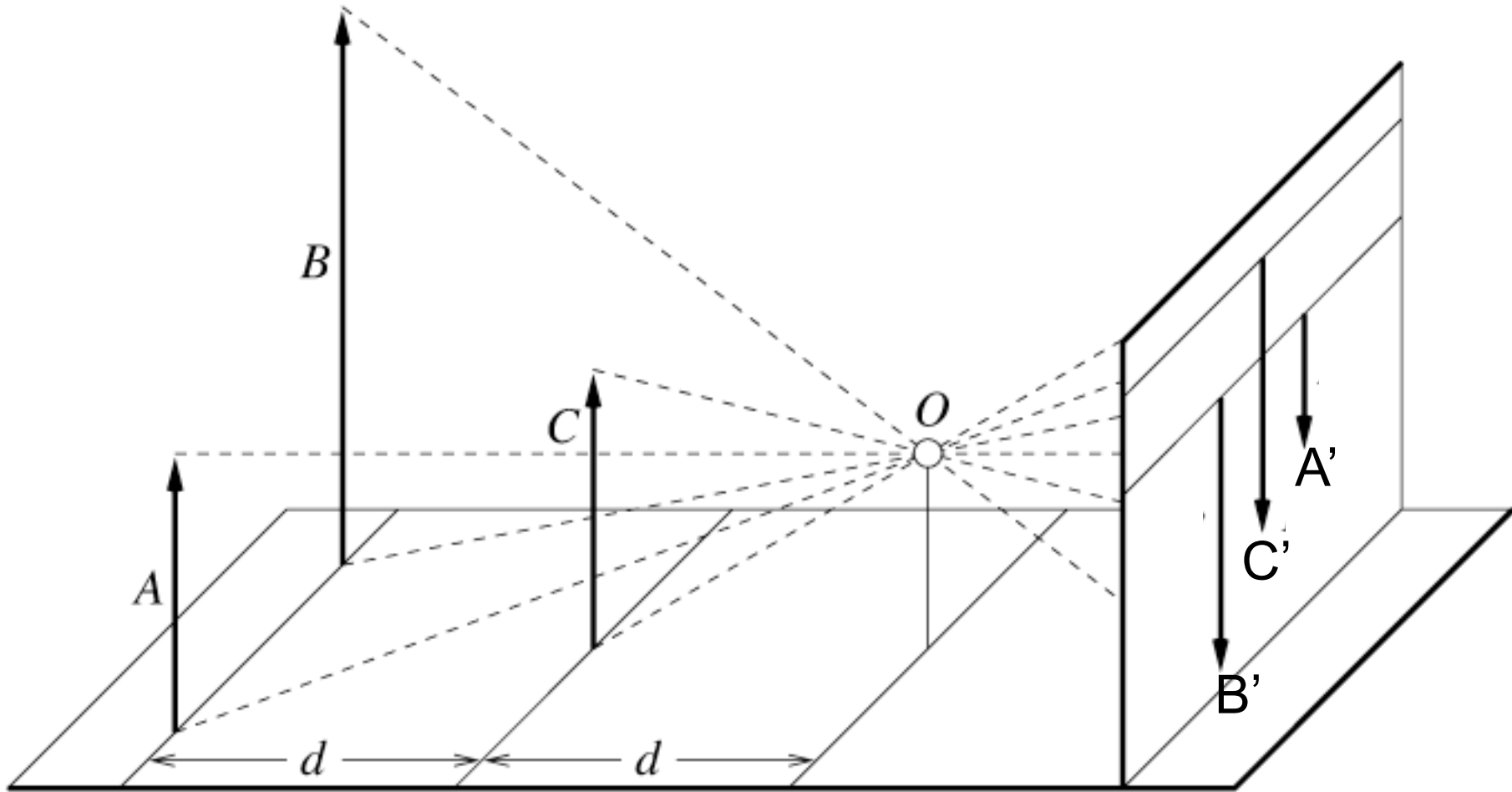


688



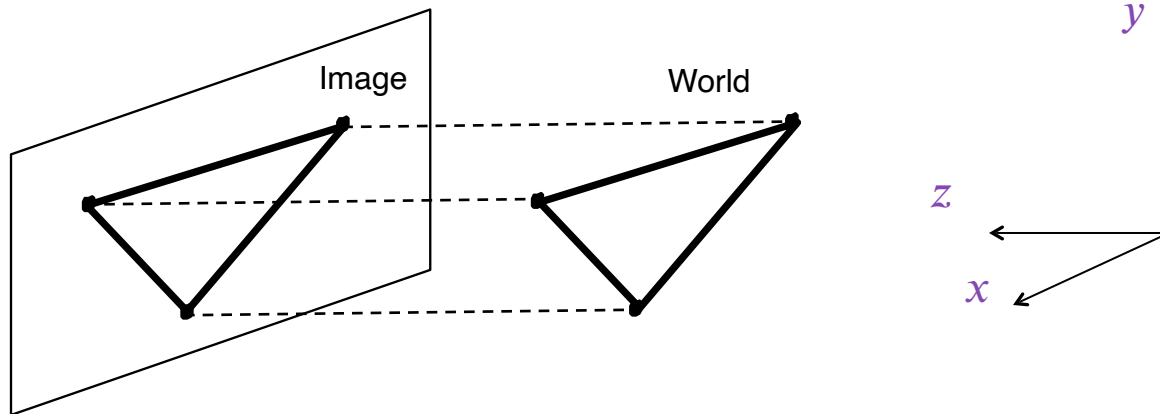
332

Lengths Can't Be Trusted...



Orthographic or Parallel Projection

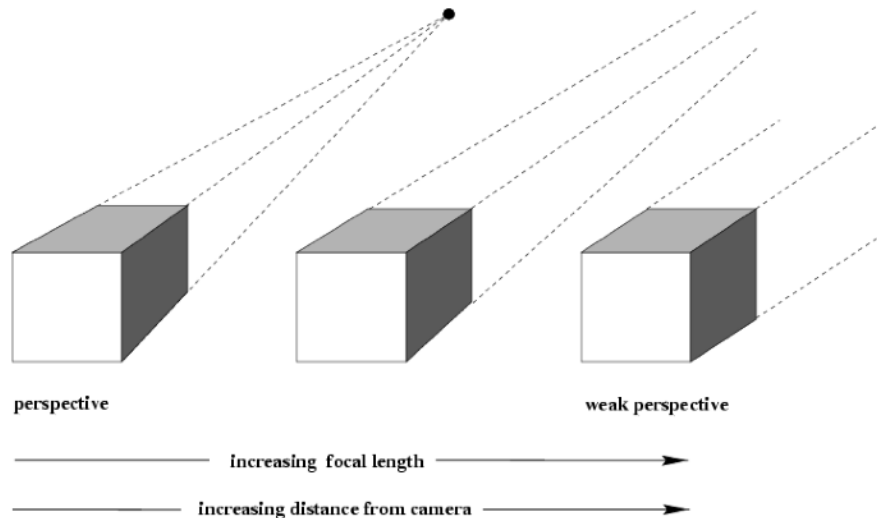
- Special case of perspective projection
 - Distance from center of projection to image plane is infinite
 - Projection equation: simply drop the z coordinate!



$$(x, y, z) \rightarrow (x, y)$$

Orthographic or Parallel Projection

- Move (infinitely) far away, and zoom in proportionately



Orthographic or Parallel Projection

- Special case of perspective projection
 - Distance from center of projection to image plane is infinite
 - Projection equation: simply drop the z coordinate!

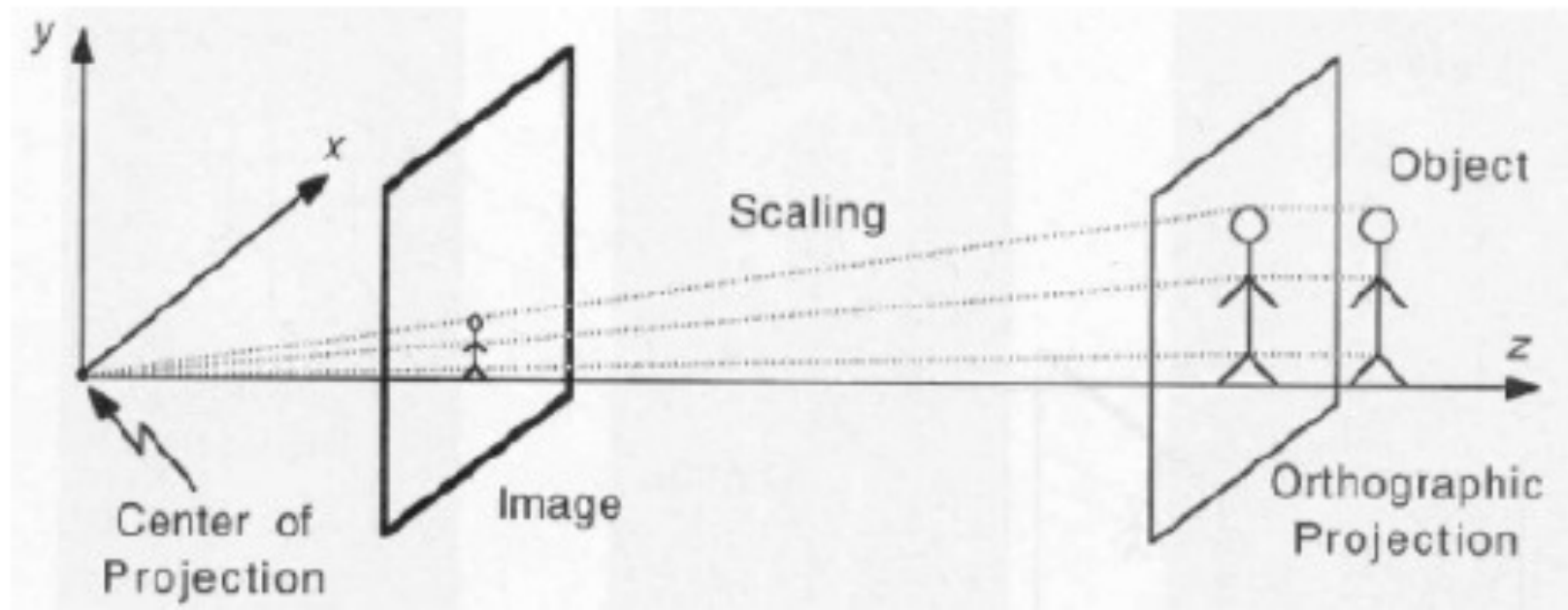


SimCity 2000

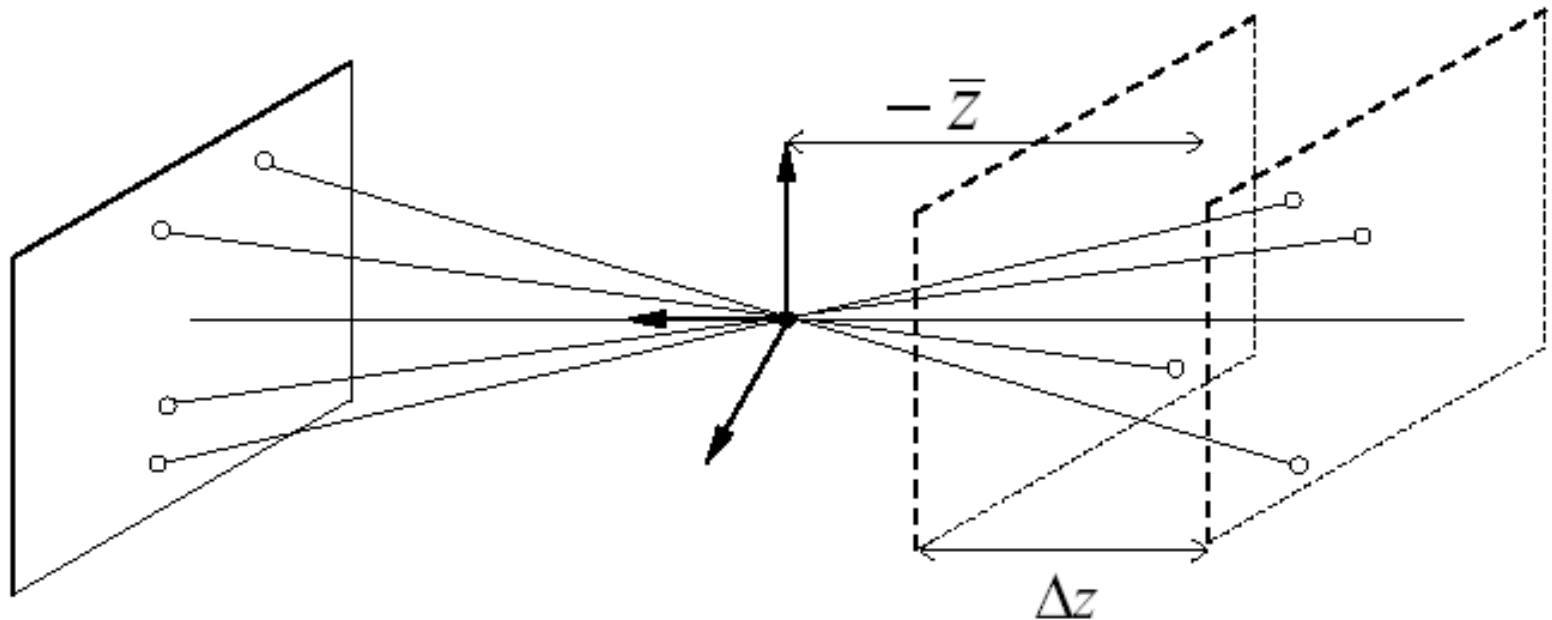


12th century Chinese scroll
(via [A. Hertzmann](#))

Scaled Orthographic or “Weak Perspective”



Scaled Orthographic or “Weak Perspective”

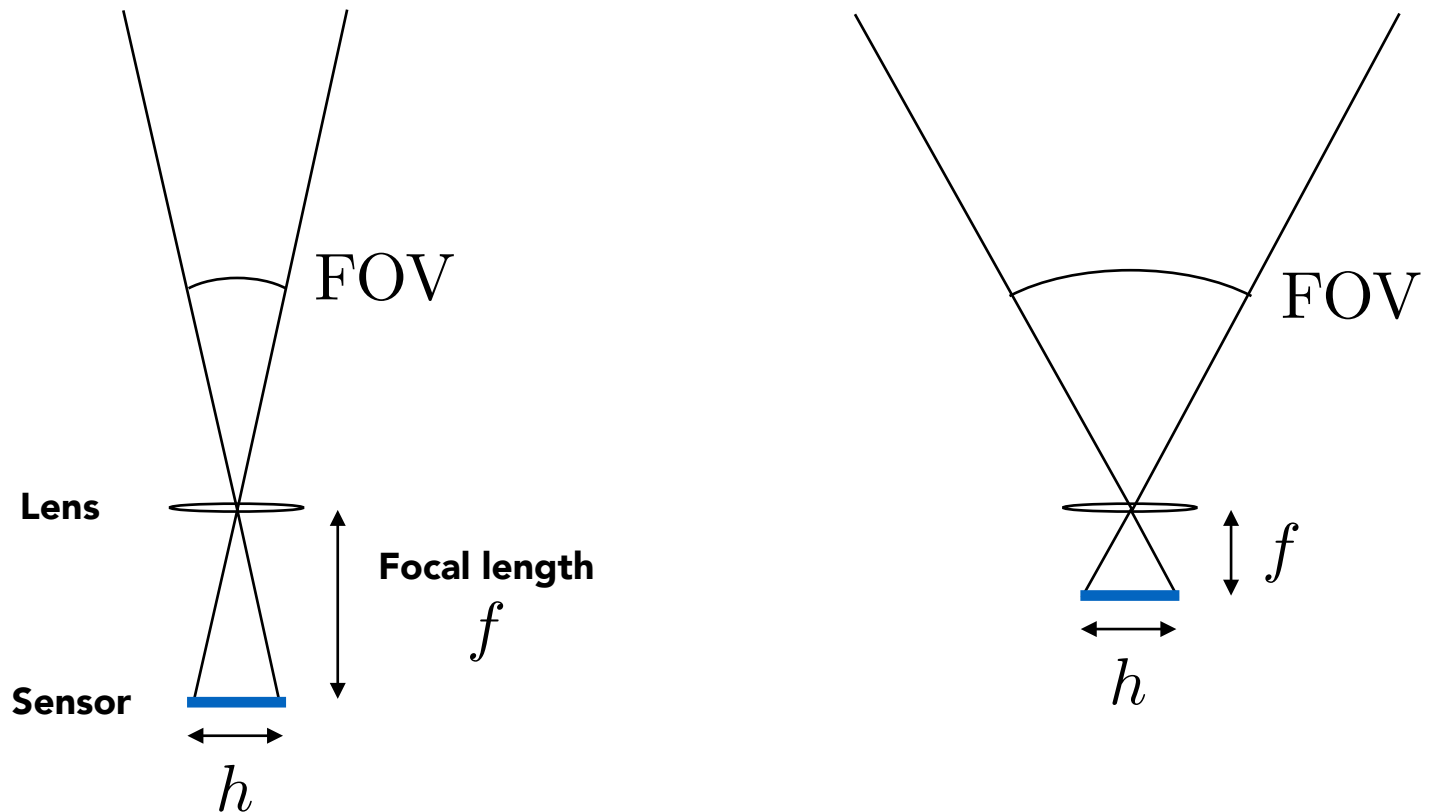


$$\text{If } \Delta z \ll -\bar{z} : \begin{aligned} x' &\approx -mx \\ y' &\approx -my \end{aligned} \quad m = -\frac{f'}{\bar{z}}$$

Justified if scene depth is small relative to average distance from camera

Field of View (Zoom)

