

**Lecture 16:**

# **Cameras & Lenses**

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**Computer Graphics and Imaging**  
**UC Berkeley CS184/284A**

# Rendering with Realistic Camera Model



**Credit: Bertrand Benoit. "Sweet Feast," 2009. [Blender /VRay]**



# Rendering with Realistic Camera Model

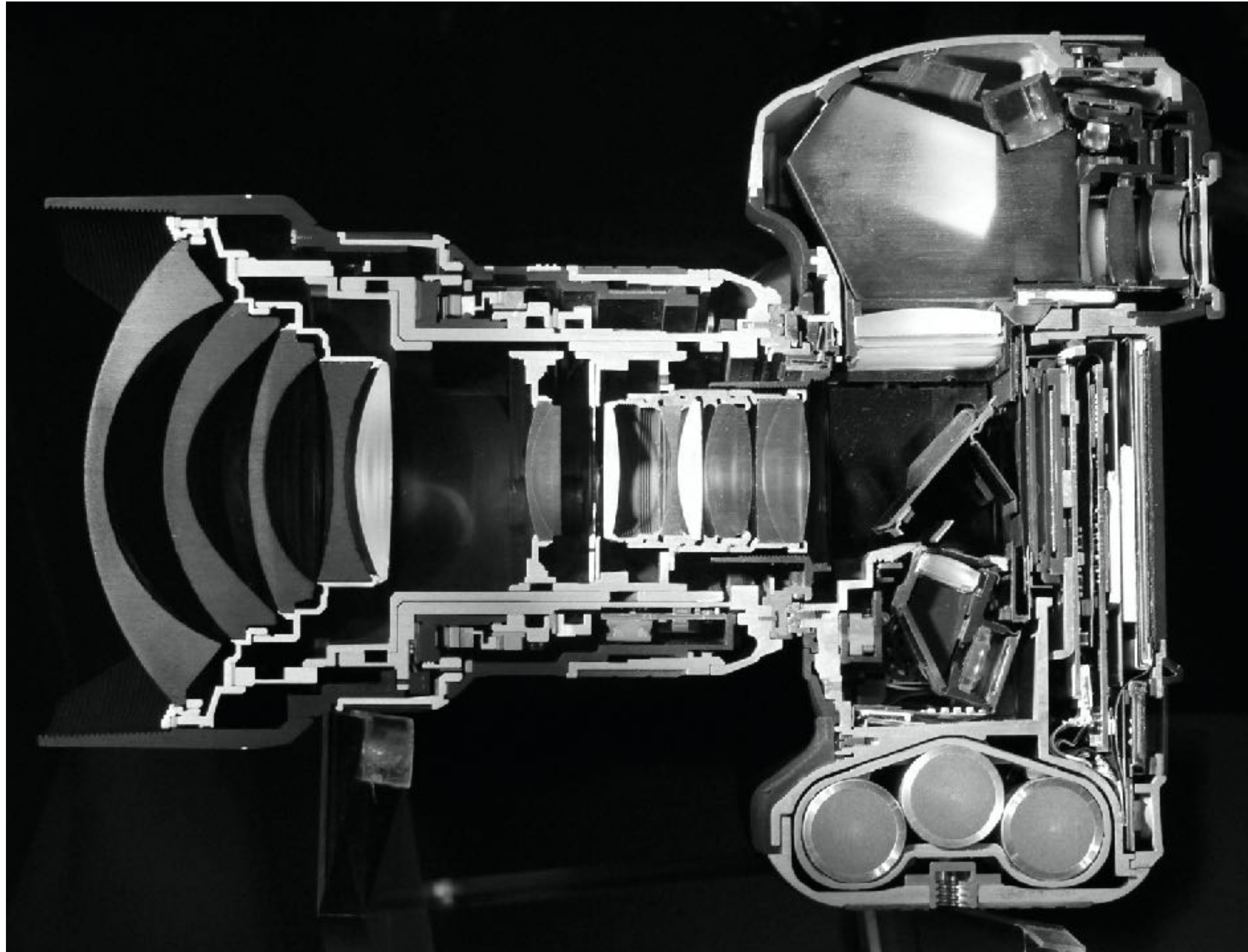


**Credit: Giuseppe Albergo. "Colibri" [Blender]**

# **Image Capture Overview**



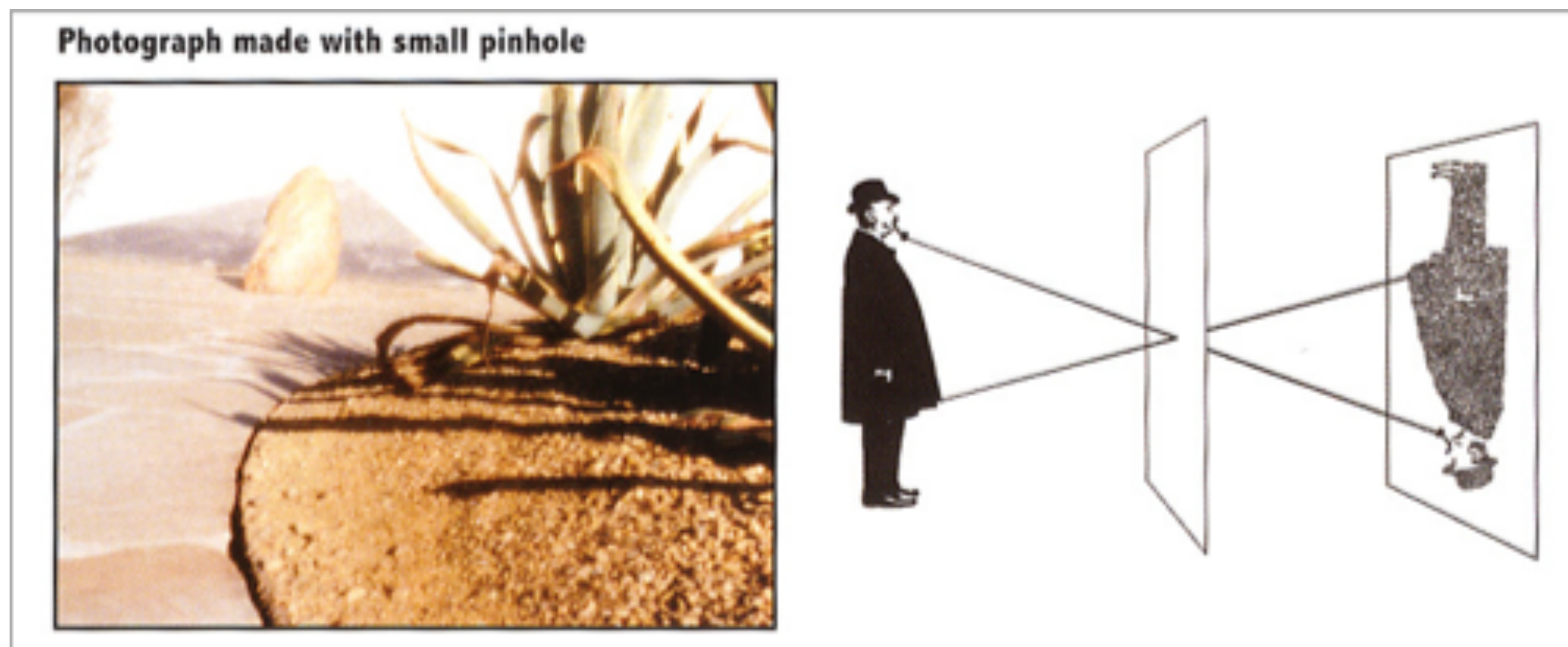
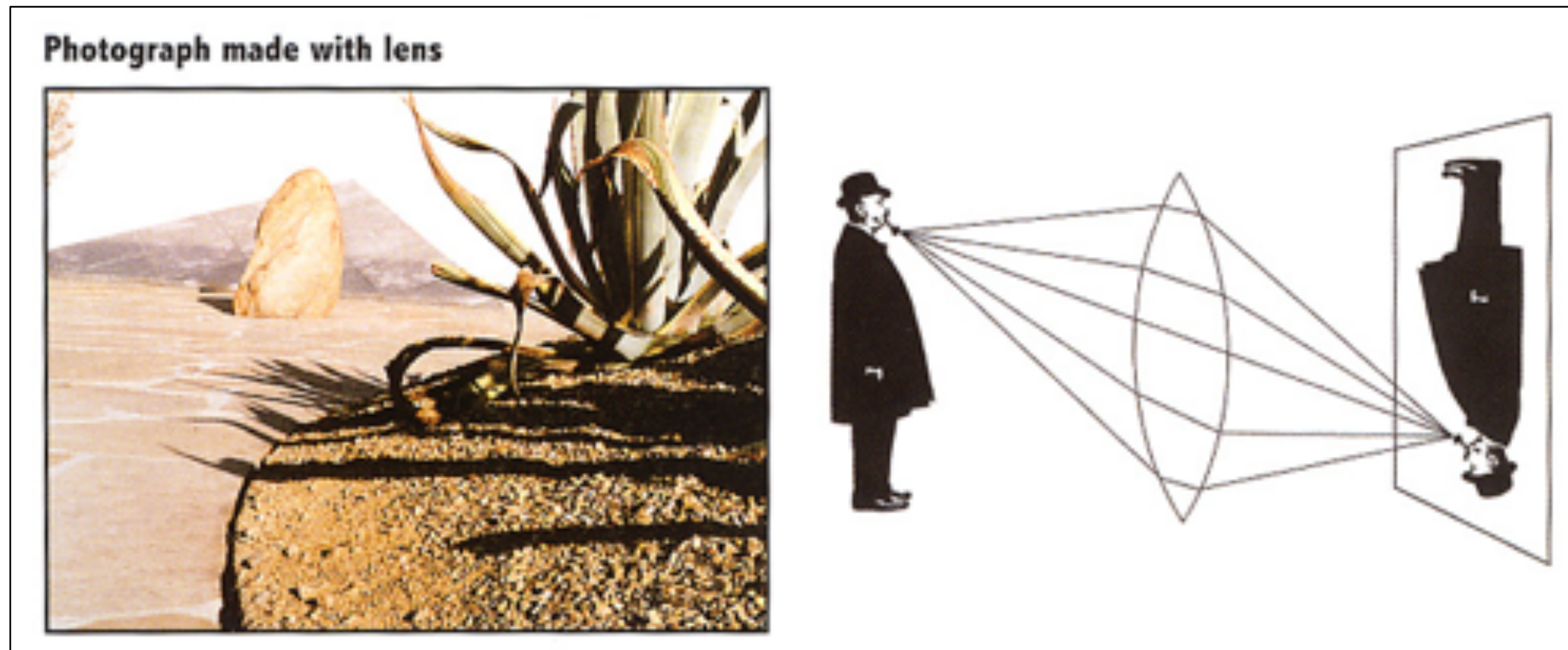
# What's Happening Inside the Camera?