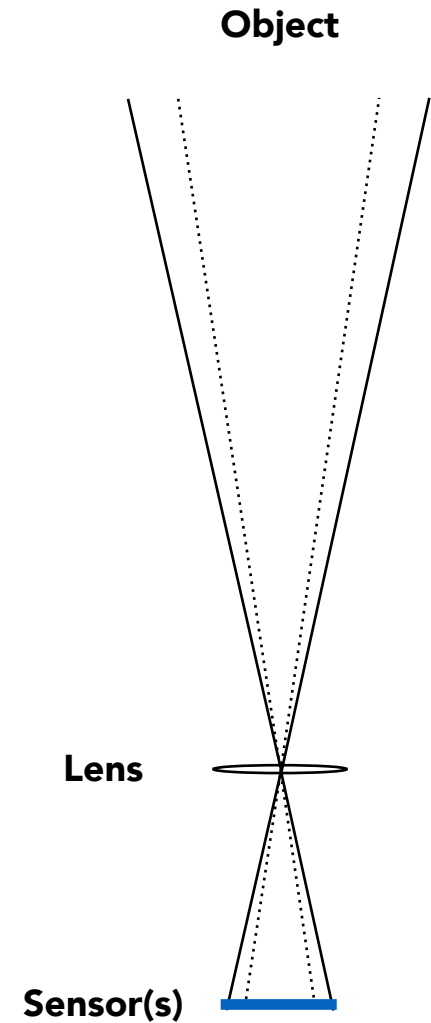
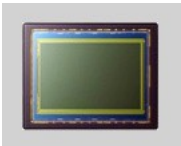
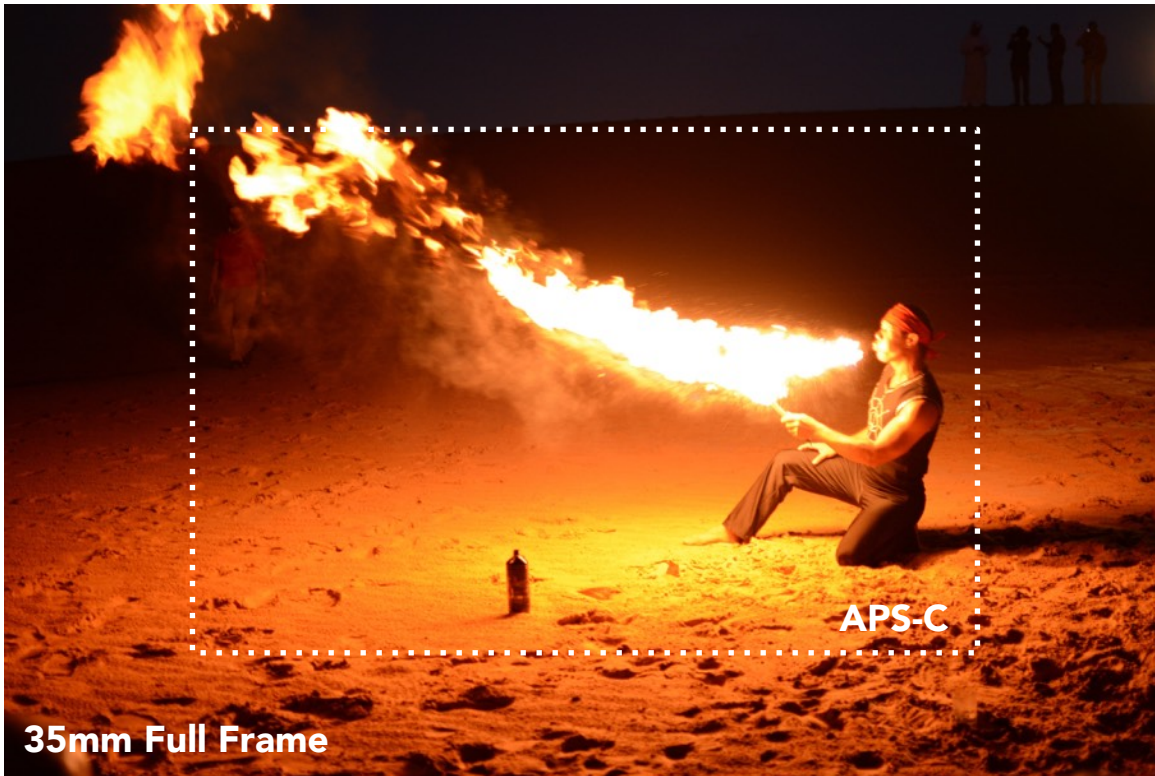
Effect of Focal Length on FOV



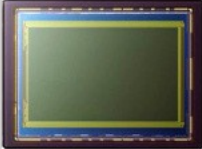
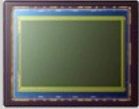
For a fixed sensor size, decreasing the focal length increases the field of view.

$$\text{FOV} = 2 \arctan \left(\frac{h}{2f} \right)$$

Effect of Sensor Size on FOV



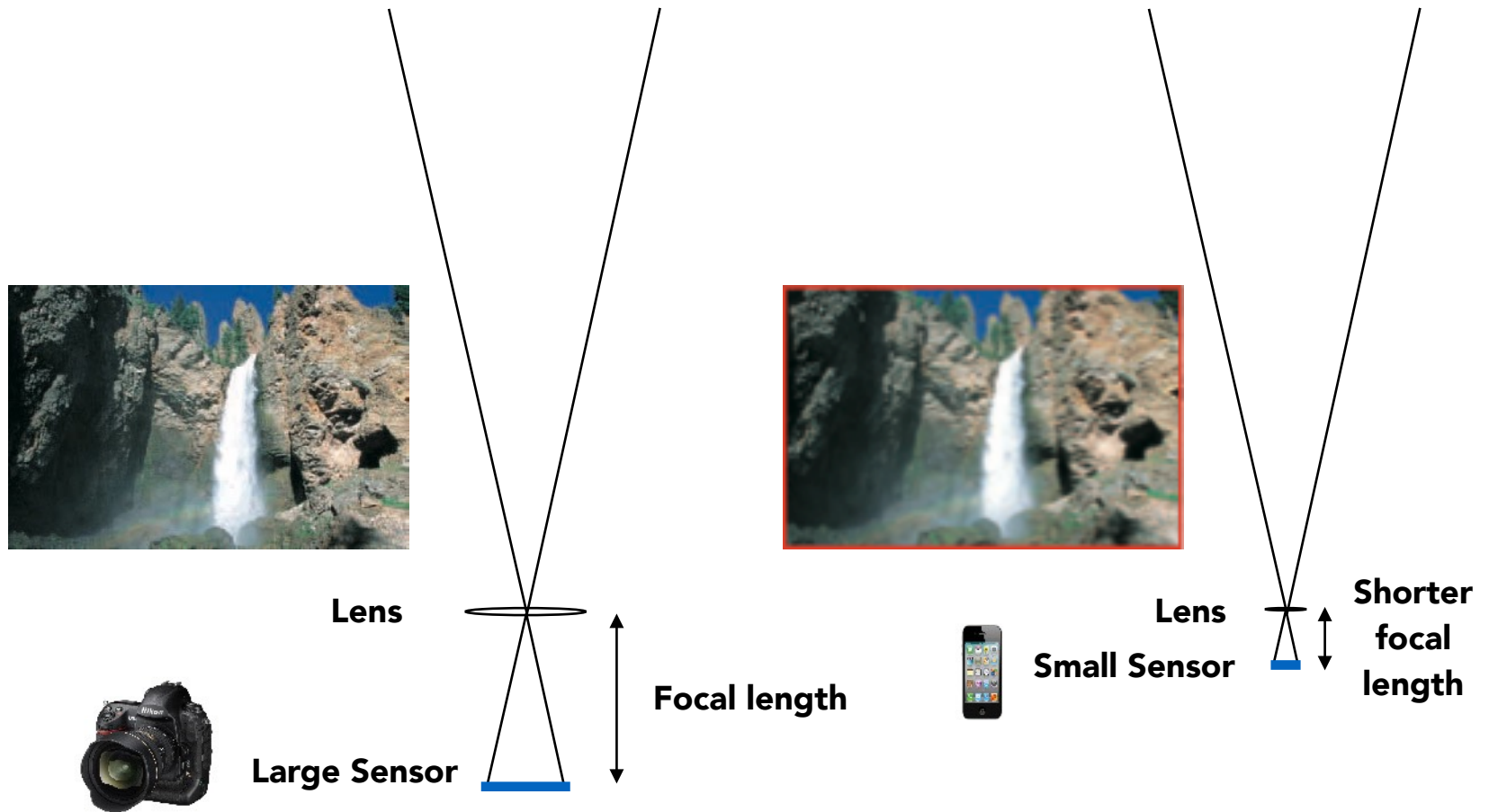
Sensor Sizes

Sensor Name	Medium Format	Full Frame	APS-H	APS-C	4/3	1"	1/1.63"	1/2.3"	1/3.2"
Sensor Size	53.7 x 40.2mm	36 x 23.9mm	27.9x18.6mm	23.6x15.8mm	17.3x13mm	13.2x8.8mm	8.38x5.59mm	6.16x4.62mm	4.54x3.42mm
Sensor Area	21.59 cm ²	8.6 cm ²	5.19 cm ²	3.73 cm ²	2.25 cm ²	1.16 cm ²	0.47 cm ²	0.28 cm ²	0.15 cm ²
Crop Factor	0.64	1.0	1.29	1.52	2.0	2.7	4.3	5.62	7.61
Image									
Example									



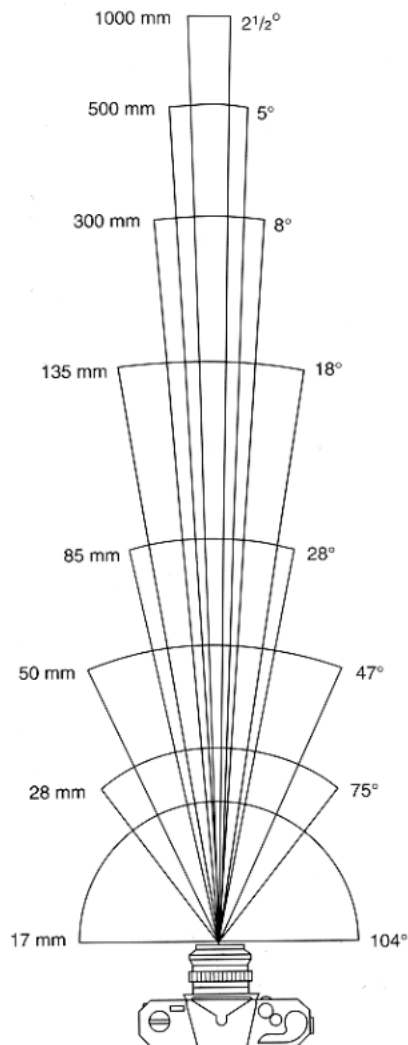
Credit:

Maintain FOV on Smaller Sensor?



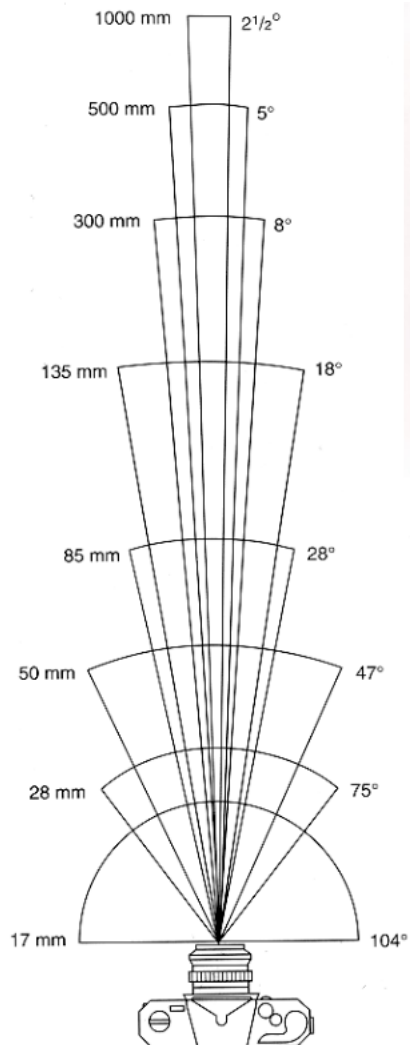
To maintain FOV, decrease focal length of lens
in proportion to width/height of sensor

Focal Length v. Field of View



- For historical reasons, it is common to refer to angular field of view by focal length of a lens used on 35mm-format film (36 x 24mm)
- Examples of focal lengths on 35mm format:
 - » 17mm is wide angle 104°
 - » 50mm is a "normal" lens 47°
 - » 200mm is telephoto lens 12°
- Careful! When we say current cell phones have approximately 24mm "equivalent" focal length, this uses the above convention. The physical focal length is often 5-6 times shorter, because the sensor is correspondingly smaller

Focal Length v. Field of View



15mm (fisheye)



14mm



24mm

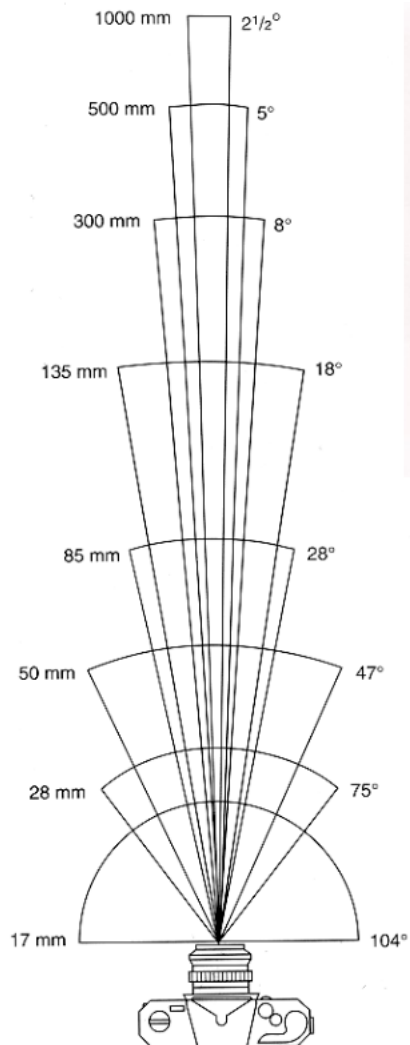


24mm



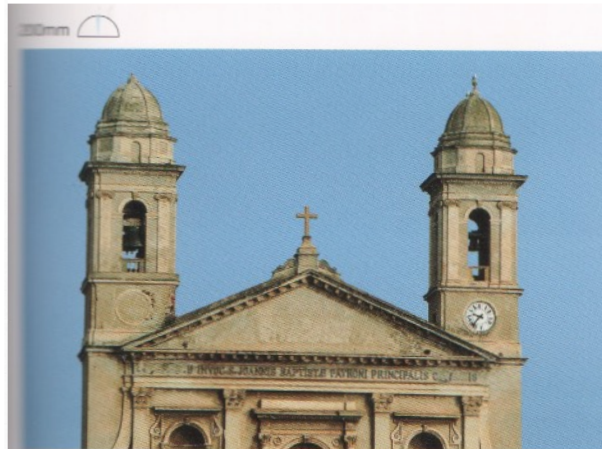
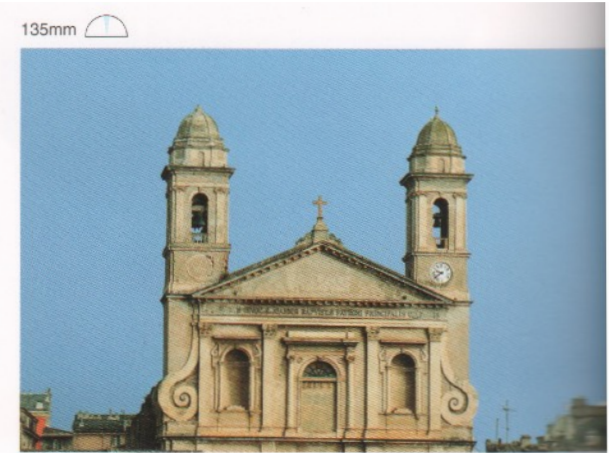
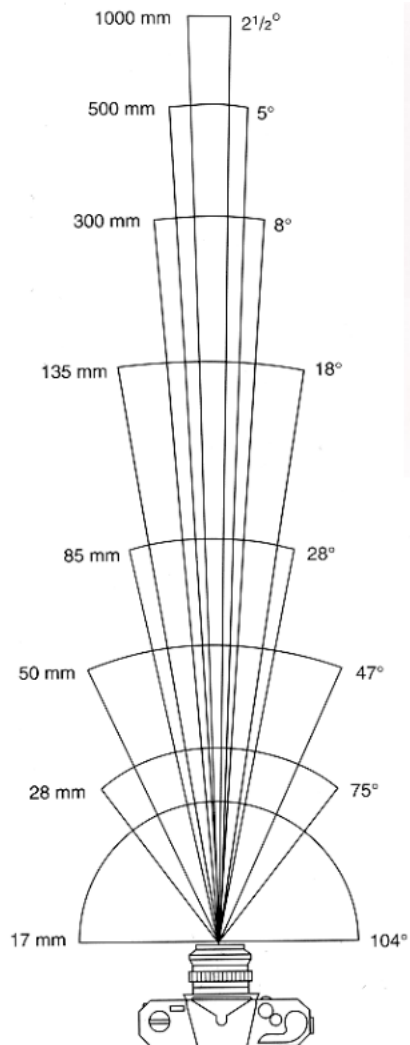
From London and Upton, and Canon EF Lens Work III

Focal Length v. Field of View



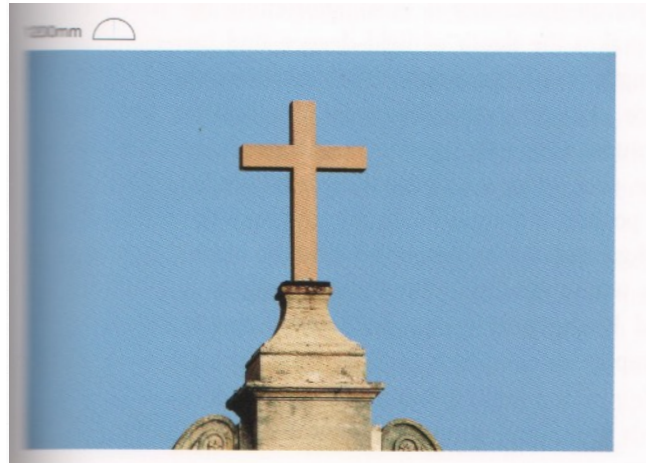
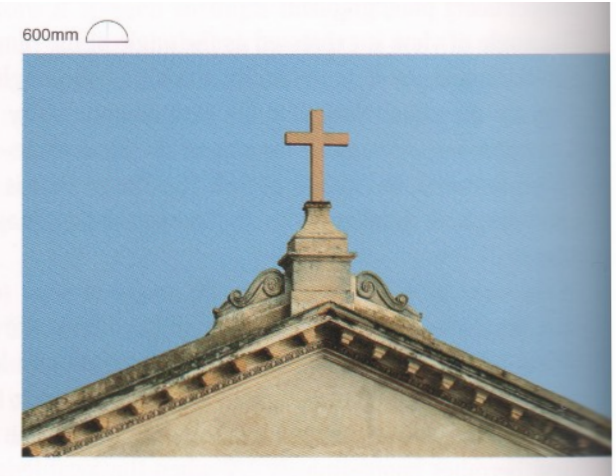
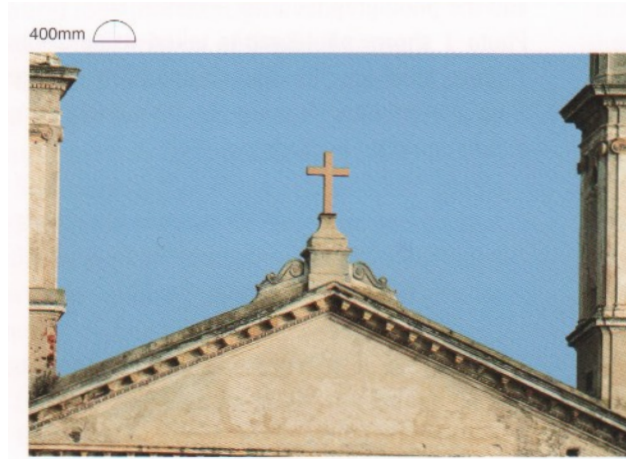
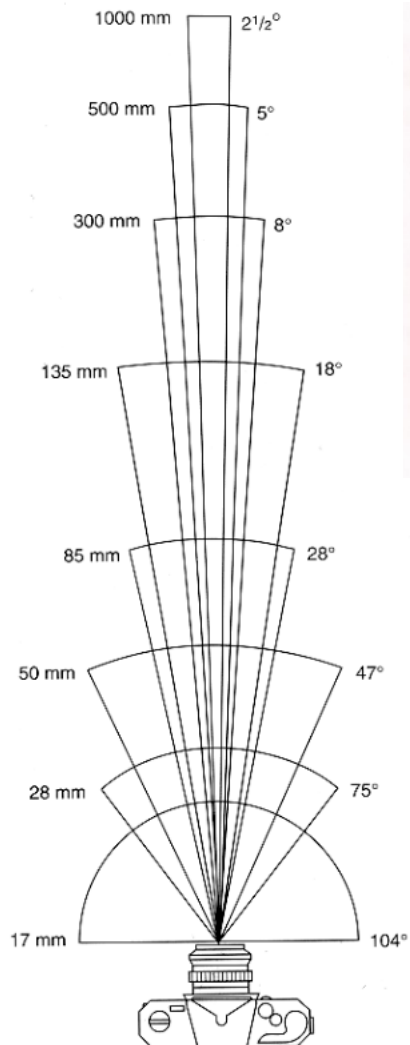
From London and Upton, and Canon EF Lens Work III

Focal Length v. Field of View



From London and Upton, and Canon EF Lens Work III

Focal Length v. Field of View



From London and Upton, and Canon EF Lens Work III

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/>



800mm f5.6 L IS



600mm f4 L IS II



200-400mm f4 L IS



500mm f4 L IS II



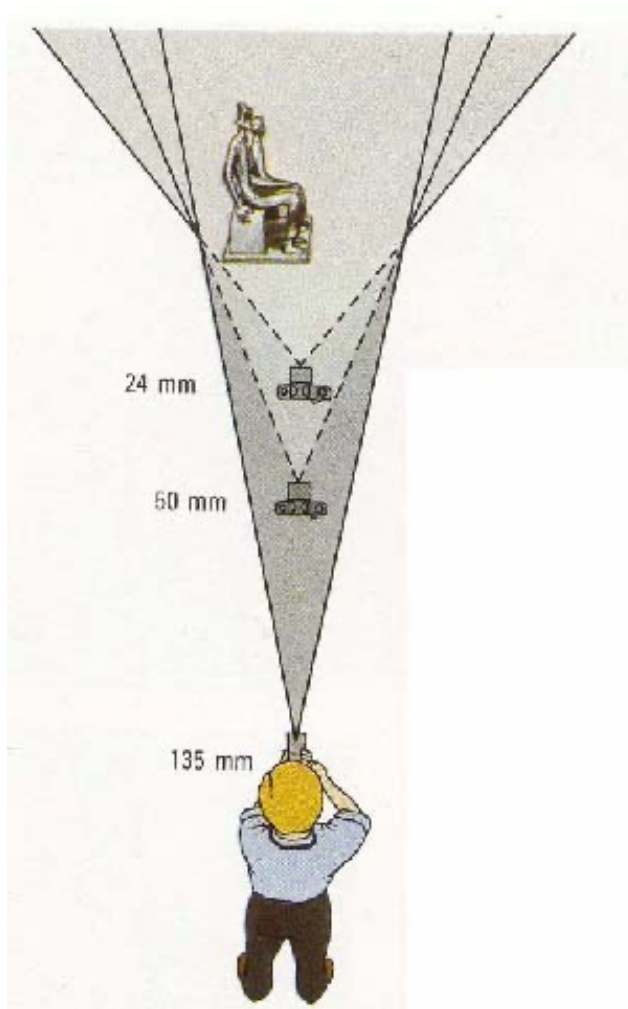
400mm f2.8 L IS II



300mm f2.8 L IS II

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

Perspective Compression



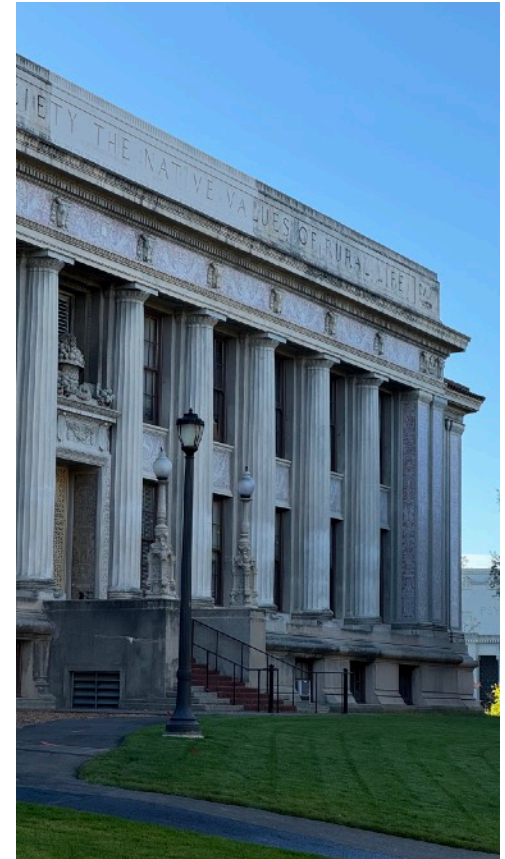
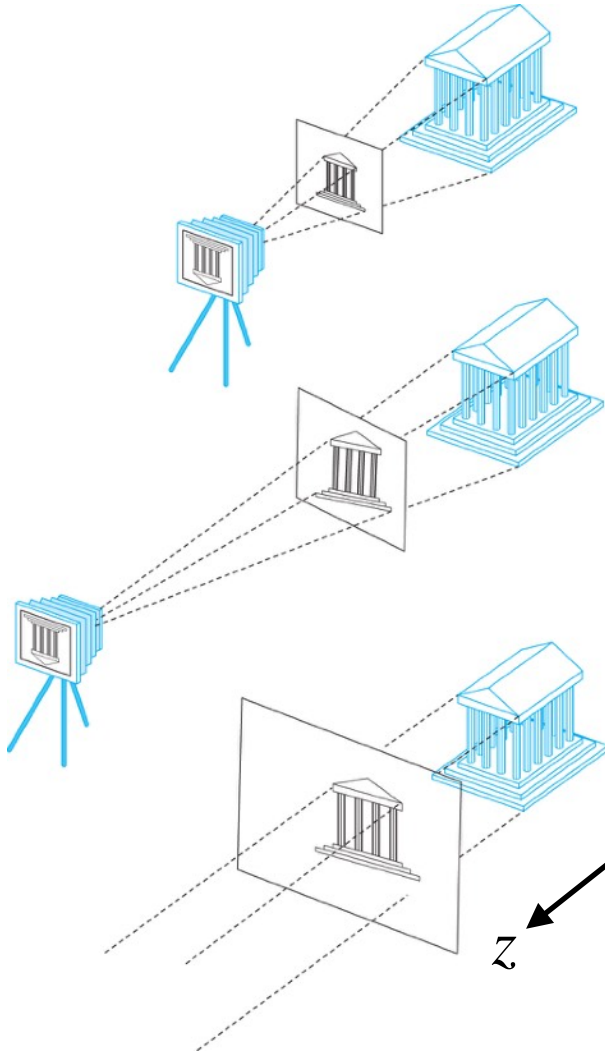
Large FOV, small f
Camera close to car



Small FOV, large f
Camera far from the car

Perspective Compression

- Move away and zoom in proportionately



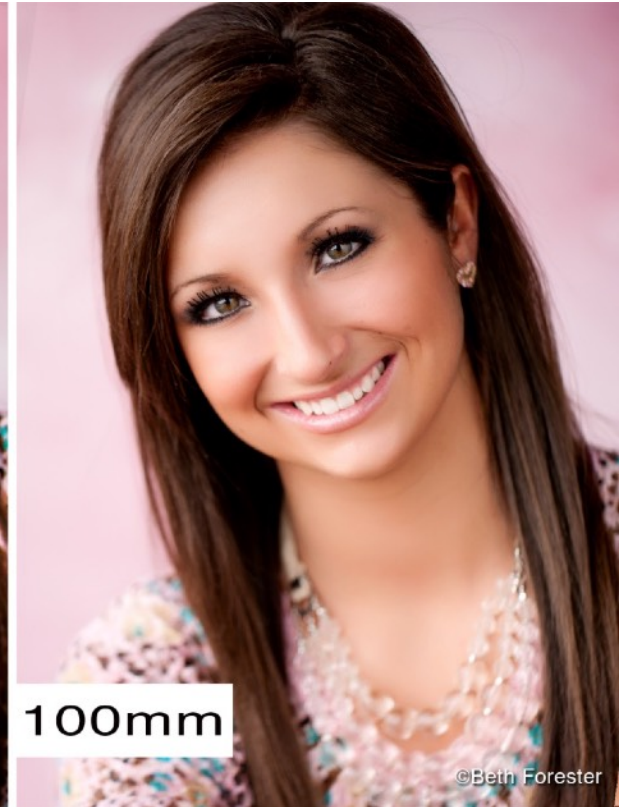
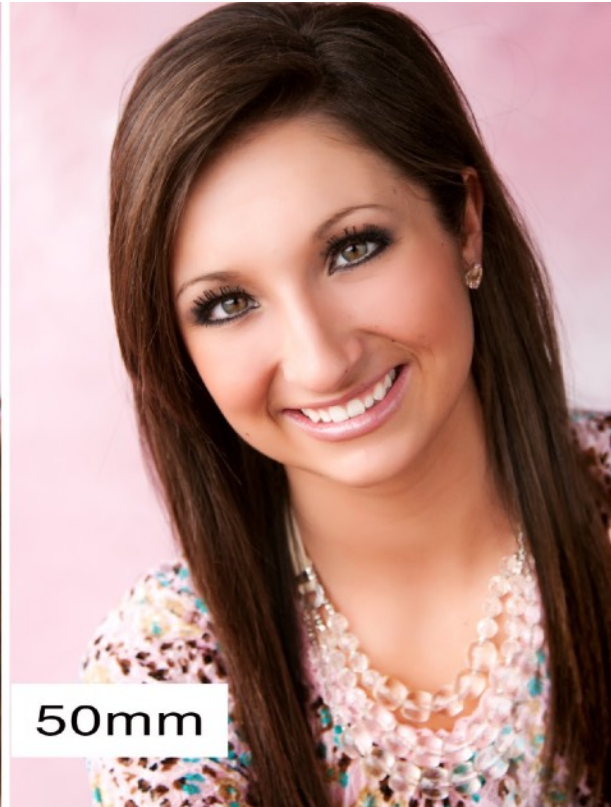


Dolly Zoom (“Vertigo Shot”)



First used by Alfred Hitchcock in “Vertigo” 1958

Focal Length / Viewpoint in Portraiture



Focal Length / Viewpoint in Portraiture



16 mm

In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

Focal Length / Viewpoint in Portraiture

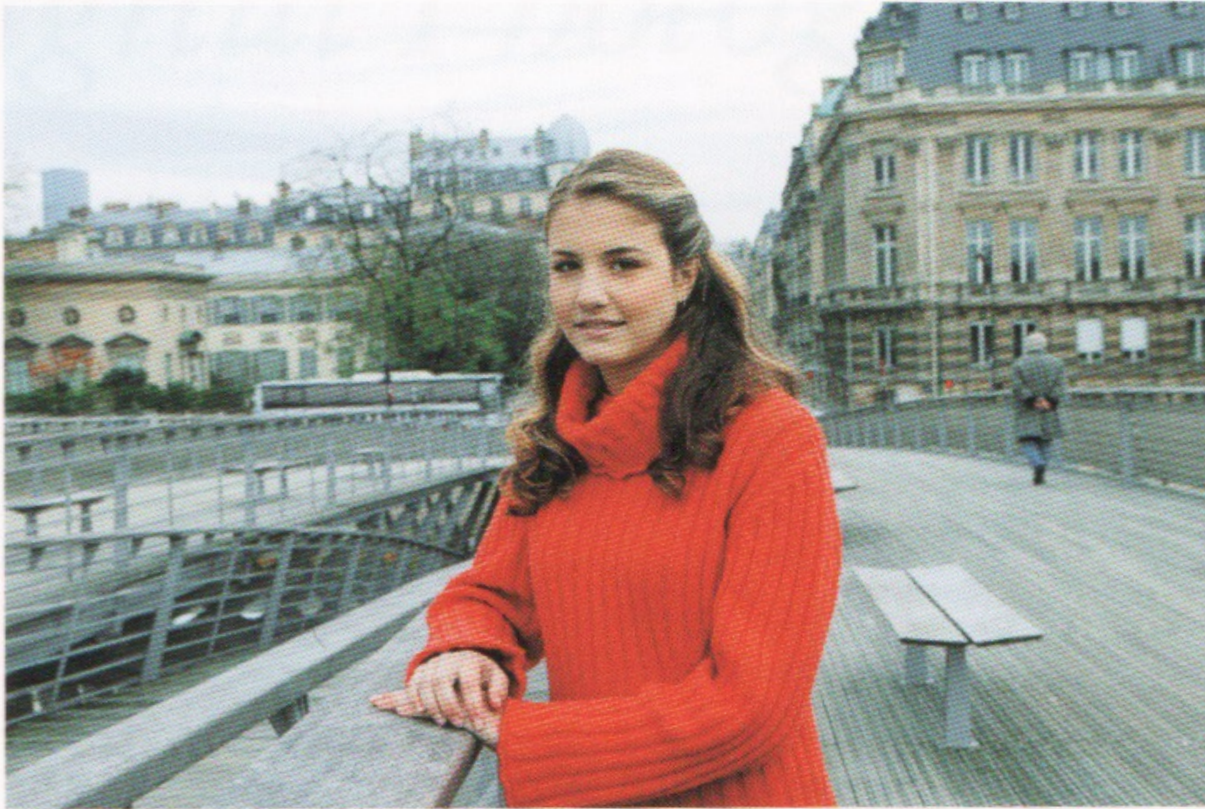


24 mm

In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

Focal Length / Viewpoint in Portraiture



50 mm

In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

From Canon EF Lens Work III

Focal Length / Viewpoint in Portraiture



135 mm

In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

From Canon EF Lens Work III

Focal Length / Viewpoint in Portraiture



200 mm

In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

Focal Length / Viewpoint in Portraiture

16mm



24mm



50mm



200mm



135mm



In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

From Canon EF Lens Work III

Focal Length / Viewpoint in Portraiture



16 mm (110°)

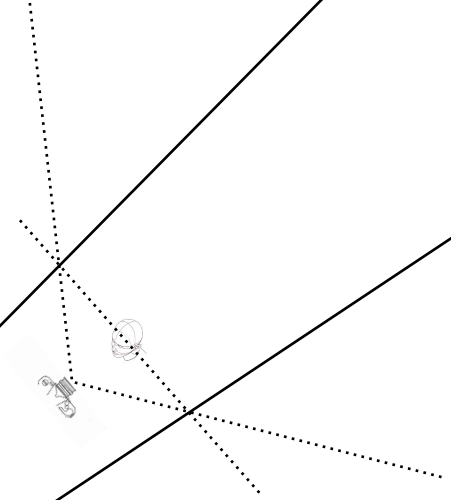
**Up close and zoomed wide
with short focal length**

Focal Length / Viewpoint in Portraiture



200 mm (12°)

**Walk back and zoom in
with long focal length**



Perspective Composition (Photographer's Mindset)



Wide angle: 15mm, f/2.8



Wide angle: 18mm, 1/750, f/8



Normal: 50mm, 1/80, f/1.4



Normal: 64mm, 1/3200, f/2.8



Telephoto: 150mm, 1/640, f/1.8

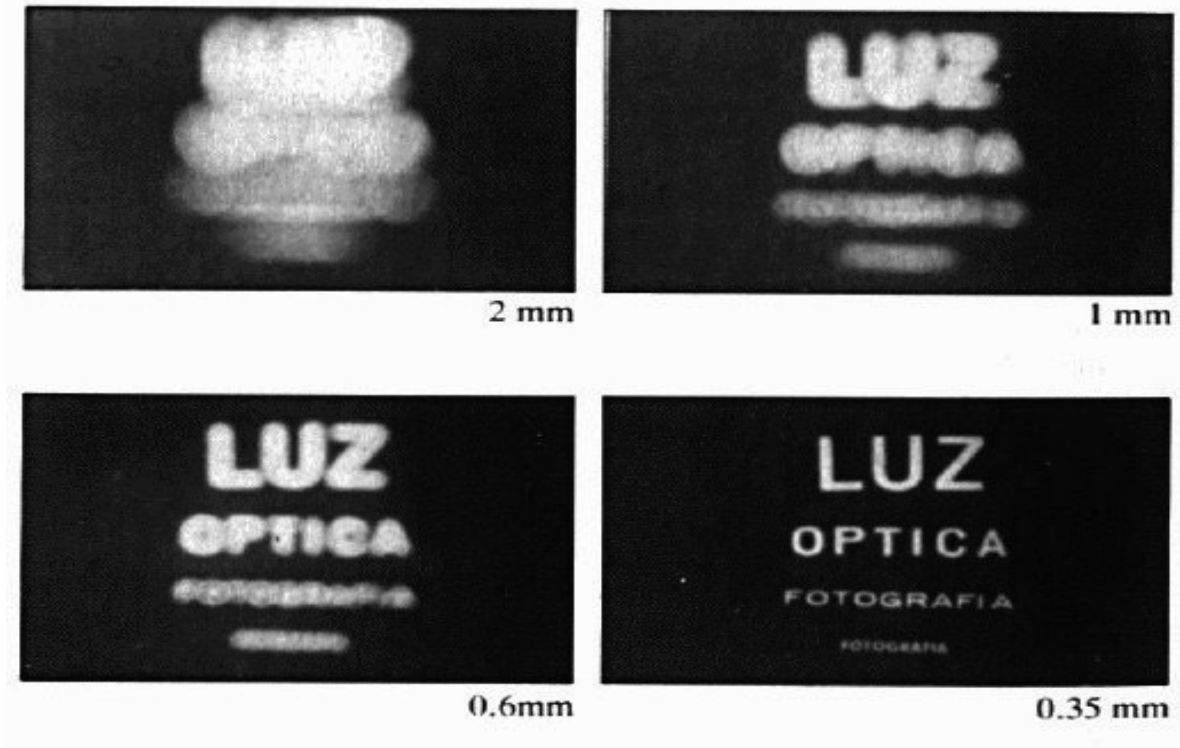
Pinholes to Lenses

DIY Pinhole Camera



Why so
blurry?