Cross-section of Nikon D3, 14-24mm F2.8 lens



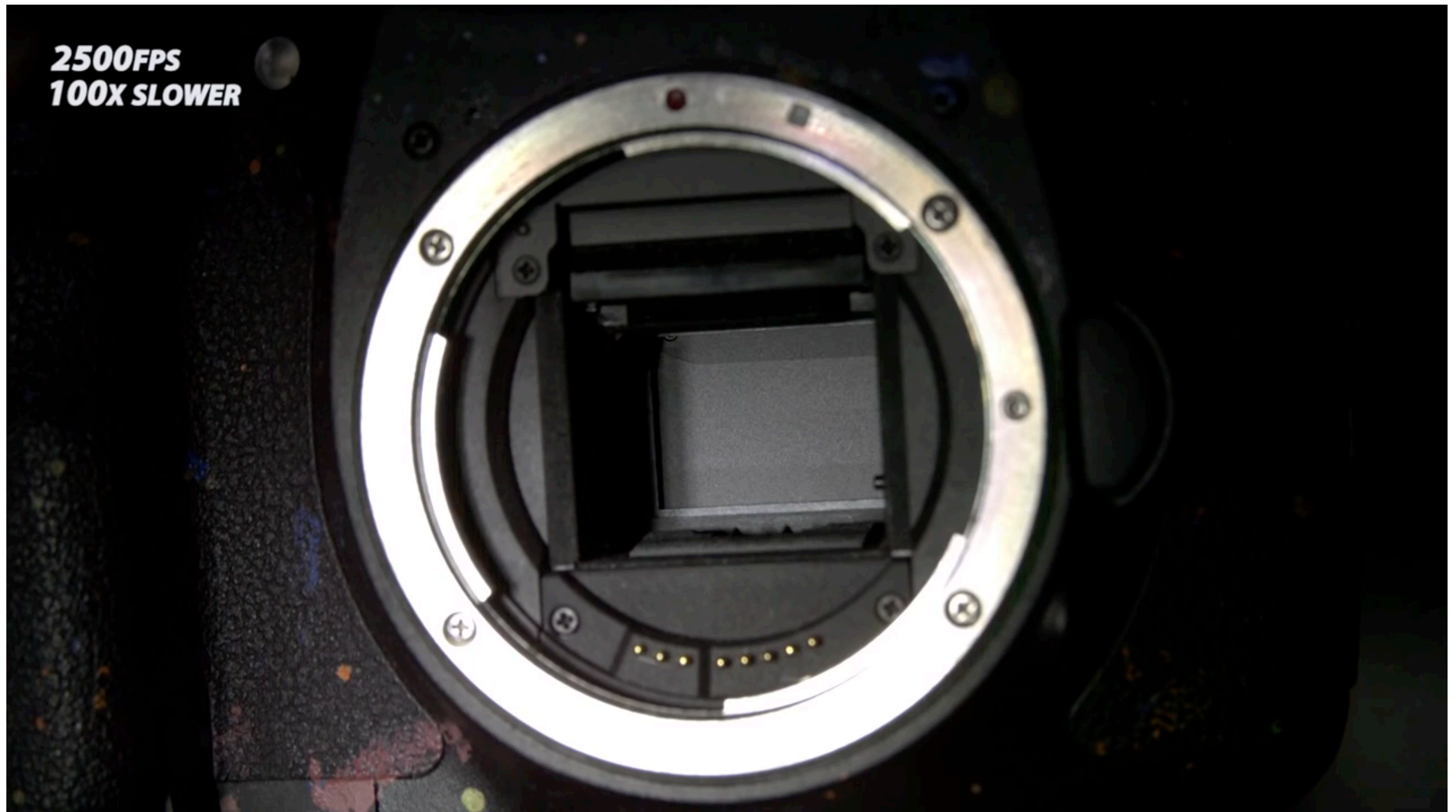
# Pinholes & Lenses Form Image on Sensor