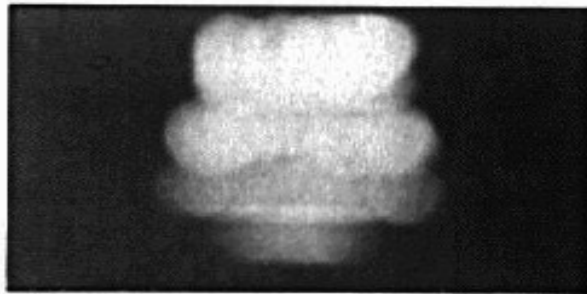
Shrinking the Aperture



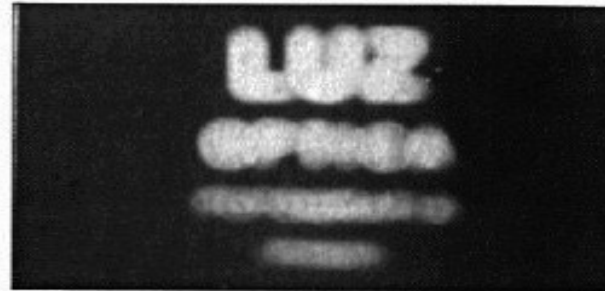
Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects...

Shrinking the Aperture



2 mm



1 mm



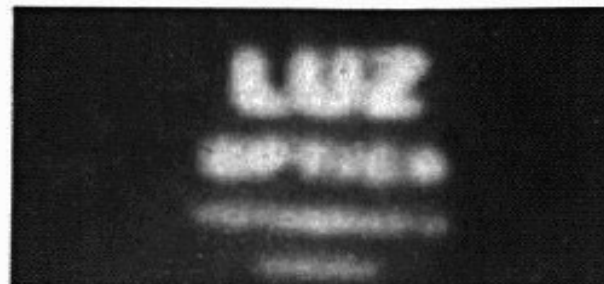
0.6 mm



0.35 mm



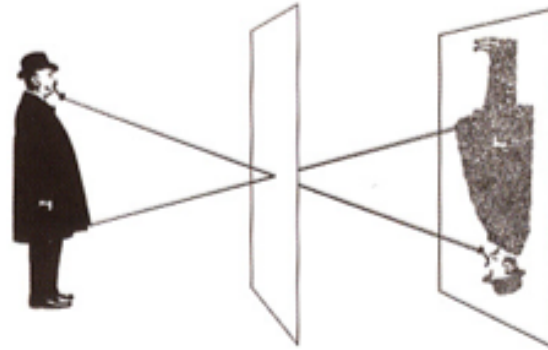
0.15 mm



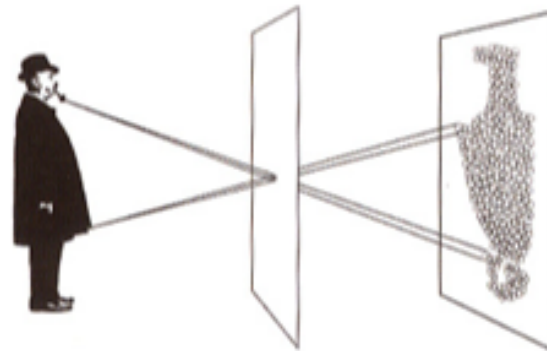
0.07 mm

Pinhole Image Formation

Photograph made with small pinhole



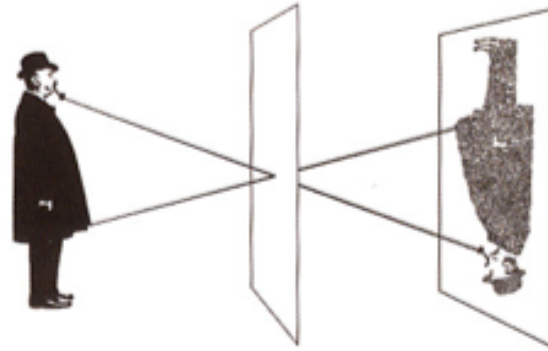
Photograph made with larger pinhole



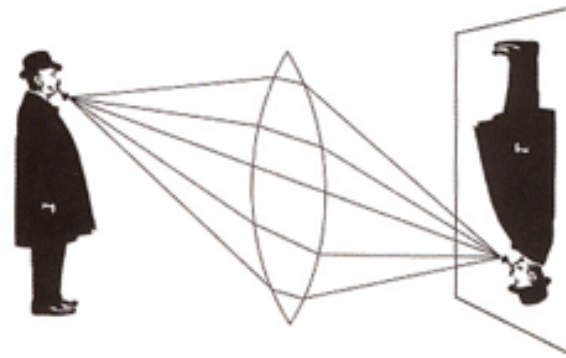
London and Upton

Lens Image Formation

Photograph made with small pinhole



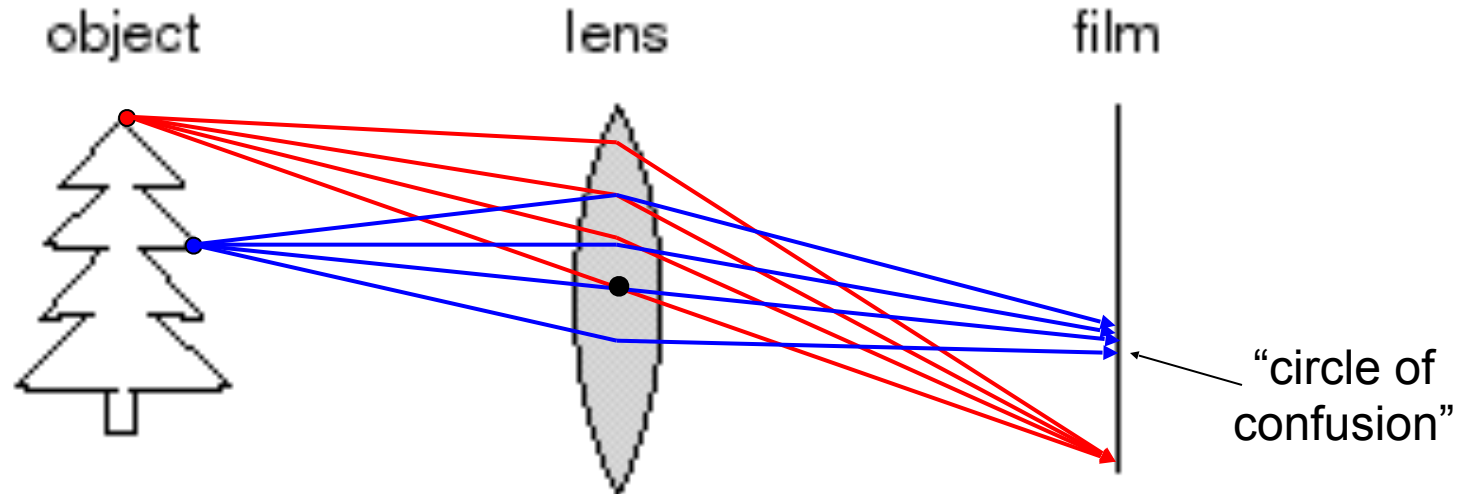
Photograph made with lens



London and Upton

Focus

Focus and Defocus



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
- Changing the shape of the lens changes this distance