London and Upton

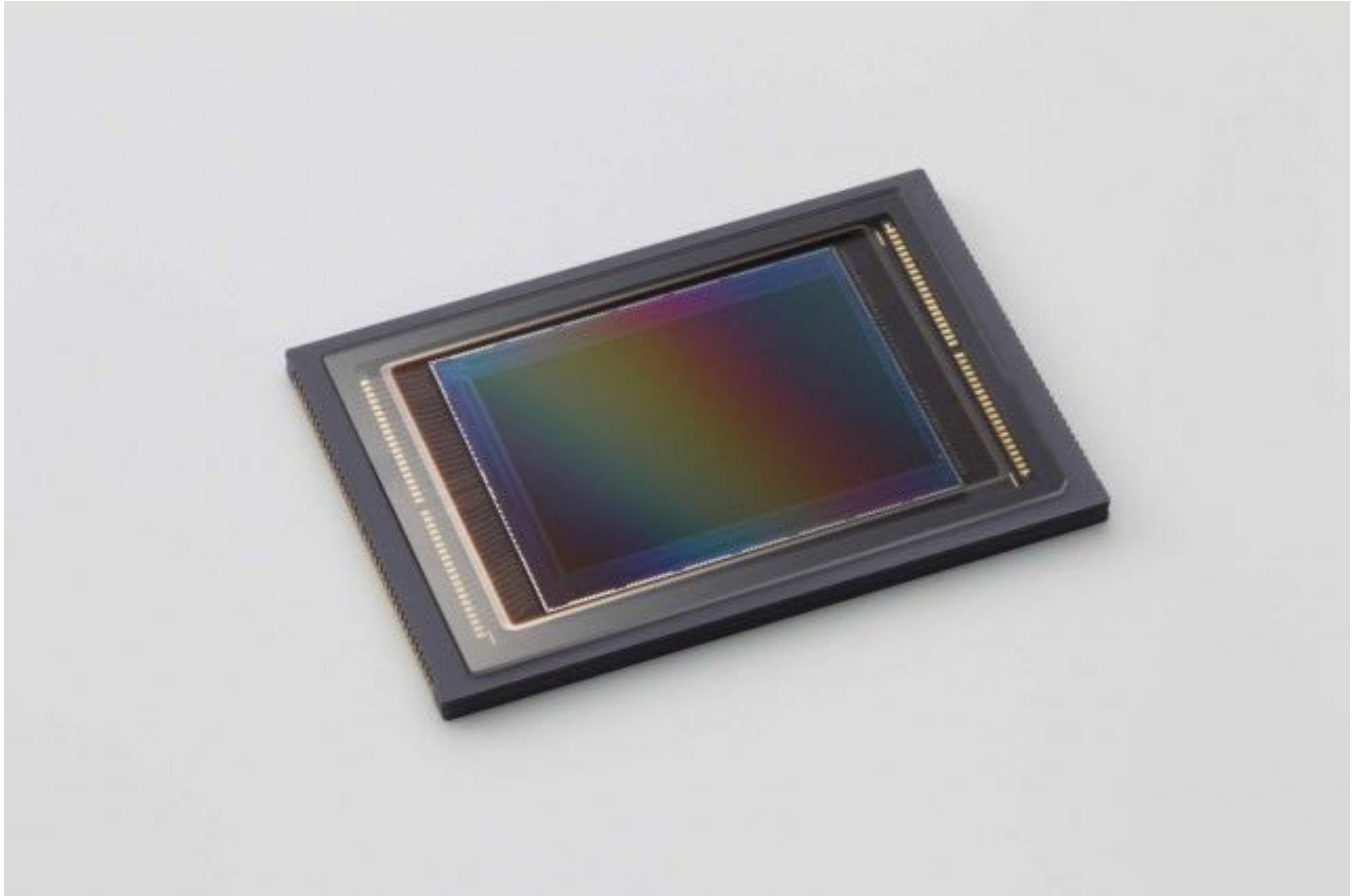


# Shutter Exposes Sensor For Precise Duration



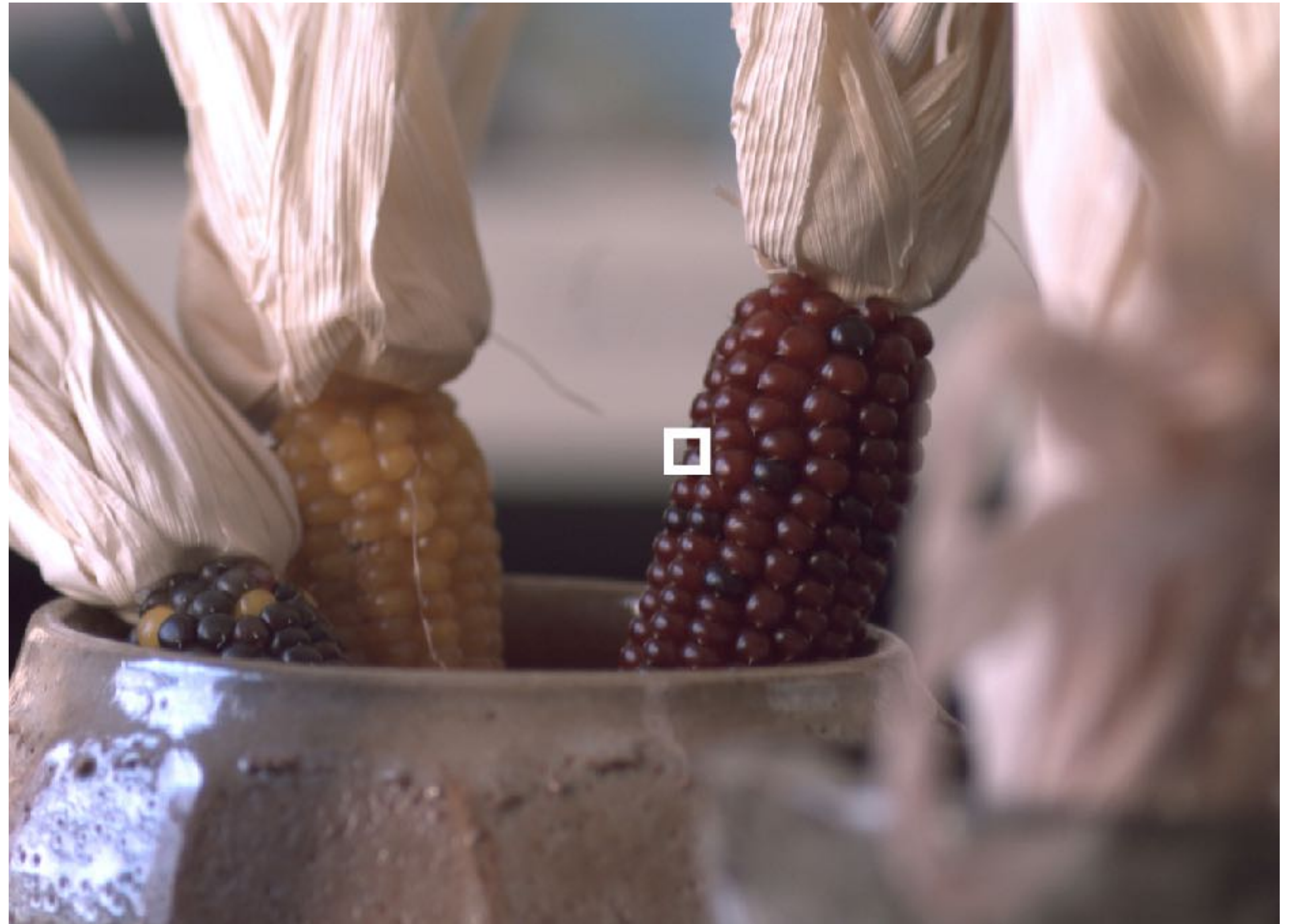
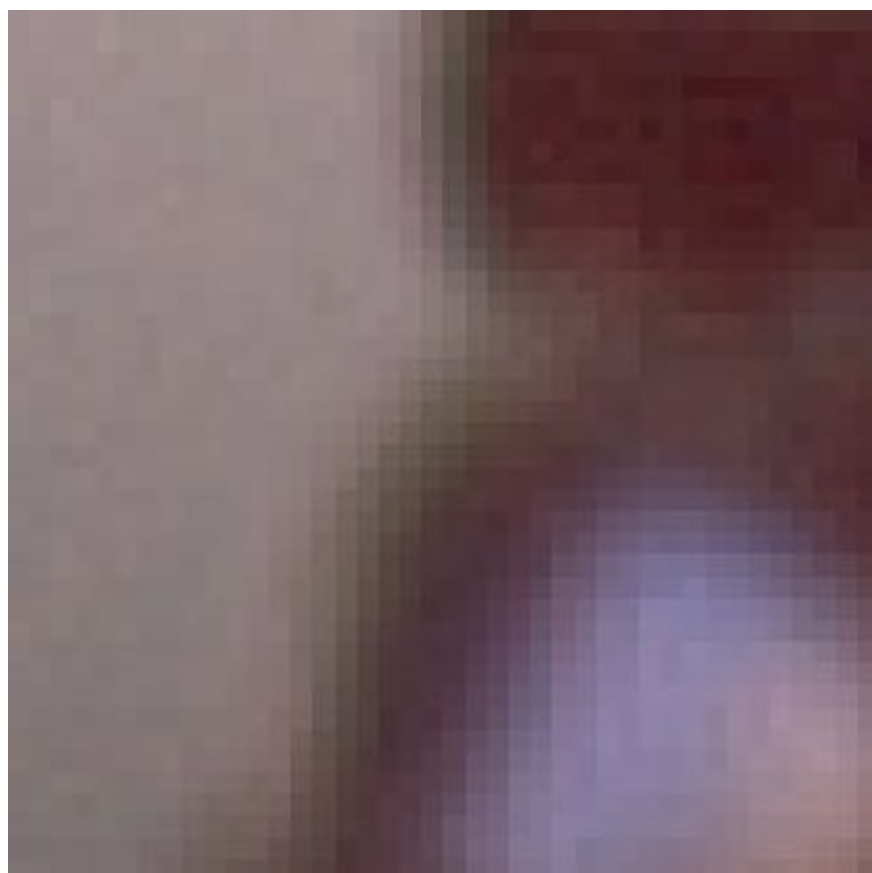
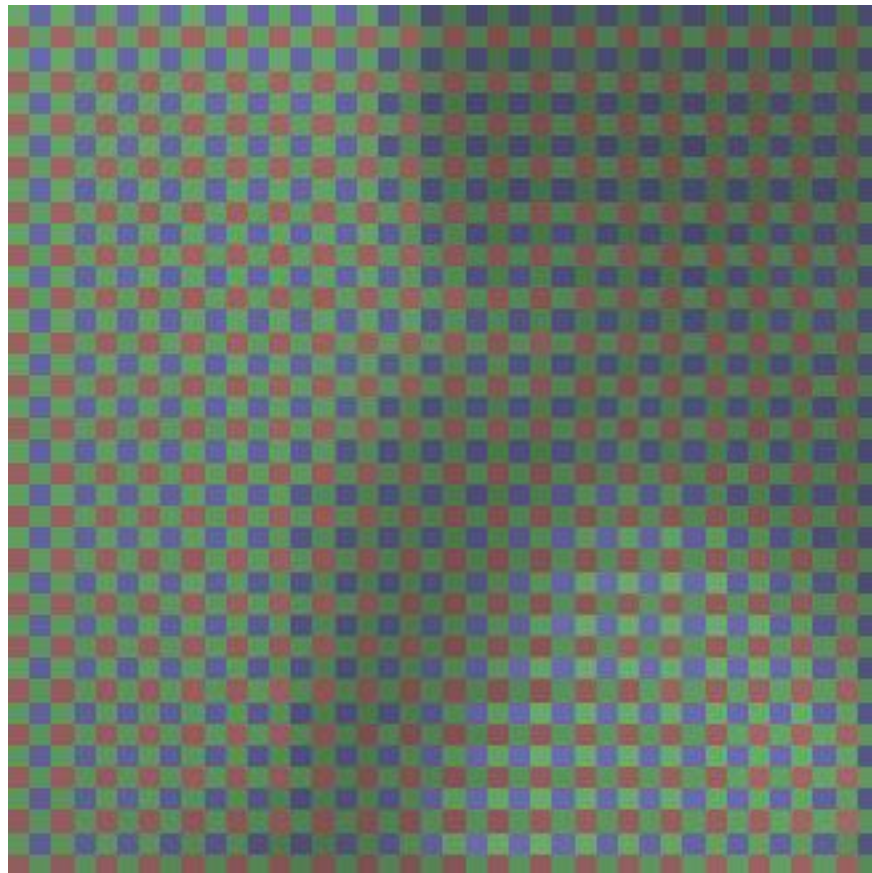
The Slow Mo Guys, <https://youtu.be/CmjeCchGRQo>