Image Focus Varies with Projection Distance

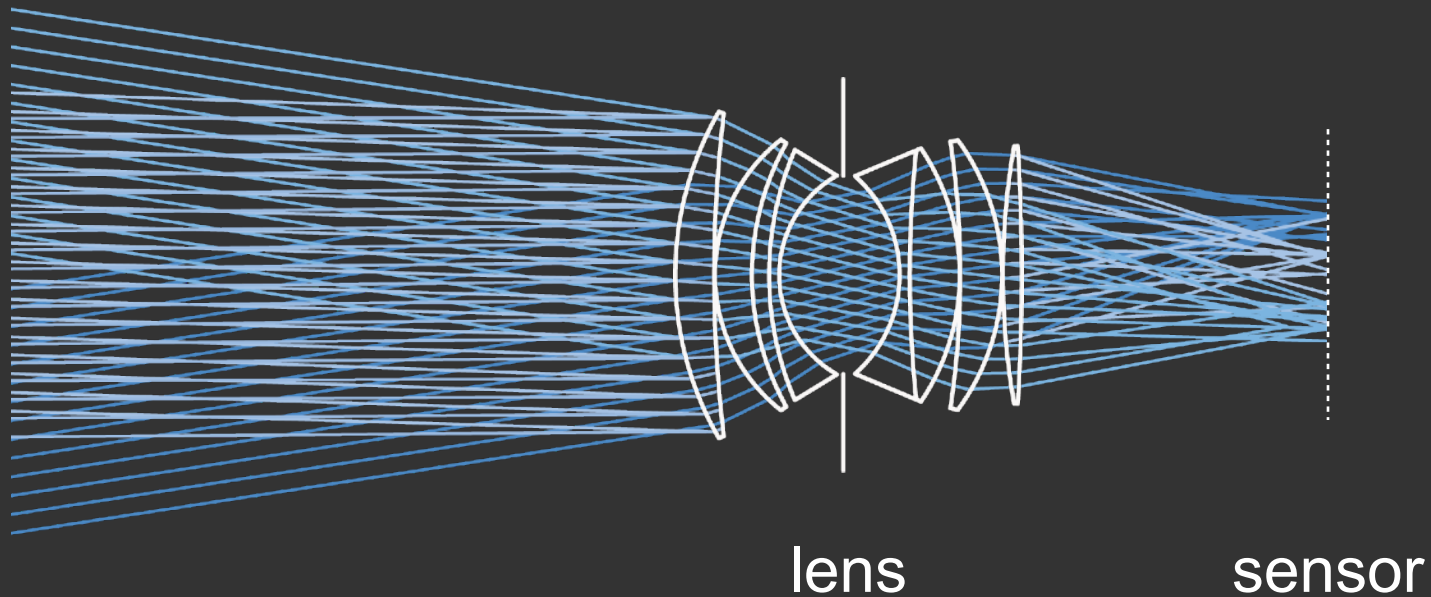


Image Focus Varies with Projection Distance

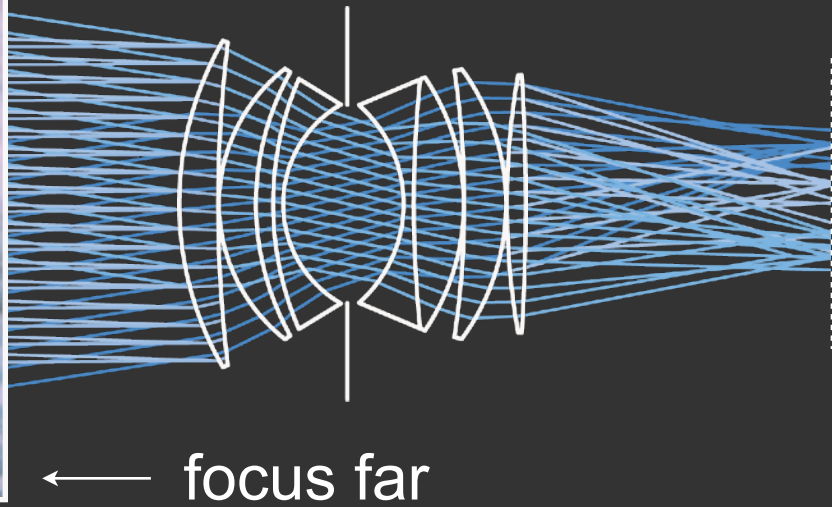


Image Focus Varies with Projection Distance

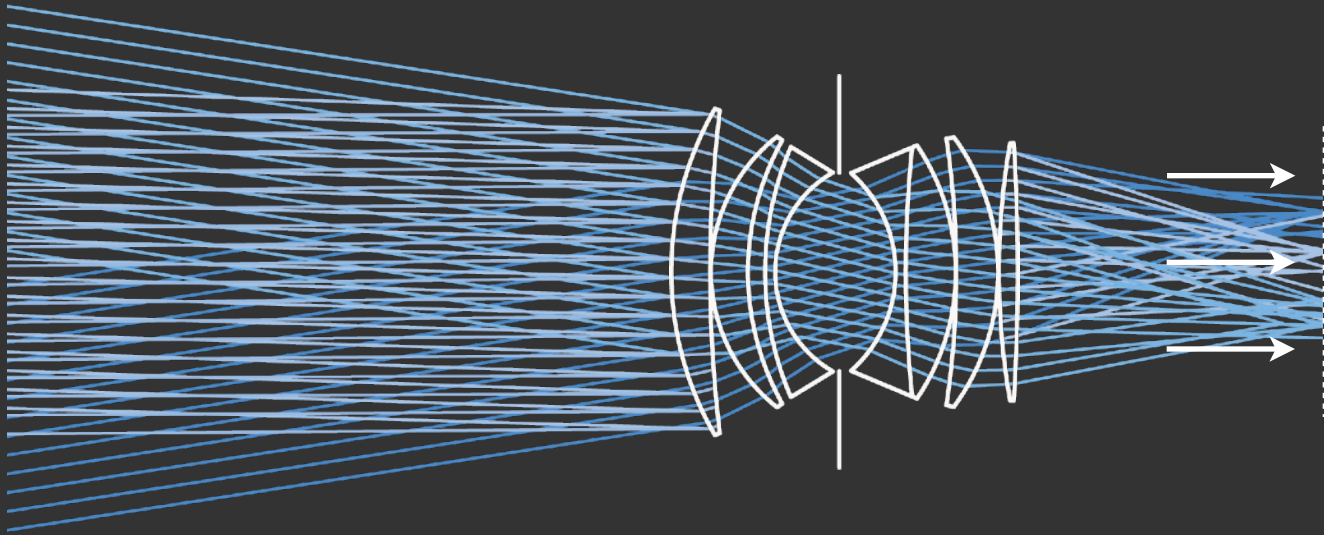


Image Focus Varies with Projection Distance

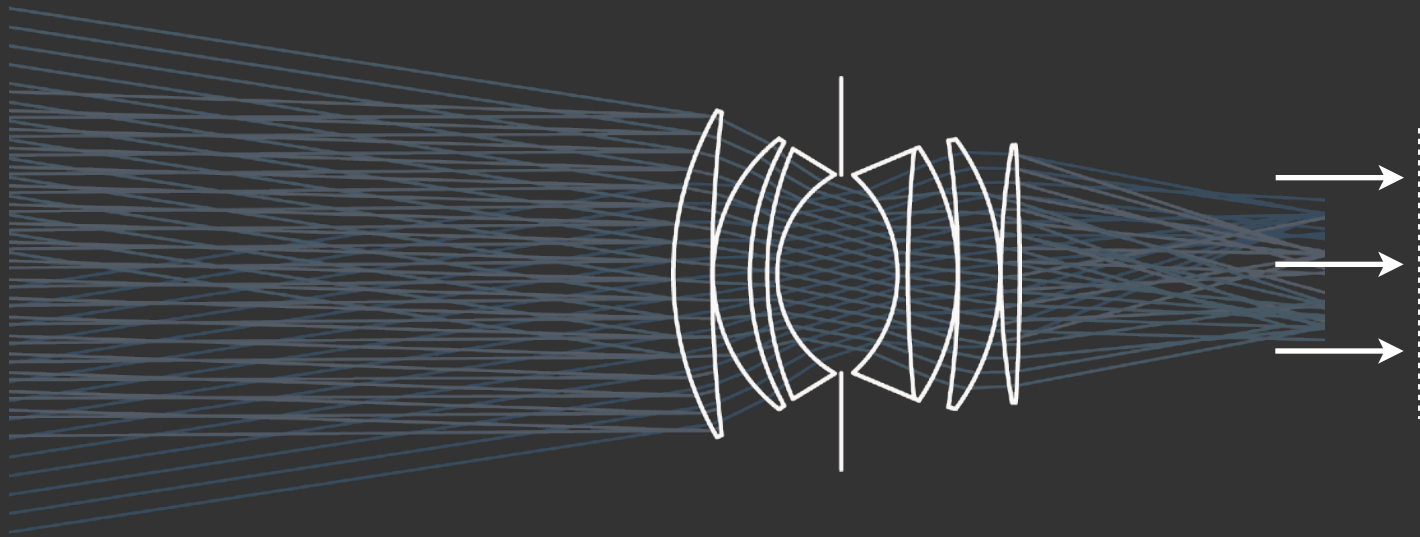


Image Focus Varies with Projection Distance

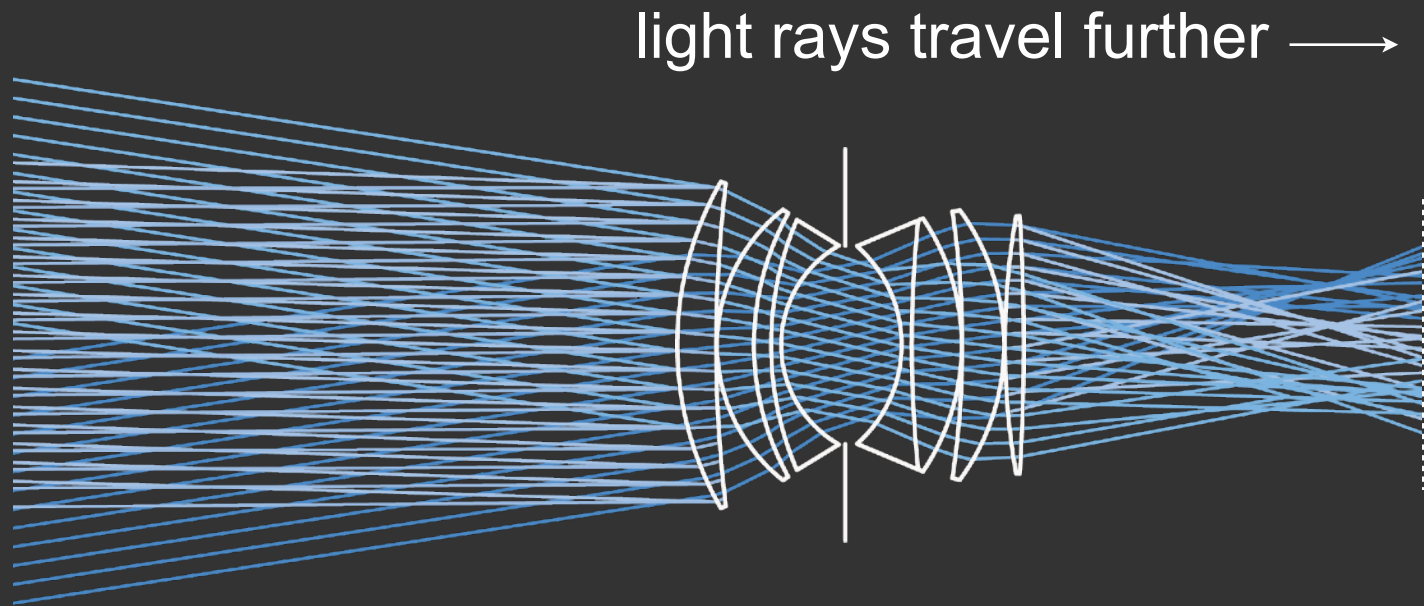
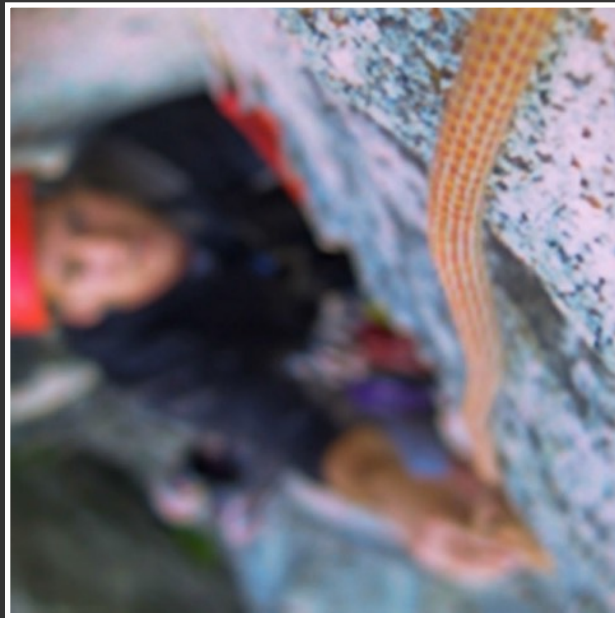


Image Focus Varies with Projection Distance



← focus close

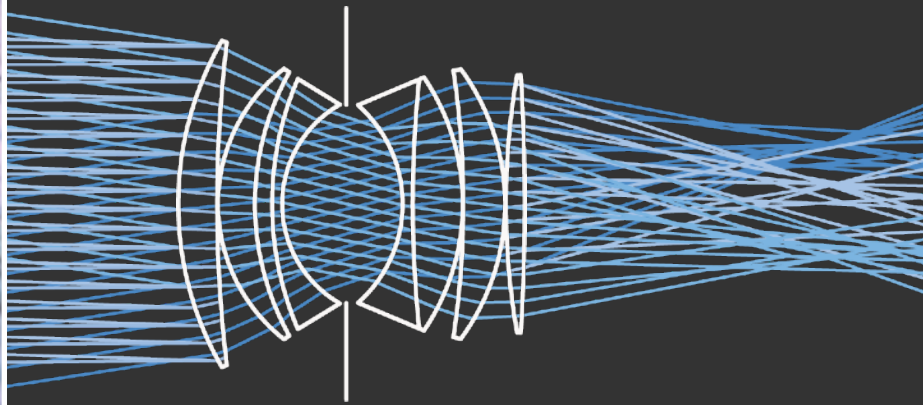
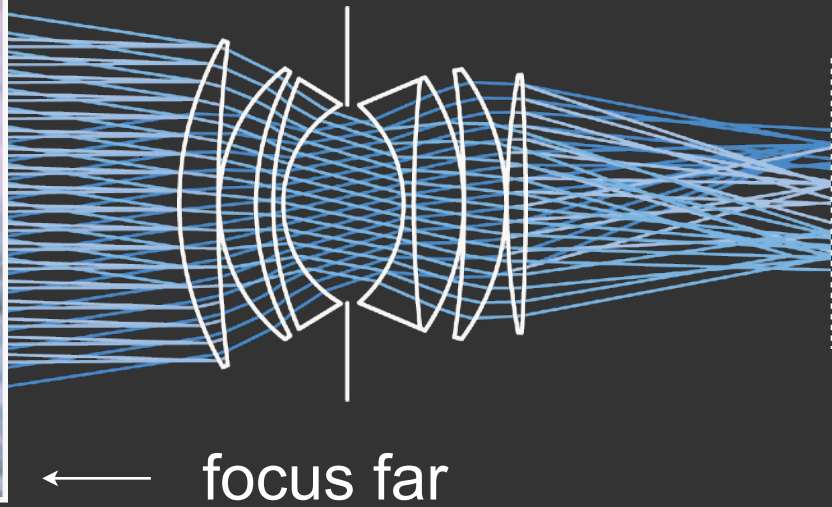
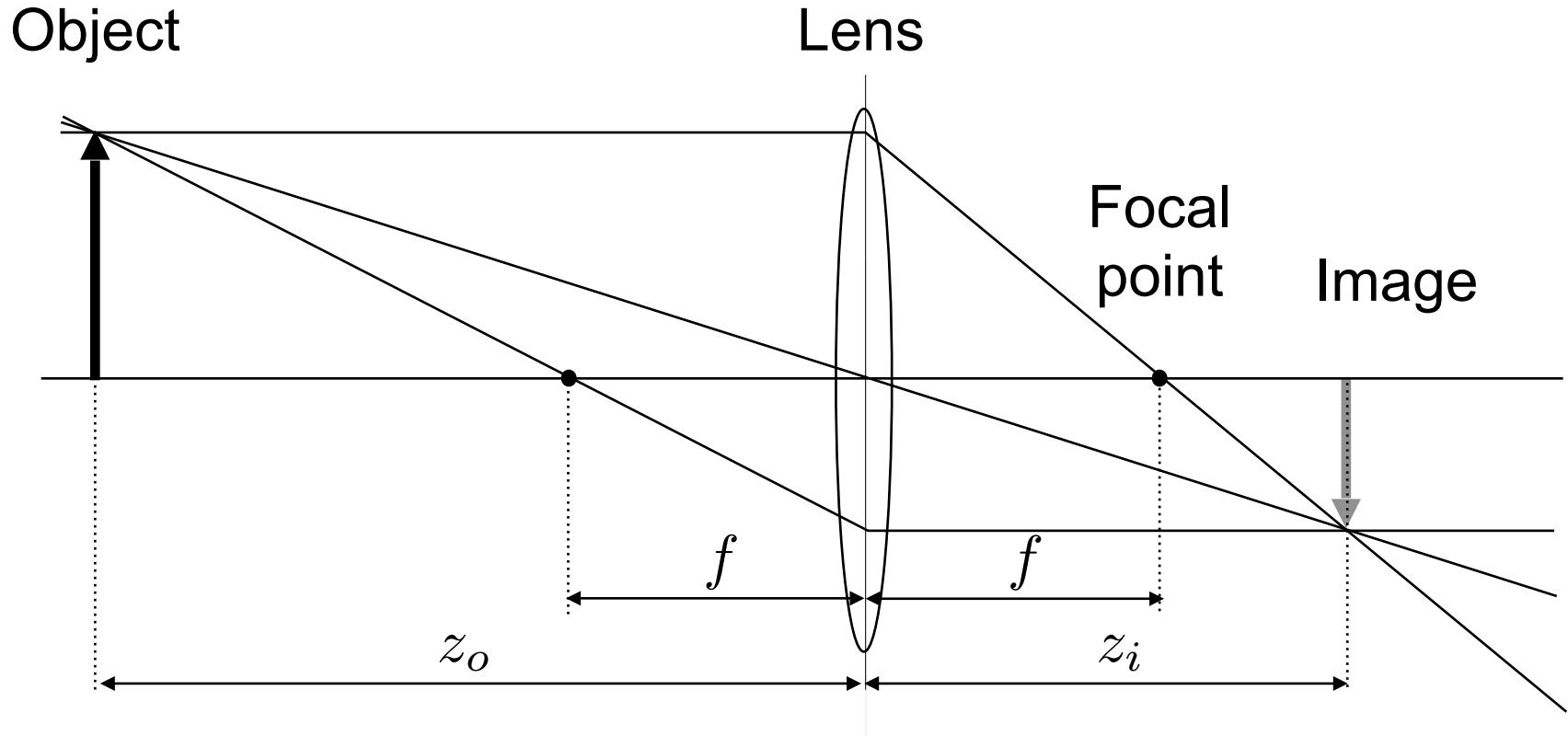


Image Focus Varies with Projection Distance



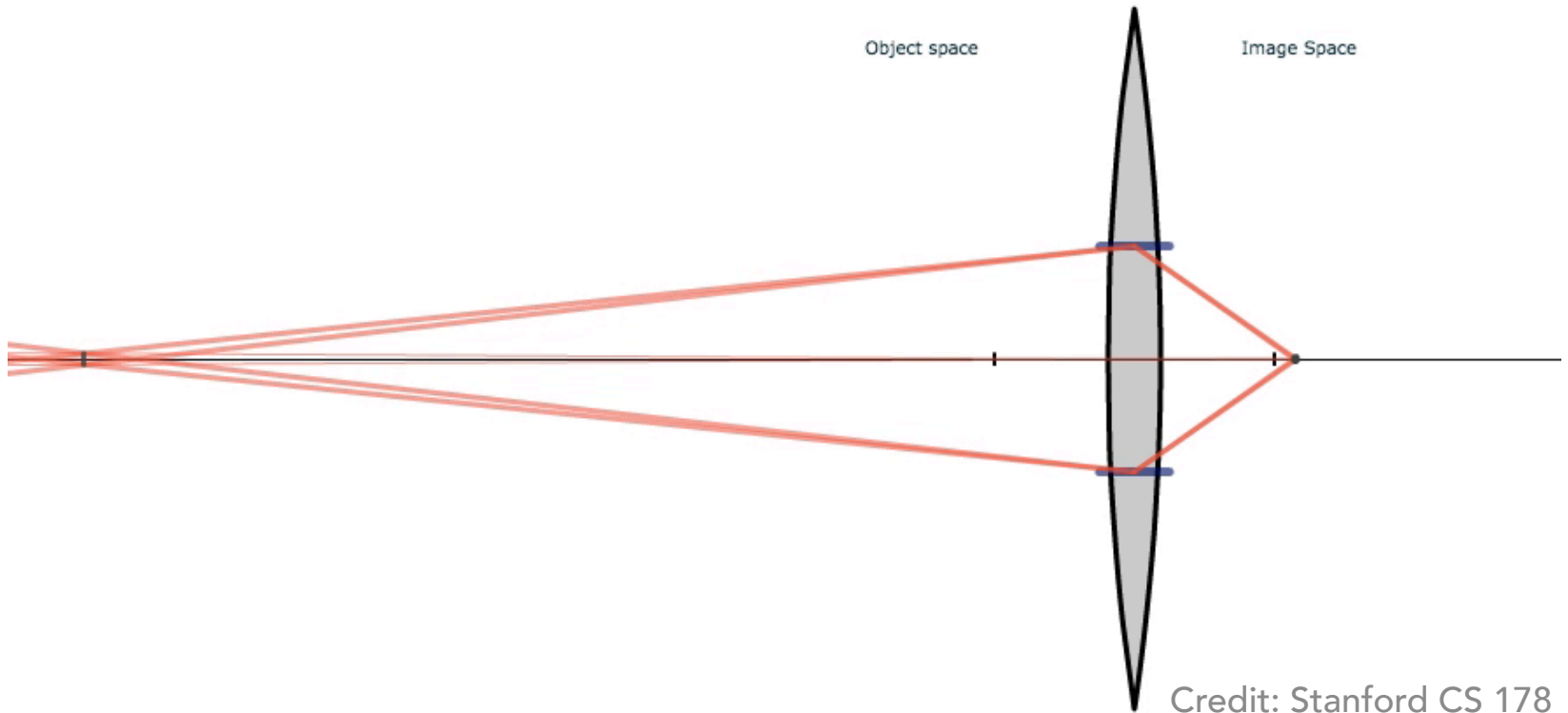
← focus far

The Ideal Thin Lens Equation



$$\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}$$

Lens Focusing – Conjugate Points



Sensor / lens gap determines plane of physical focus.

Varying Focus



Depth of Field

Depth of Field (DOF)

Large aperture opening



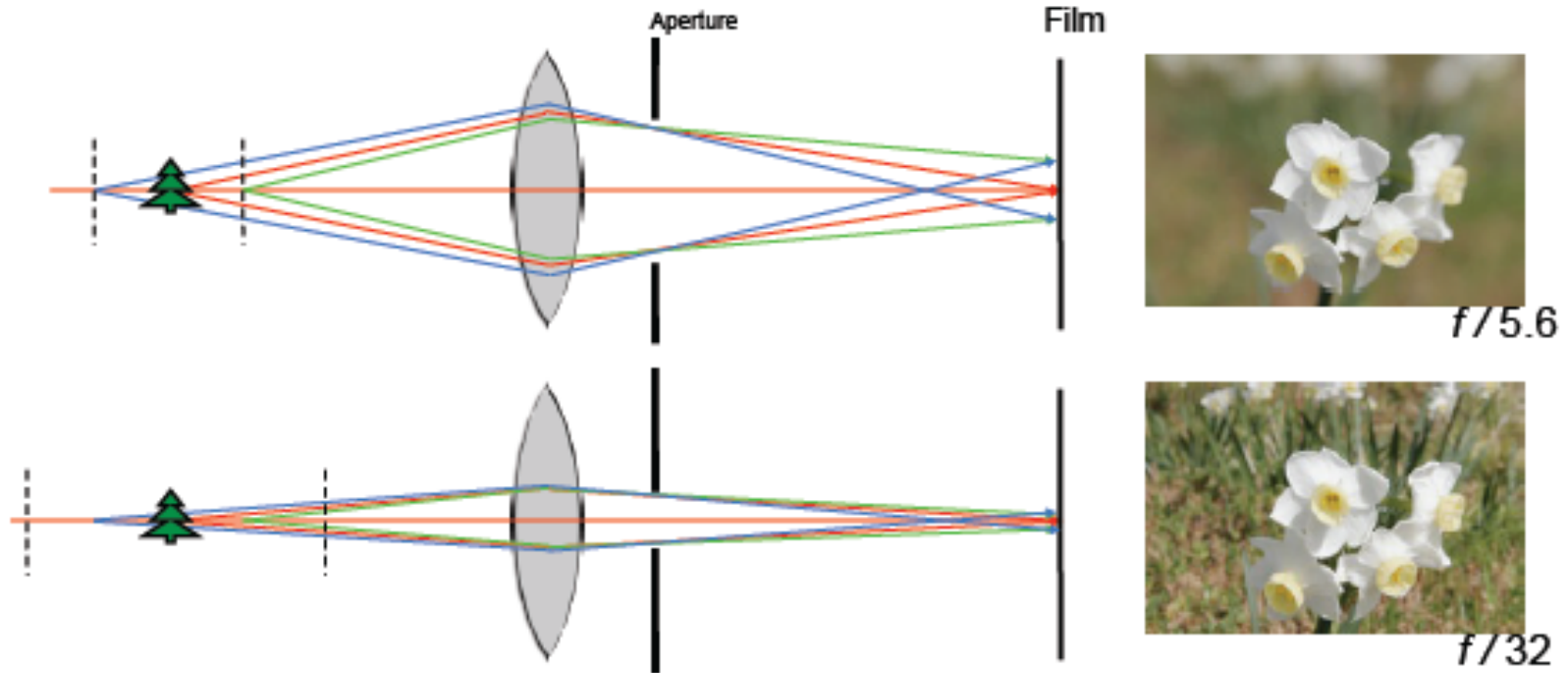
Small aperture opening



From London and Upton

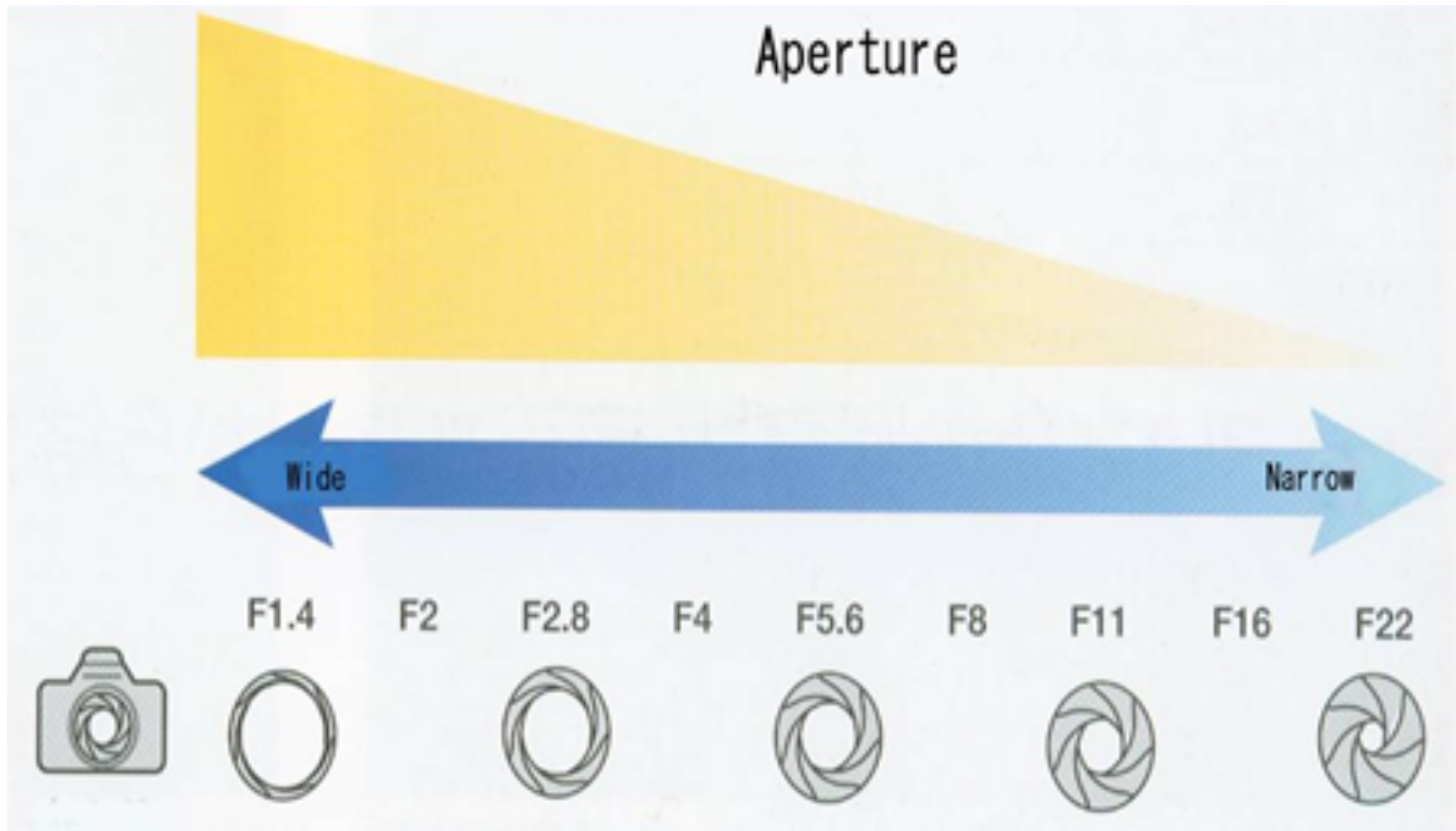
- Depth of field is the range of object depths that are rendered with acceptable sharpness in an image

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

F-number: Focal Length / Aperture Diameter



Constant Exposure: Depth of Field vs Shutter Speed



f / 4
0.01 sec



f / 11
0.1 sec



f / 32
0.8 sec

- Photographers must trade off depth of field and motion blur for moving subjects

Shallow Depth of Field Can Create a Stronger Image



From Peterson, Understanding Exposure
200mm, f/4, 1/1000 (left) and f/11, 1/125 (right)

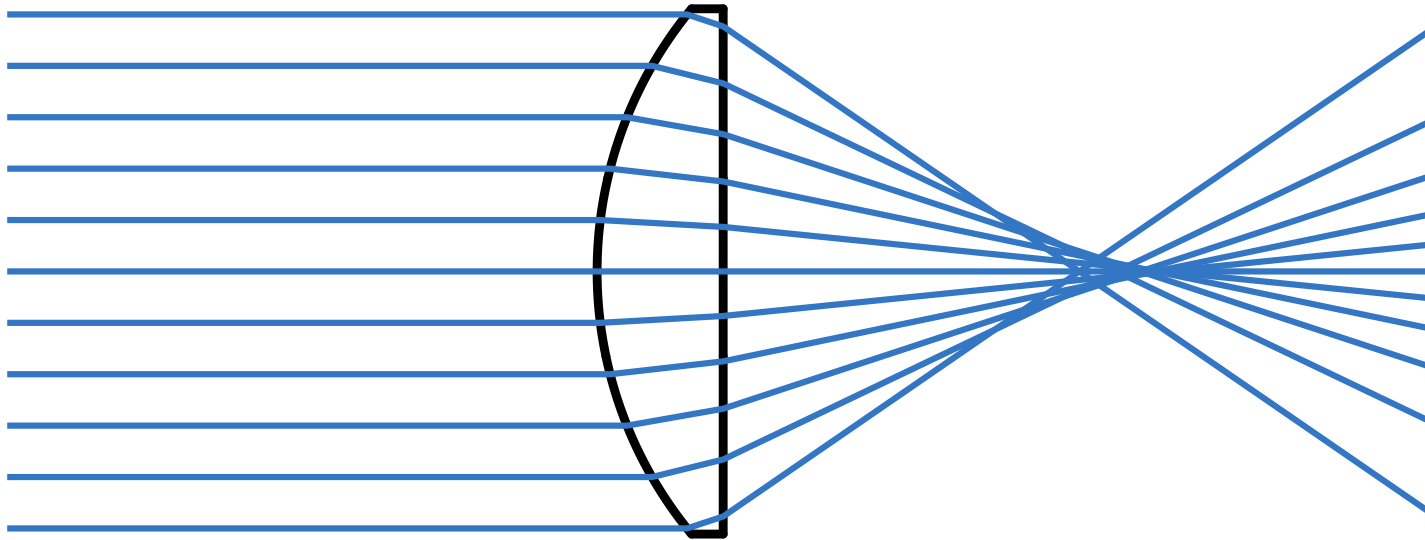
Motion Blur Can Help Tell The Story



From Peterson, Understanding Exposure
1/60, f/5.6, 180mm

Lens Flaws

Real Lens Focus Is Not Ideal – Aberrations



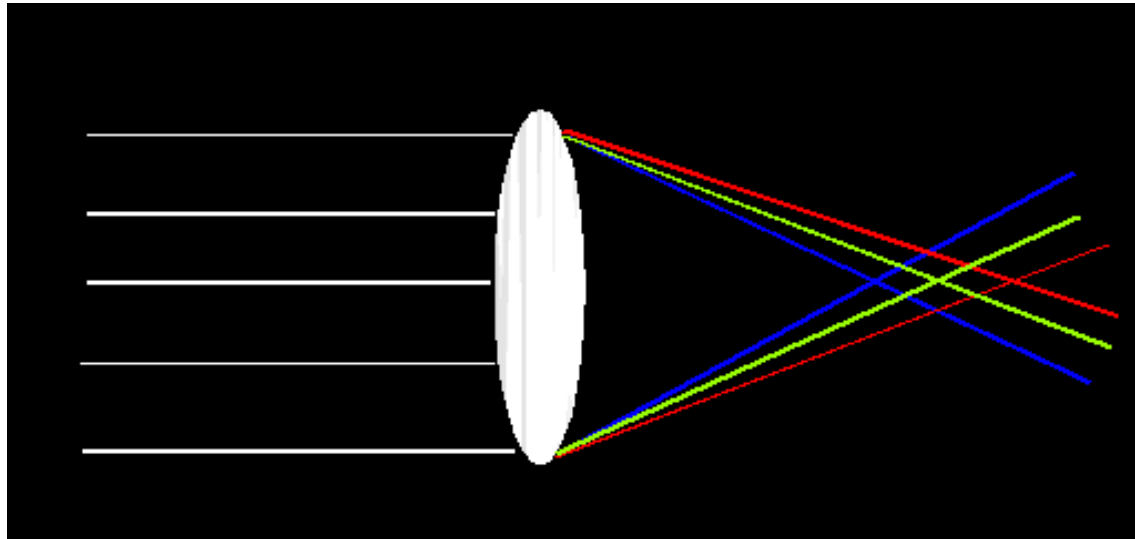
Real plano-convex lens (spherical surface shape).
Lens does not converge rays to a point anywhere.

Lens Flaws: Chromatic Aberration

Dispersion: wavelength-dependent refractive index

- (enables prism to spread white light beam into rainbow)

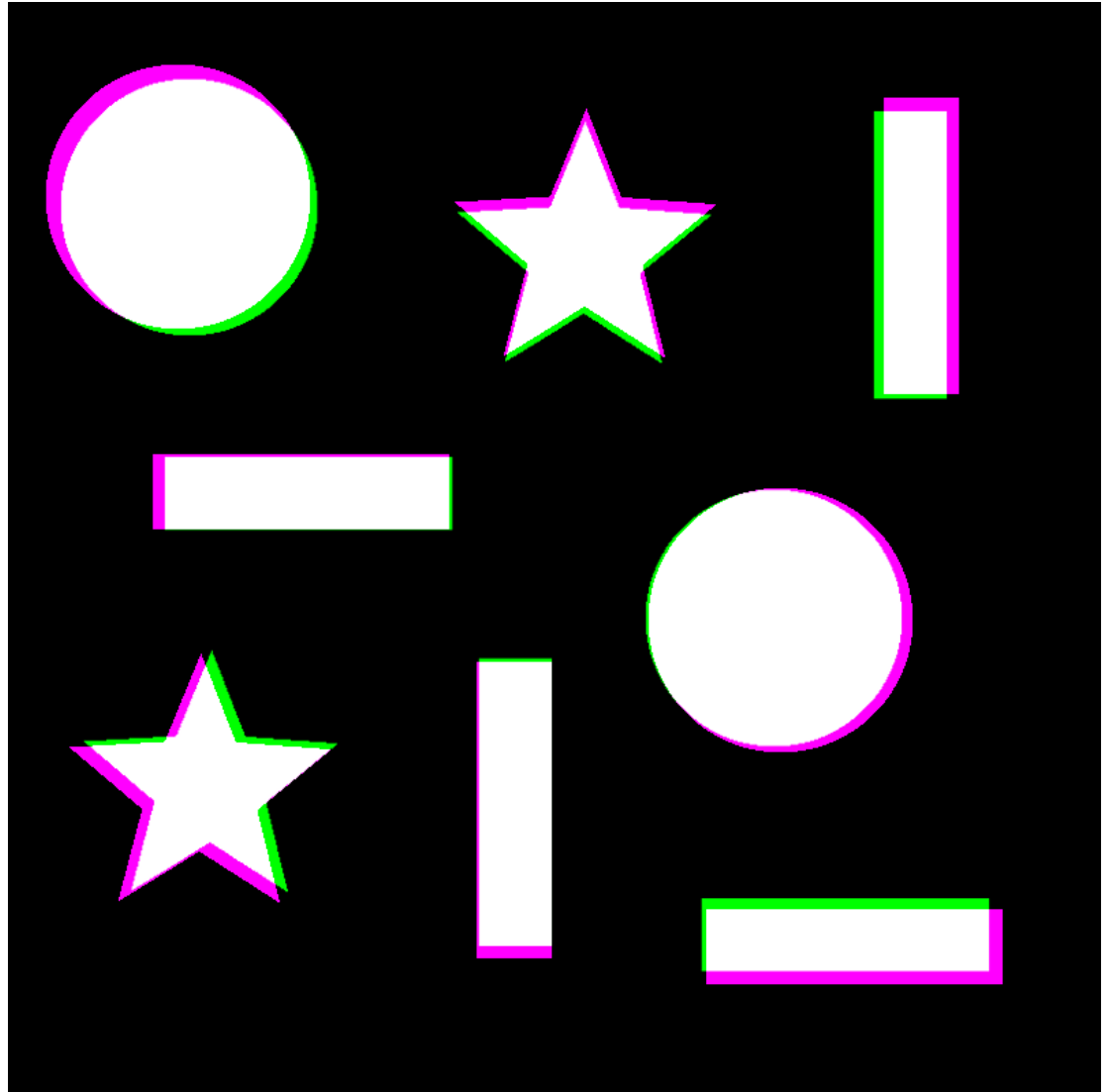
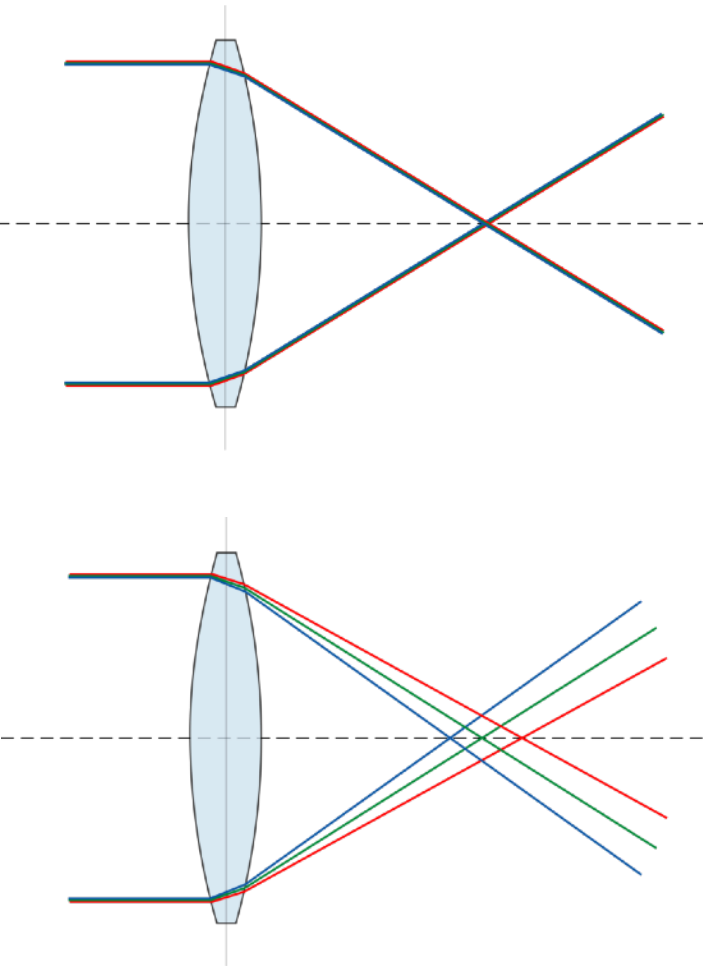
Modifies ray-bending and lens focal length: $f(\lambda)$



color fringes near edges of image

Corrections: add 'doublet' lens of flint glass, etc.

Chromatic Aberration



Chromatic Aberration

Near Lens Center



Near Lens Outer Edge

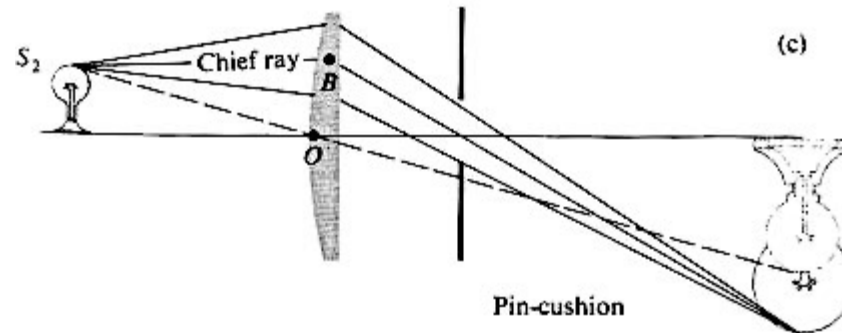
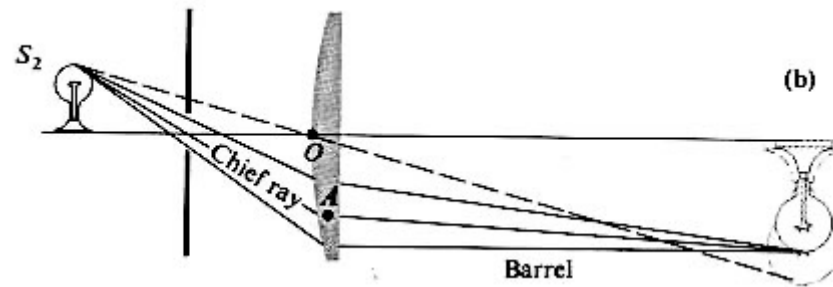
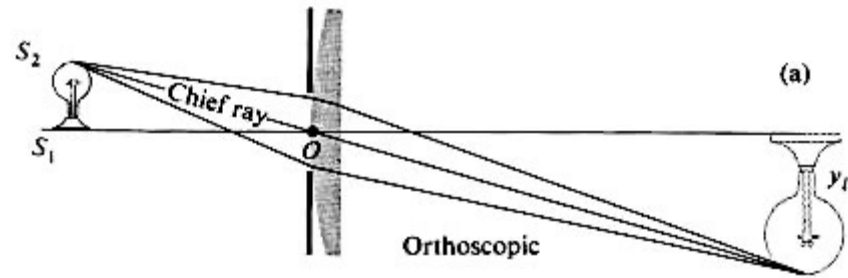