# Sensor Accumulates Irradiance During Exposure





# Image Processing: From Sensor Values to Image

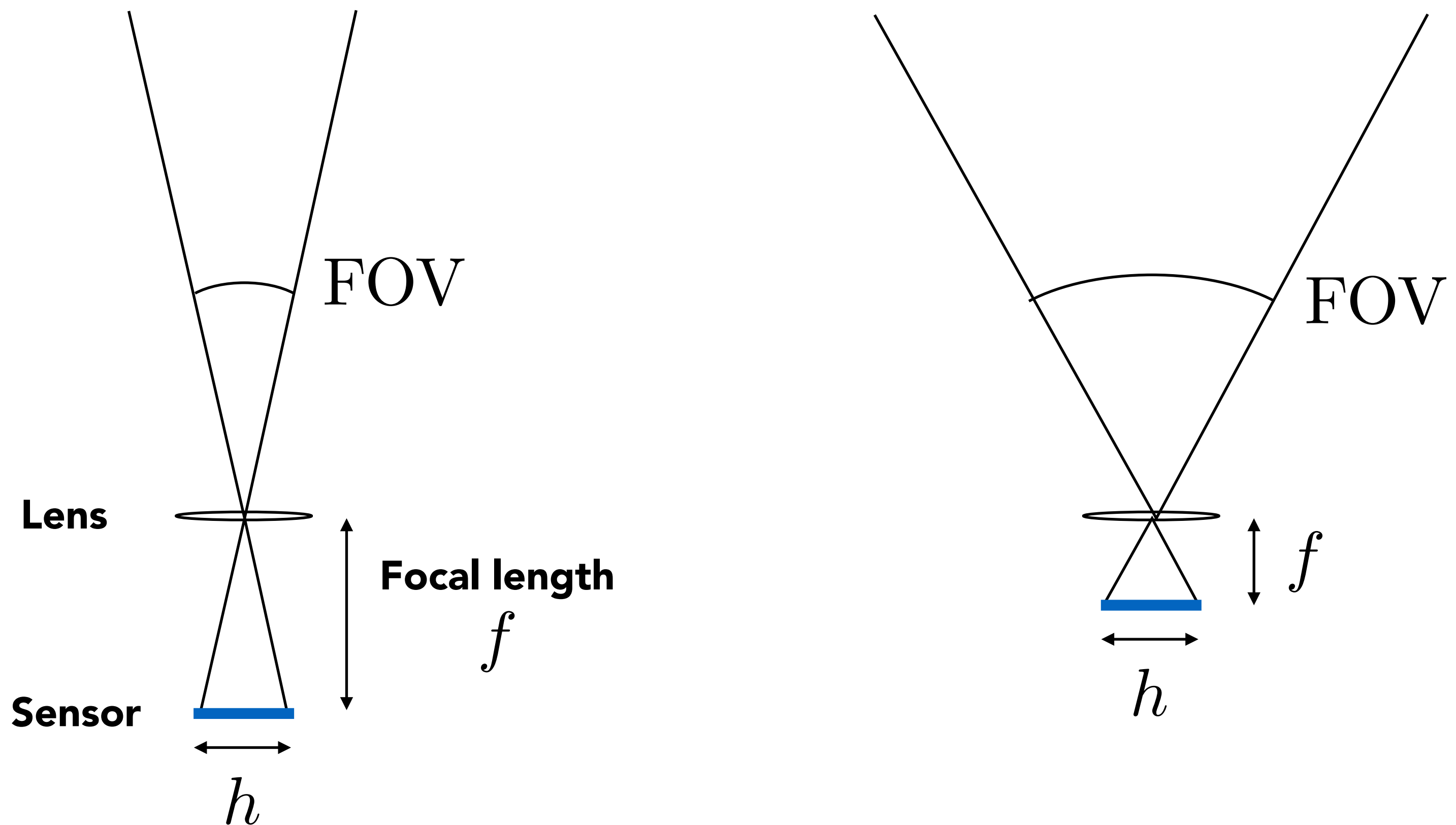


# **Optics of Image Formation:**

## **Field of View**



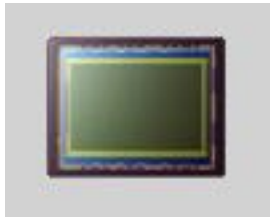
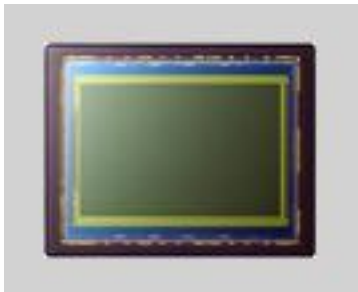
# Effect of Focal Length on FOV



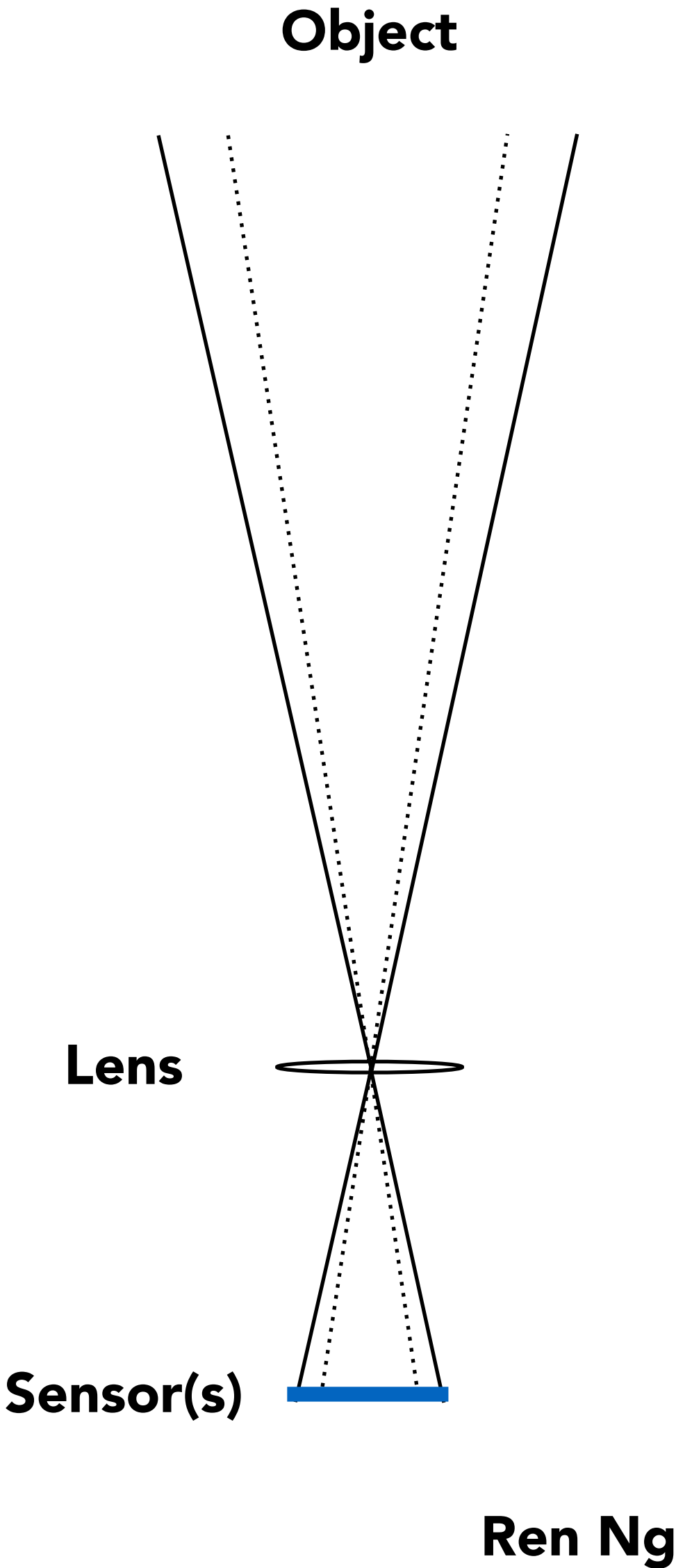
For a fixed sensor size, decreasing the focal length increases the field of view.

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

# Effect of Sensor Size on FOV



CS184/284A





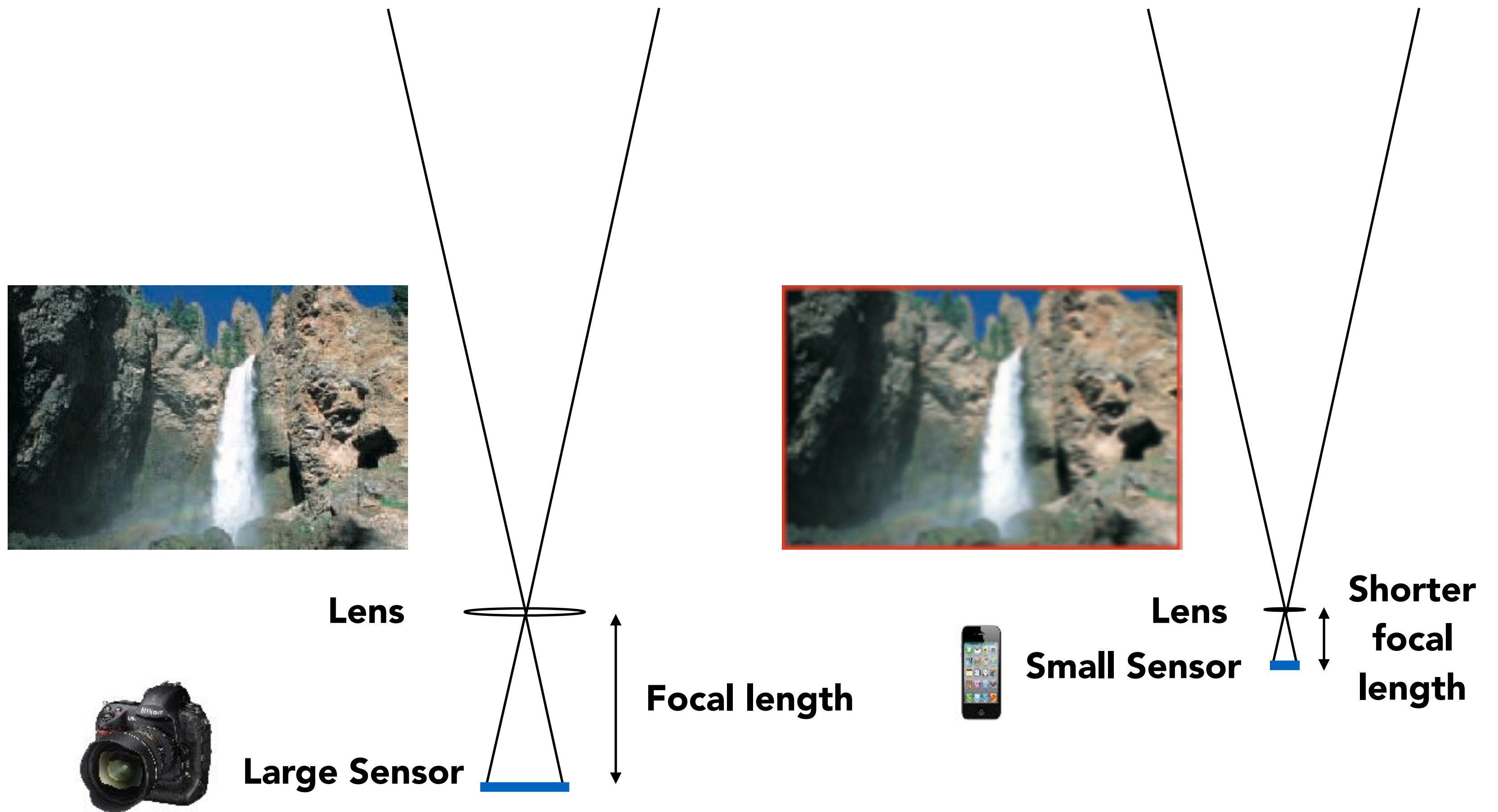
# Sensor Sizes

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 <sup>2</sup>	8.6 cm <sup>2</sup>	5.19 cm <sup>2</sup>	3.73 cm <sup>2</sup>	2.25 cm <sup>2</sup>	1.16 cm <sup>2</sup>	0.47 cm <sup>2</sup>	0.28 cm <sup>2</sup>	0.15 cm <sup>2</sup>
Crop Factor	0.64	1.0	1.29	1.52	2.0	2.7	4.3	5.62	7.61
Image									
Example									



Credit: [lensvid.com](http://lensvid.com)