Radial Distortion (e.g. 'Barrel' and 'Pin-Cushion')

straight lines curve around the image center



Radial Distortion



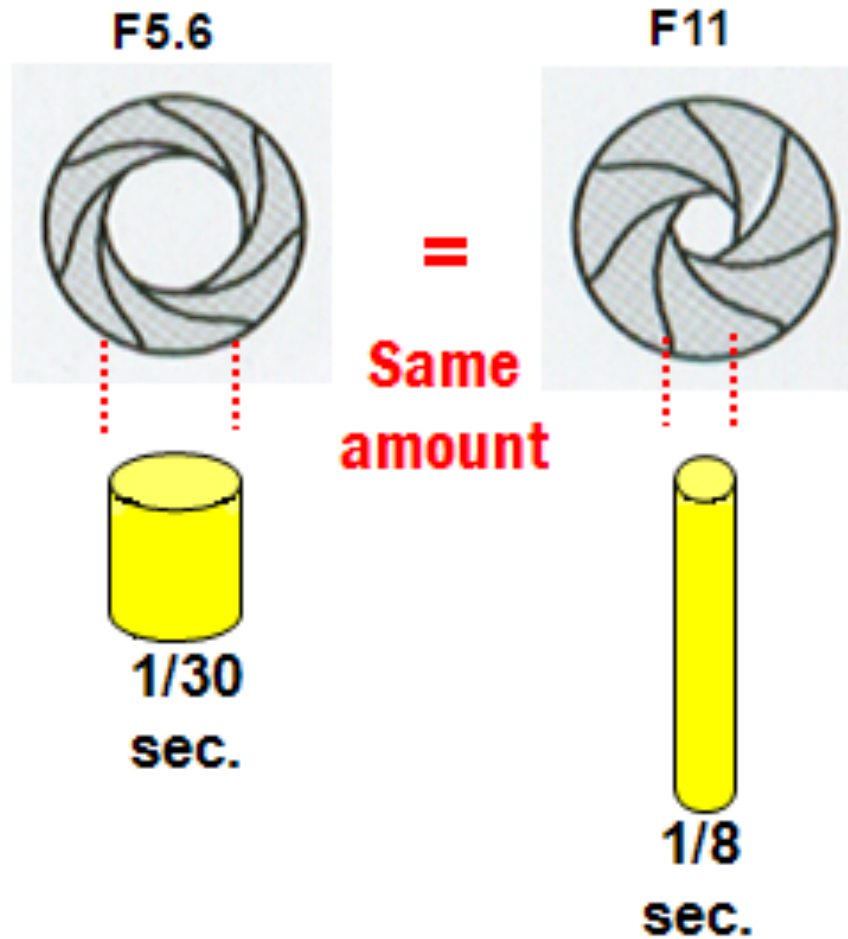
Exposure

Shutter Speed

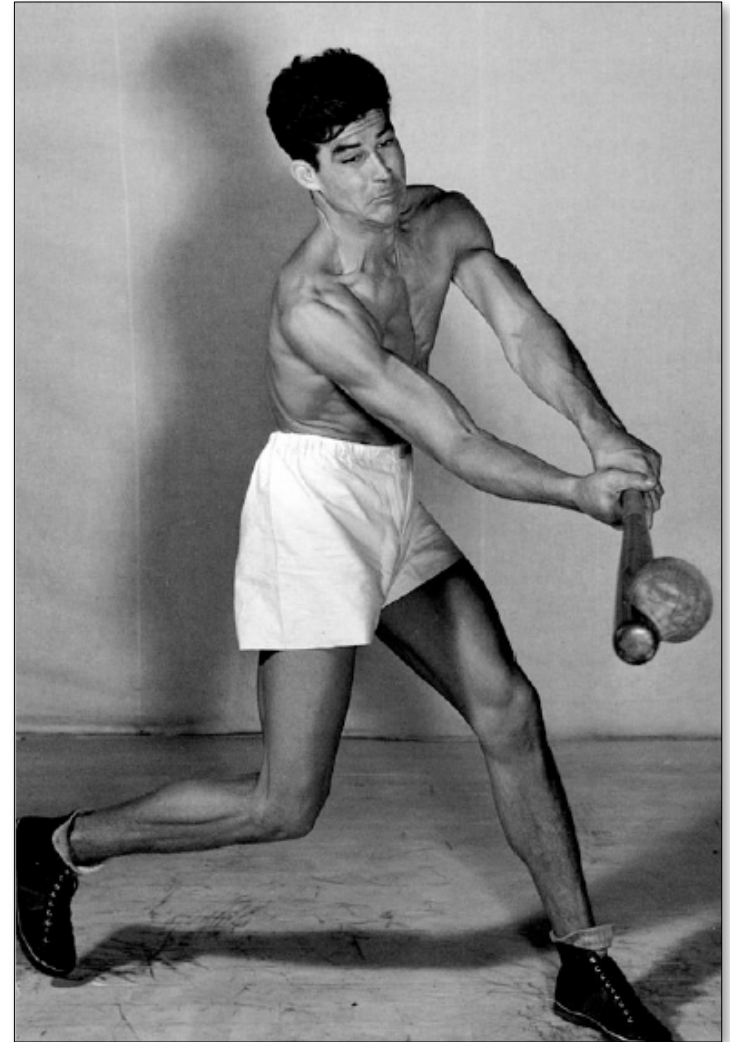
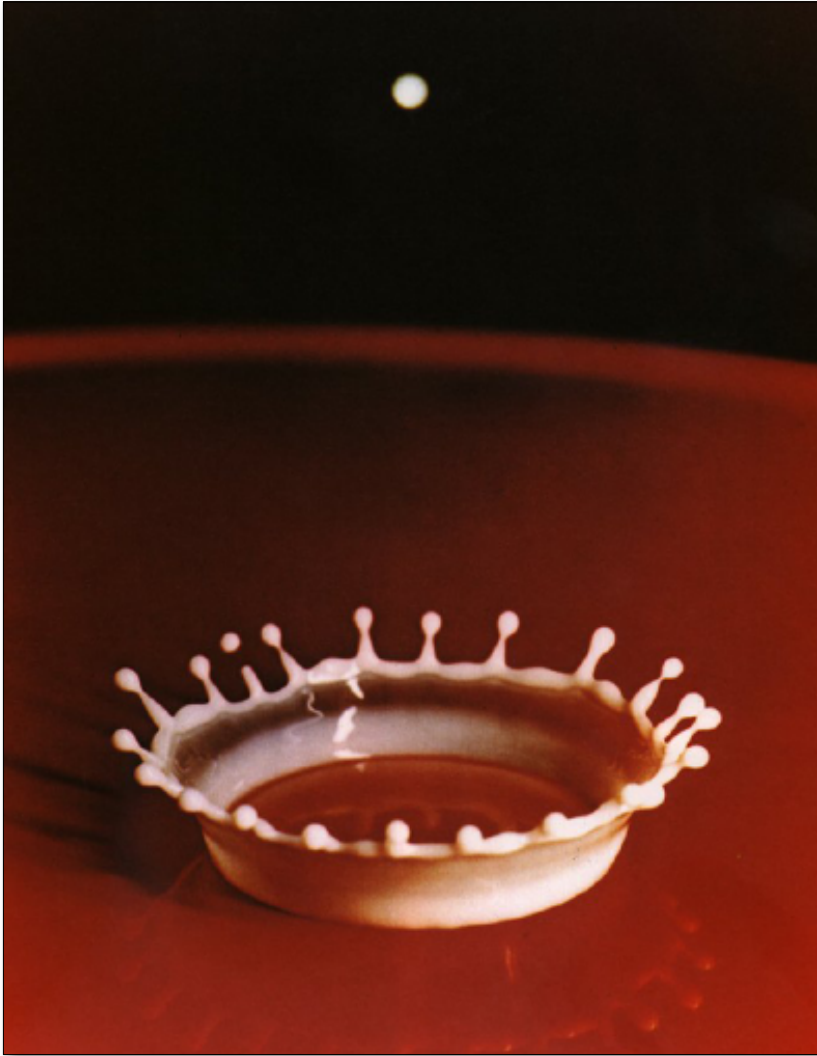


http://en.wikipedia.org/wiki/Shutter_speed

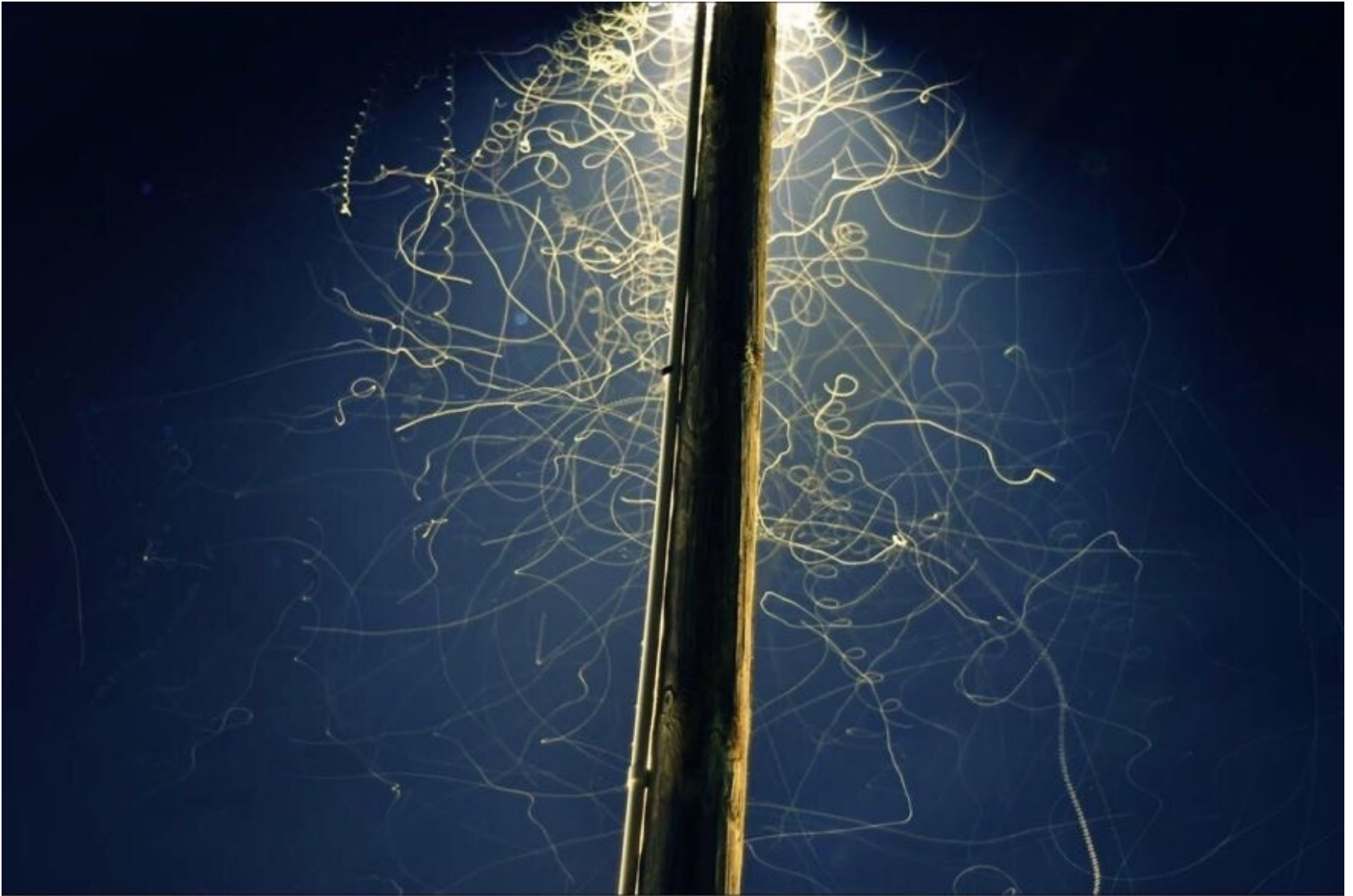
Exposure: Shutter Speed vs. Aperture



High-Speed Photography (Short Shutter)