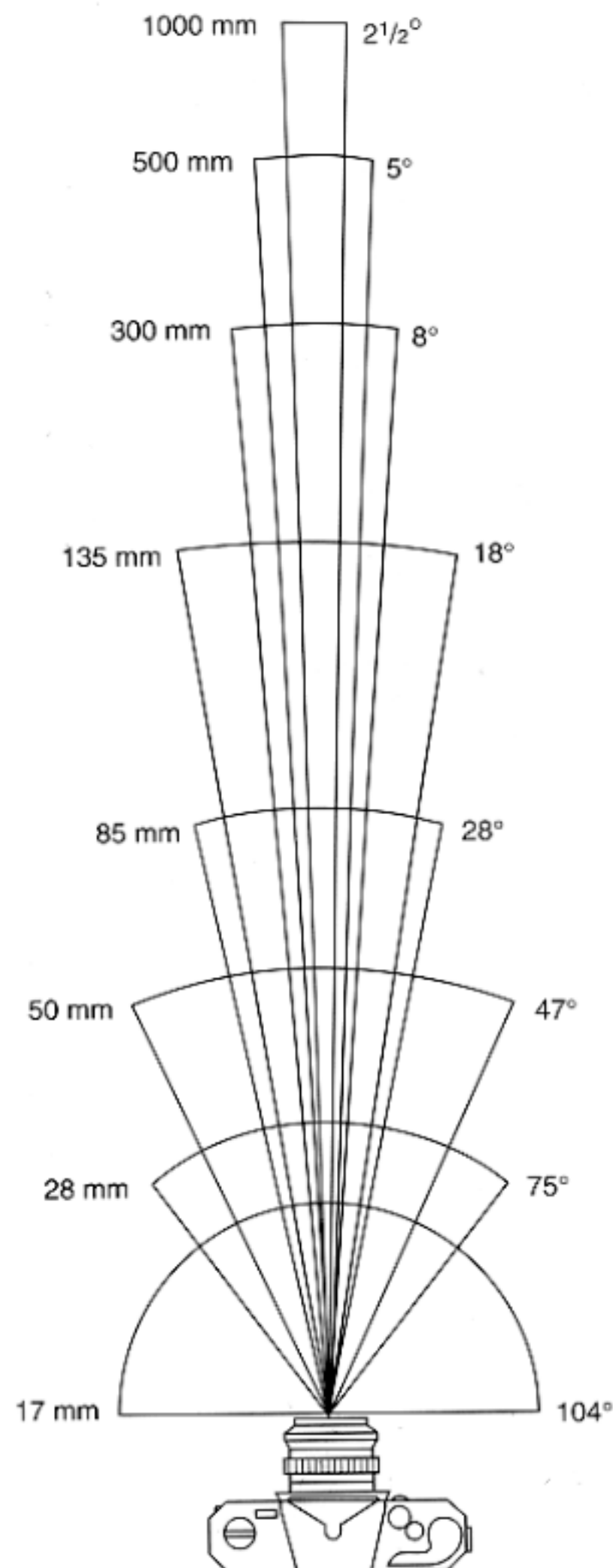
# Maintain FOV on Smaller Sensor?



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



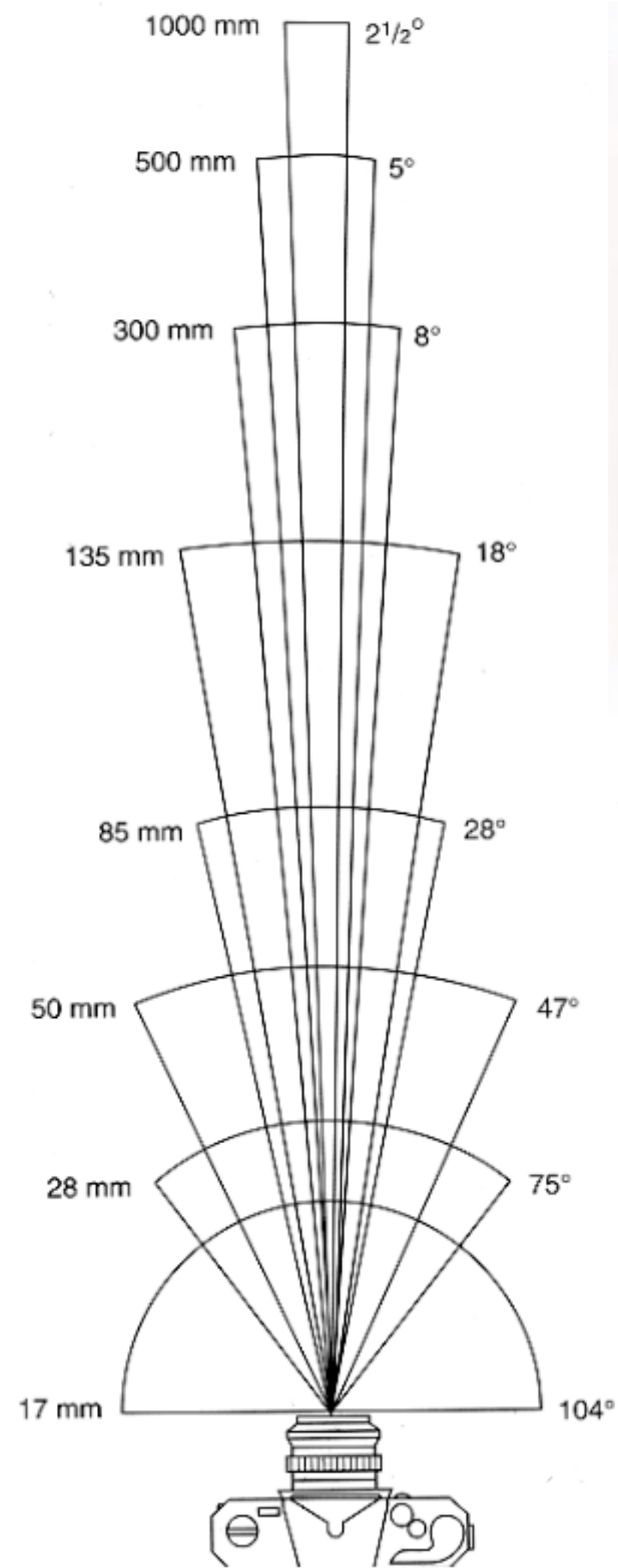
# Focal Length v. Field of View



- For historical reasons, it is common to refer to angular field of view by focal length of a lens used on a 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 28mm "equivalent" focal length, this uses the above convention. The physical focal length is often 5-6 times shorter, because the sensor is correspondingly smaller



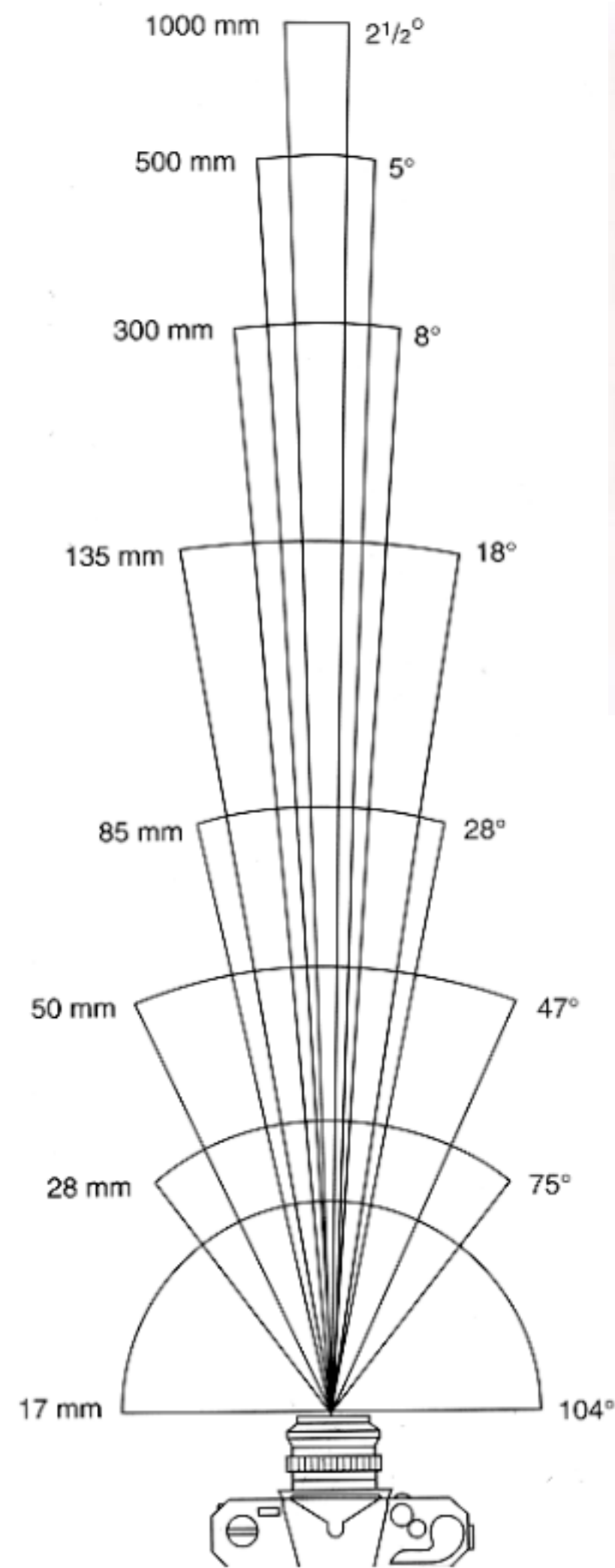
# Focal Length v. Field of View



From London and Upton, and Canon EF Lens Work III



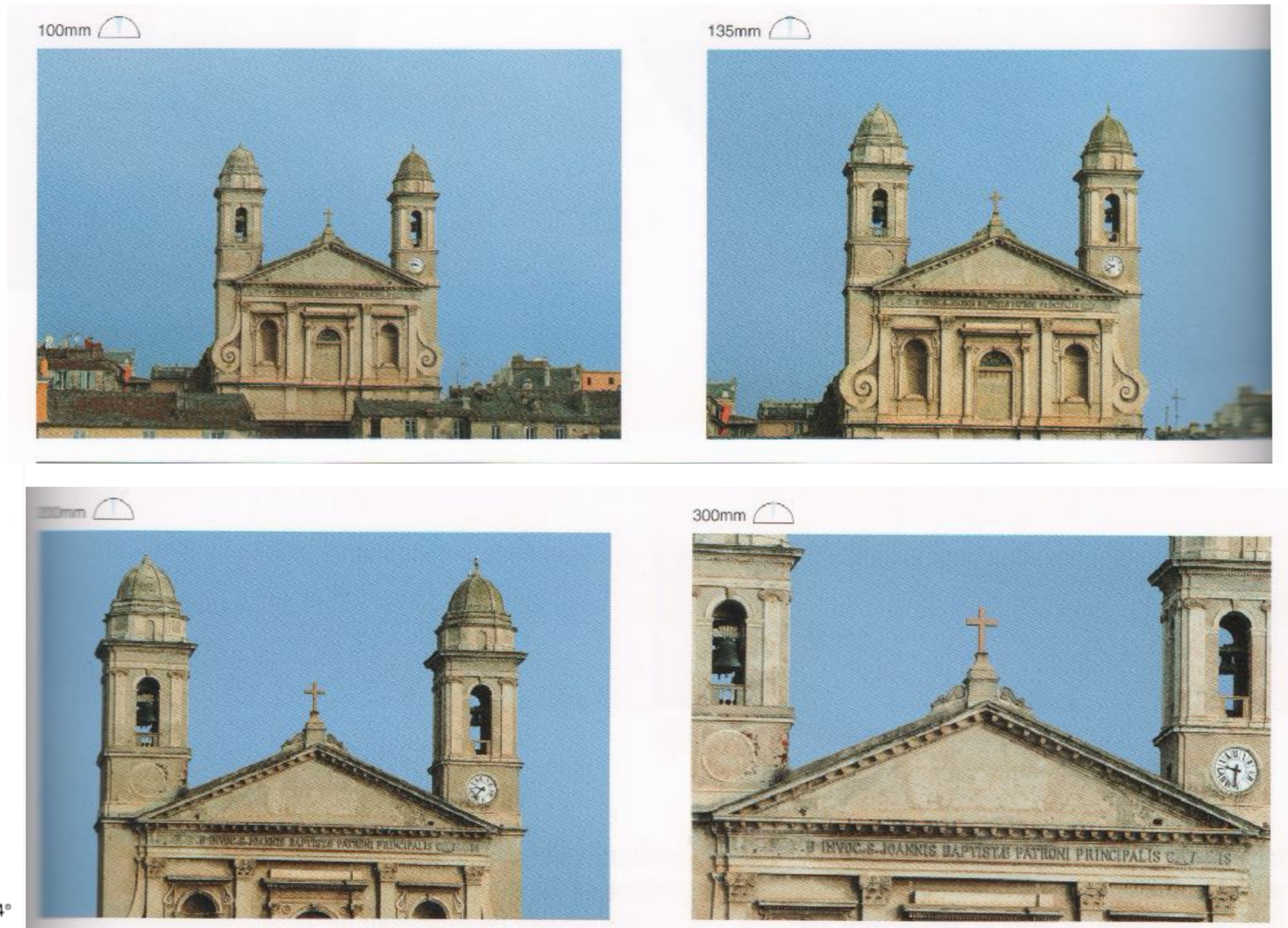
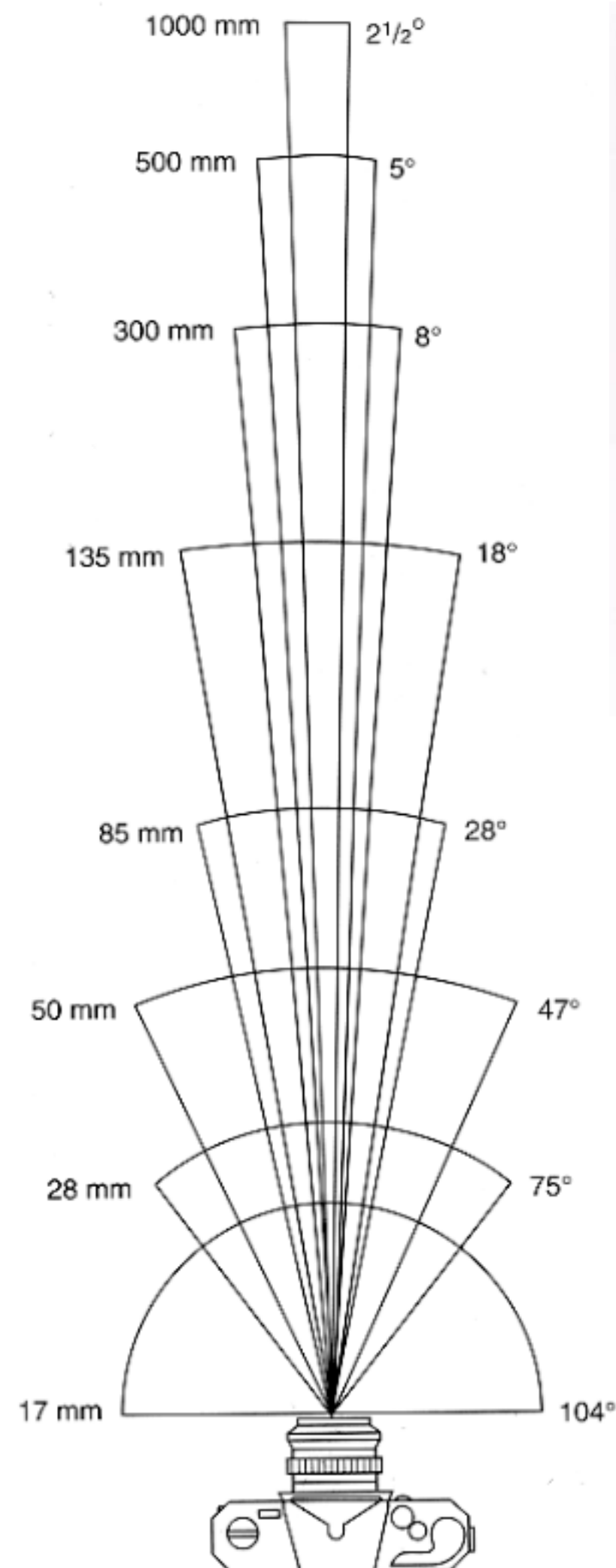
# Focal Length v. Field of View