Long-Exposure Photography



<https://www.demilked.com/best-long-exposure-photos/>

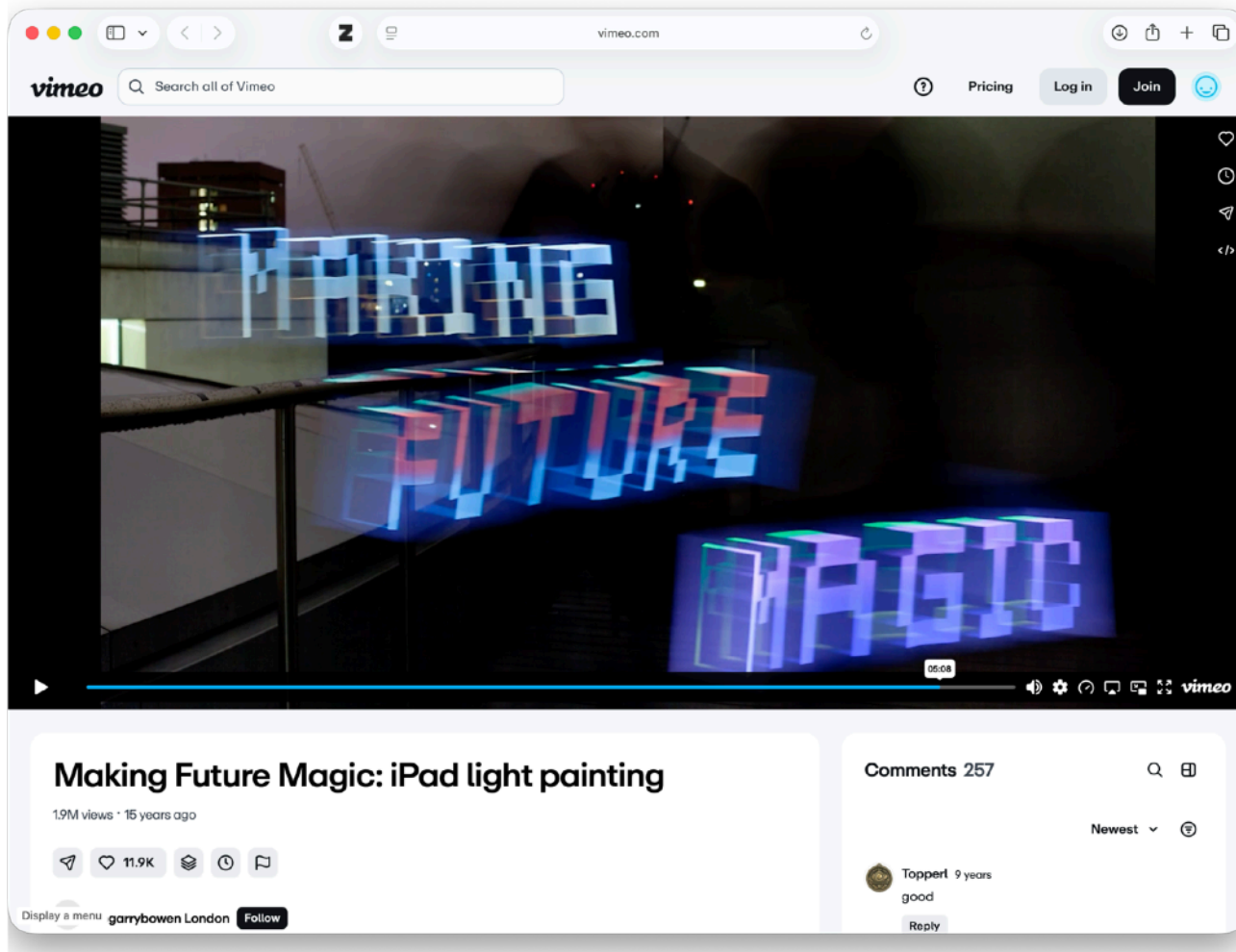


Slow Shutter Speeds - Painting with Light



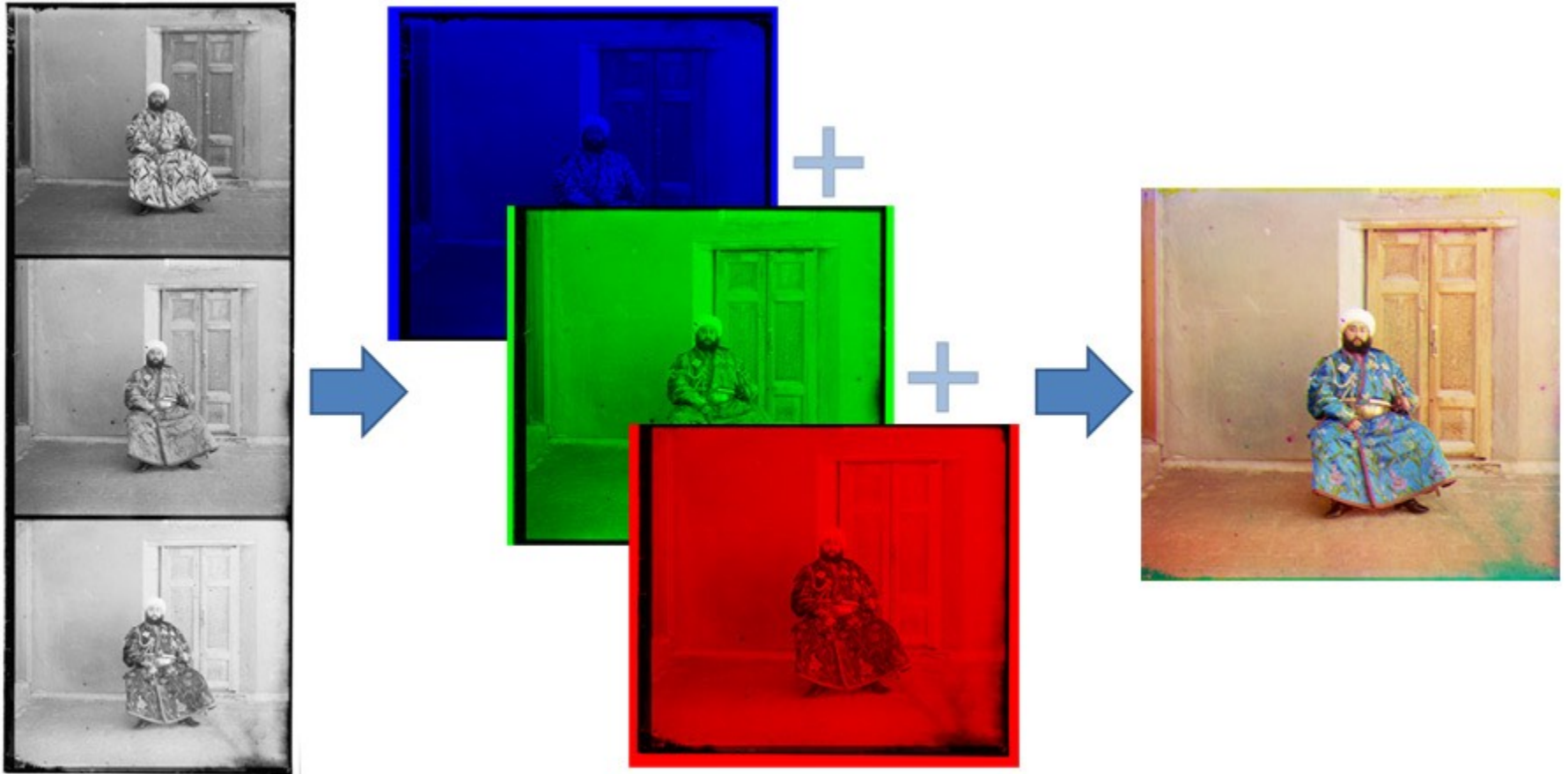
Photos by Fredo Durand

More Long-Exposure Fun



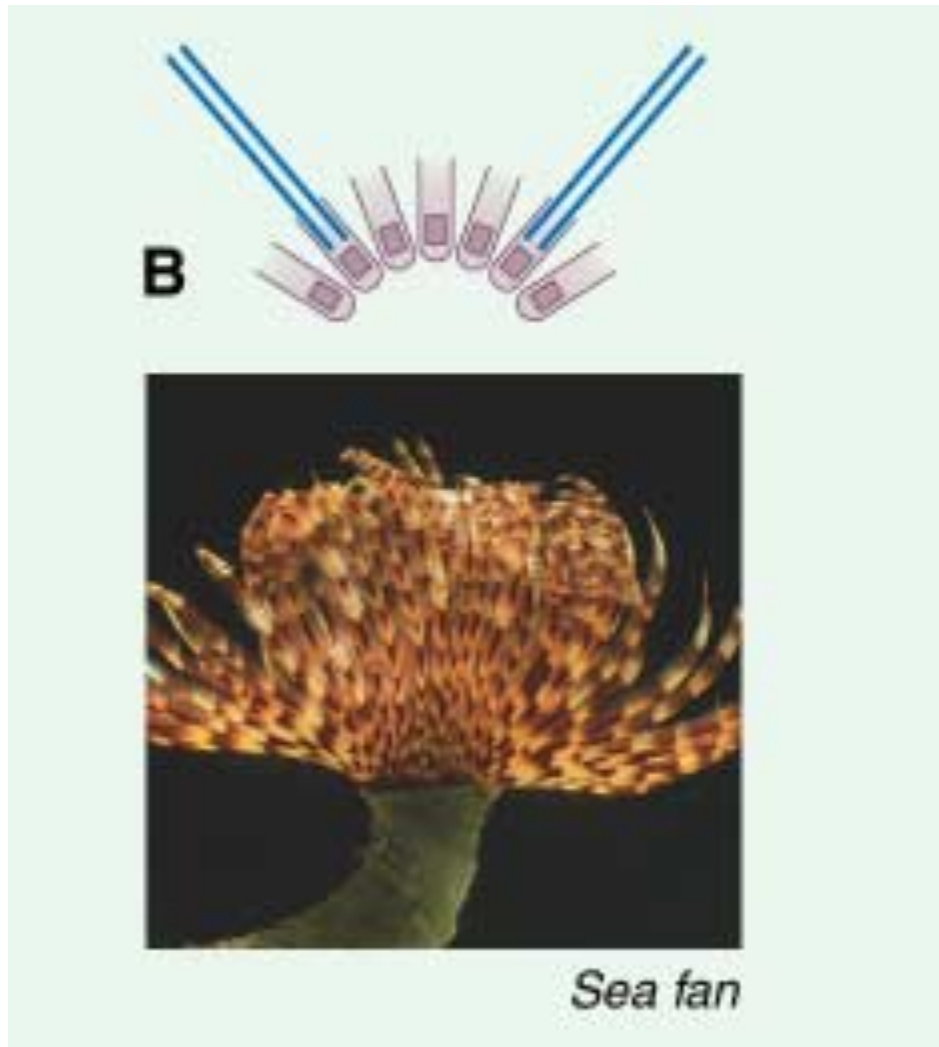
<http://vimeo.com/14958082>

Programming Project #1



Project out Today!

Extras



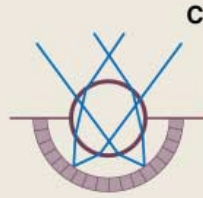
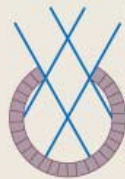
R. Fernald, Casting a Genetic Light on the Evolution of Eyes

Chambered eyes



Nautilus

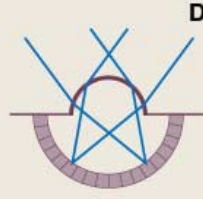
A



C



Octopus



D

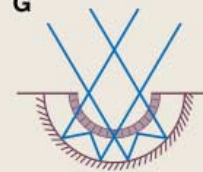


Red-tailed hawk



Scallop

G



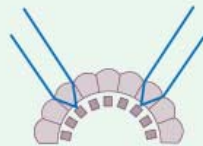
Compound eyes



B



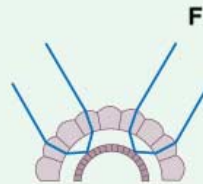
Sea fan



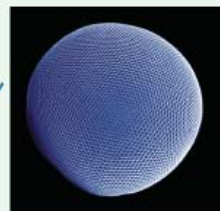
E



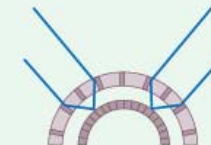
Dragonfly



F



Krill eye



H



Lobster

R. Fernald, Casting a Genetic Light on the Evolution of Eyes

Plasmonic ommatidia for lensless compound-eye vision

Leonard C. Kogos¹, Yunzhe Li¹, Jianing Liu¹, Yuyu Li¹, Lei Tian¹ & Roberto Paiella¹✉

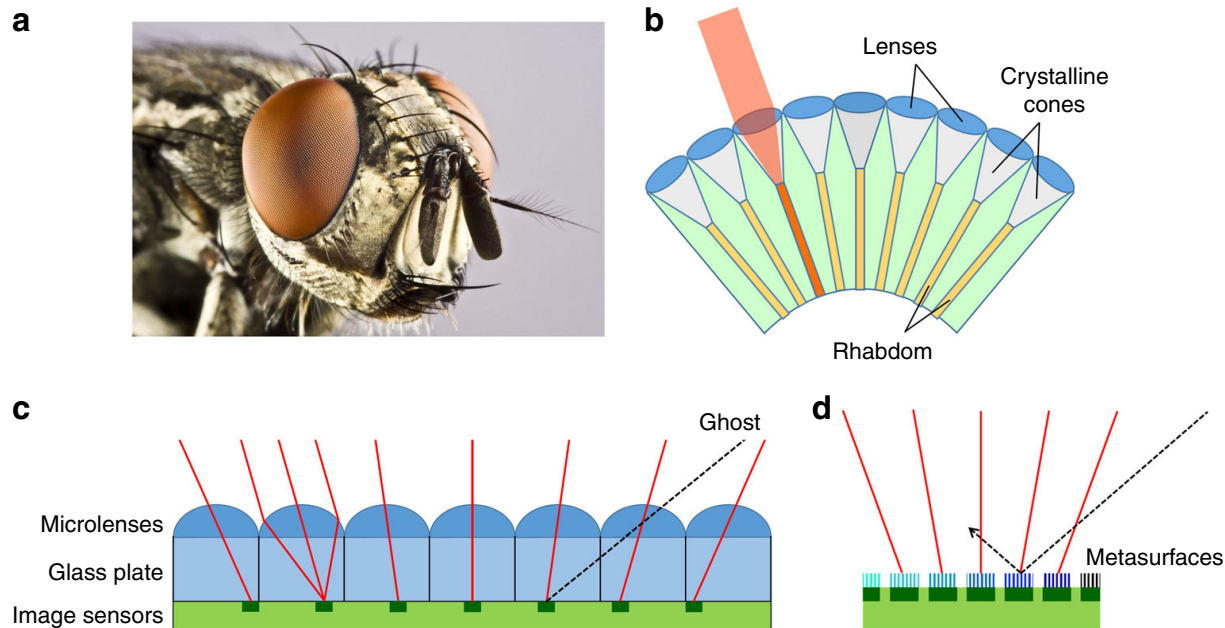


Fig. 1 Compound eyes. **a** Micrograph of the compound eyes of a horse fly. Used with permission (copyright: Michael Biehler/123RF.COM). **b** Schematic illustration of the apposition compound-eye architecture. **c** Artificial compound-eye camera based on a planar microlens array and a photodetector array separated by a glass plate. By design the two arrays have different periodicities, so that each sensor detects light incident along a different direction. **d** Compound-eye camera based on the angle-sensitive metasurfaces developed in the present work, where only light incident along a different direction is transmitted into each image sensor.



MICHAEL F. LAND & DAN-ERIC NILSSON

Animal Eyes

OABS | Oxford Animal Biology Series

Second Edition

Lens Design in 1839



Louis Daguerre



Chevalier Lens (f/16)

Lens Design in 1839

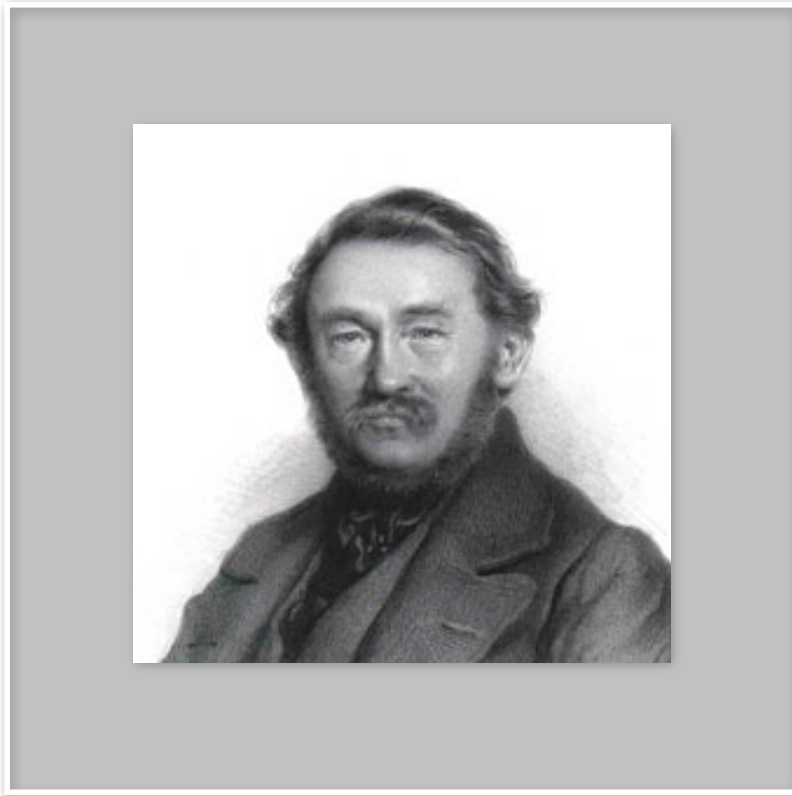


Joseph Petzval

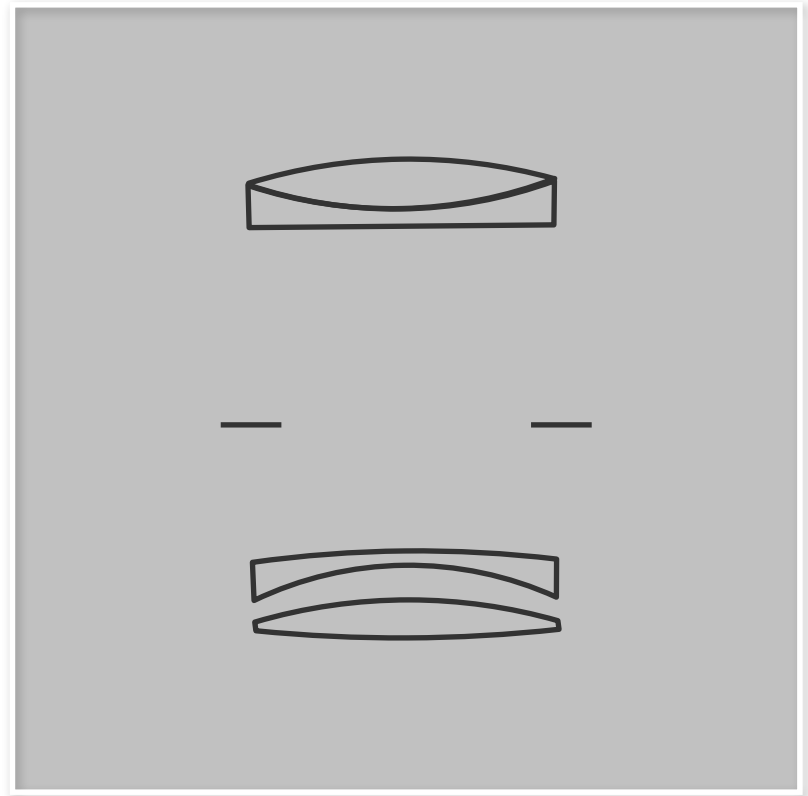


Petzval Portrait Lens (f/3.6)

Lens Design in 1839



Joseph Petzval



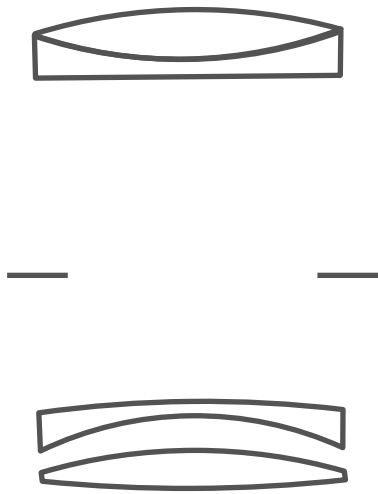
Petzval Portrait Lens (f/3.6)

Petzval Portrait Lens



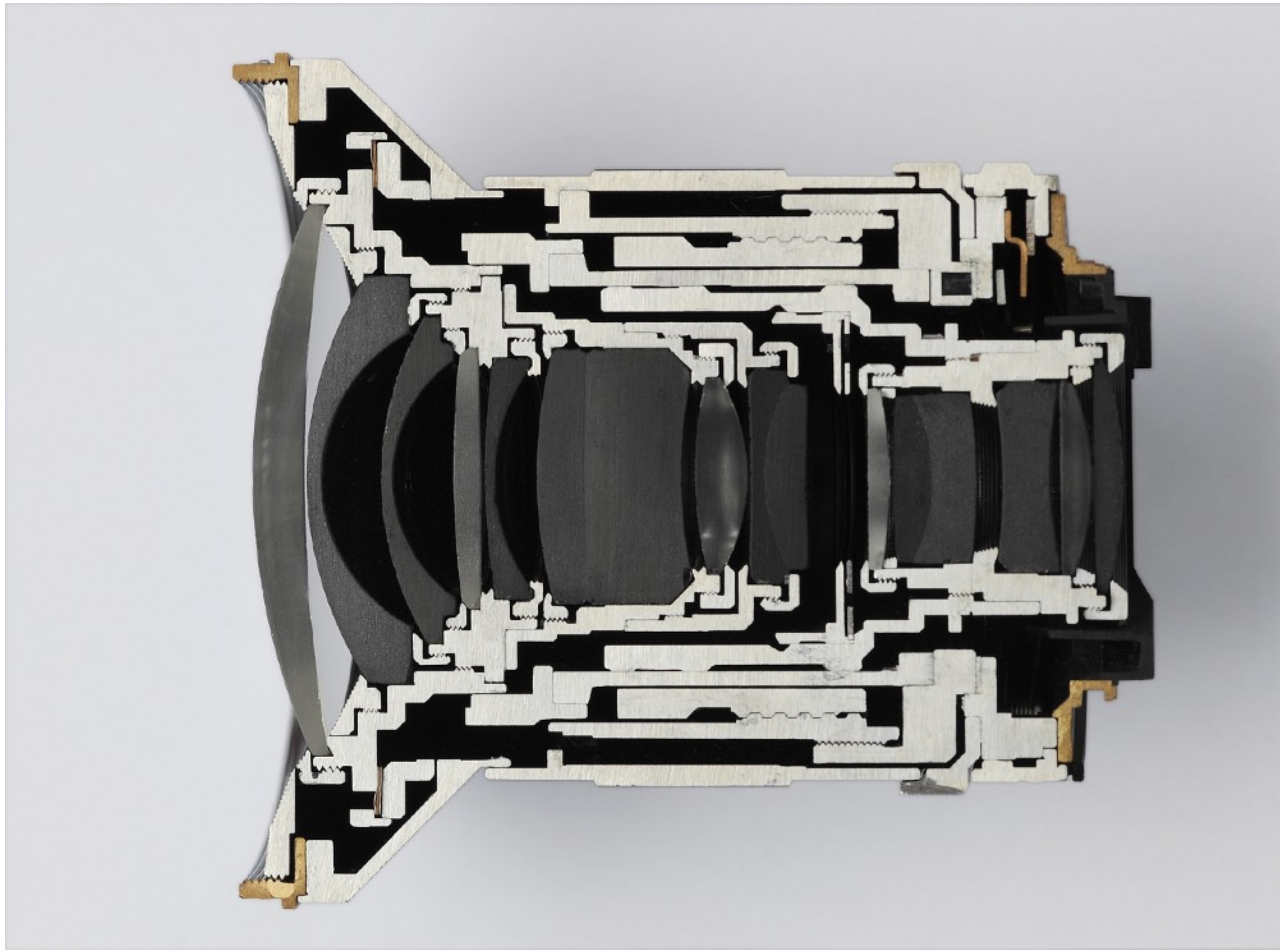
David Kashevaroff

Petzval Portrait Lens



Lomography Petzval Lens

Real Lens Designs Are Complex + Expensive



ilovephotography.com

Photographic lens cross section