From London and Upton, and Canon EF Lens Work III



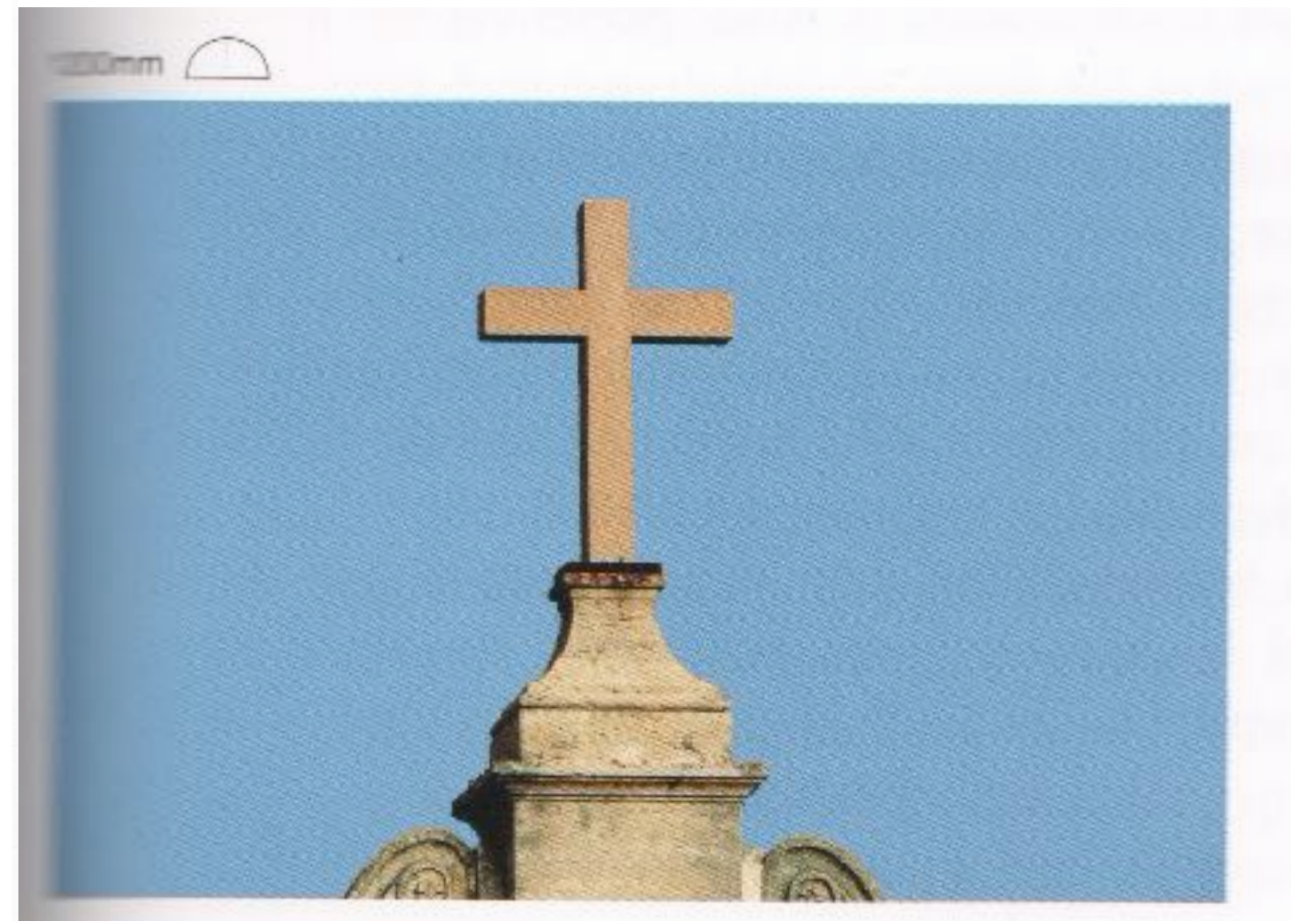
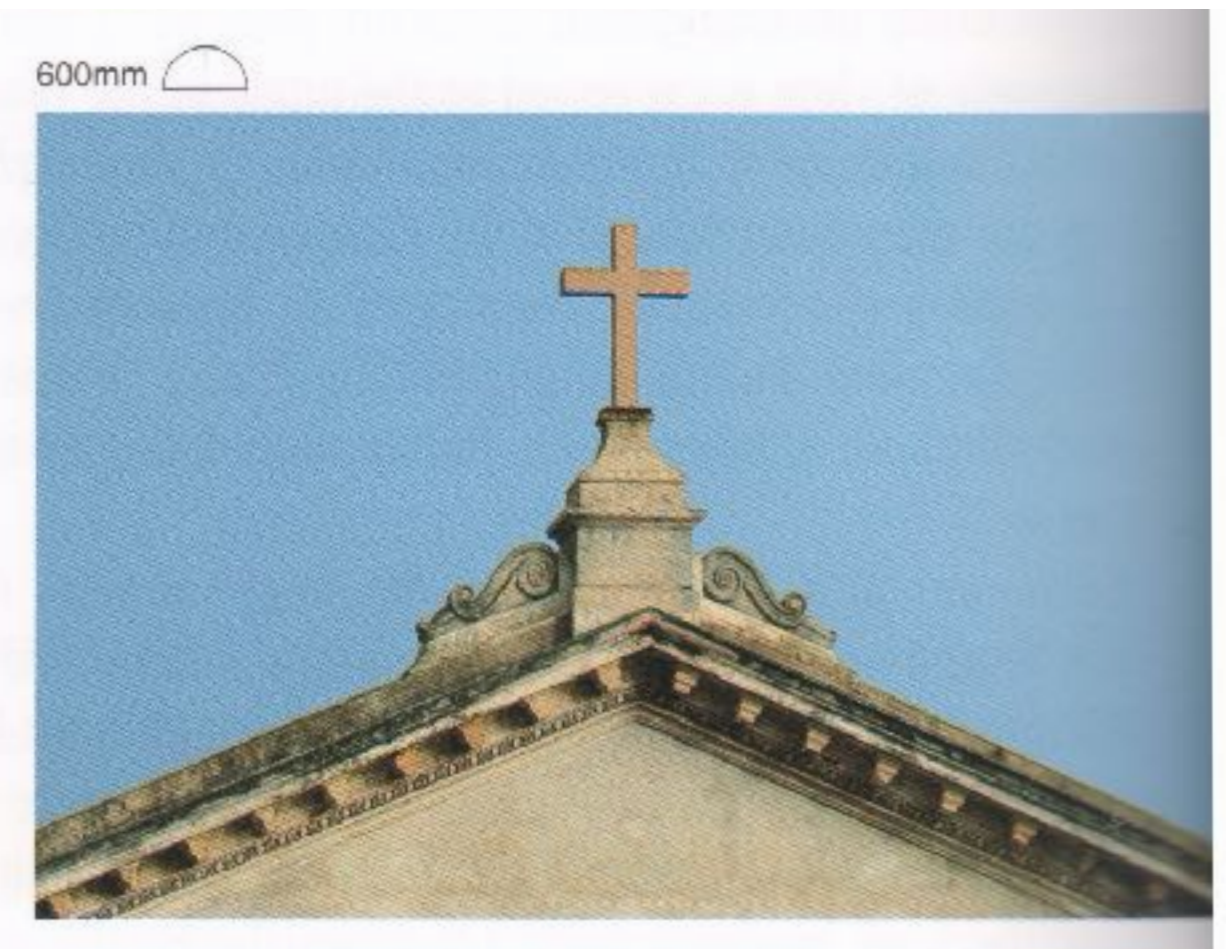
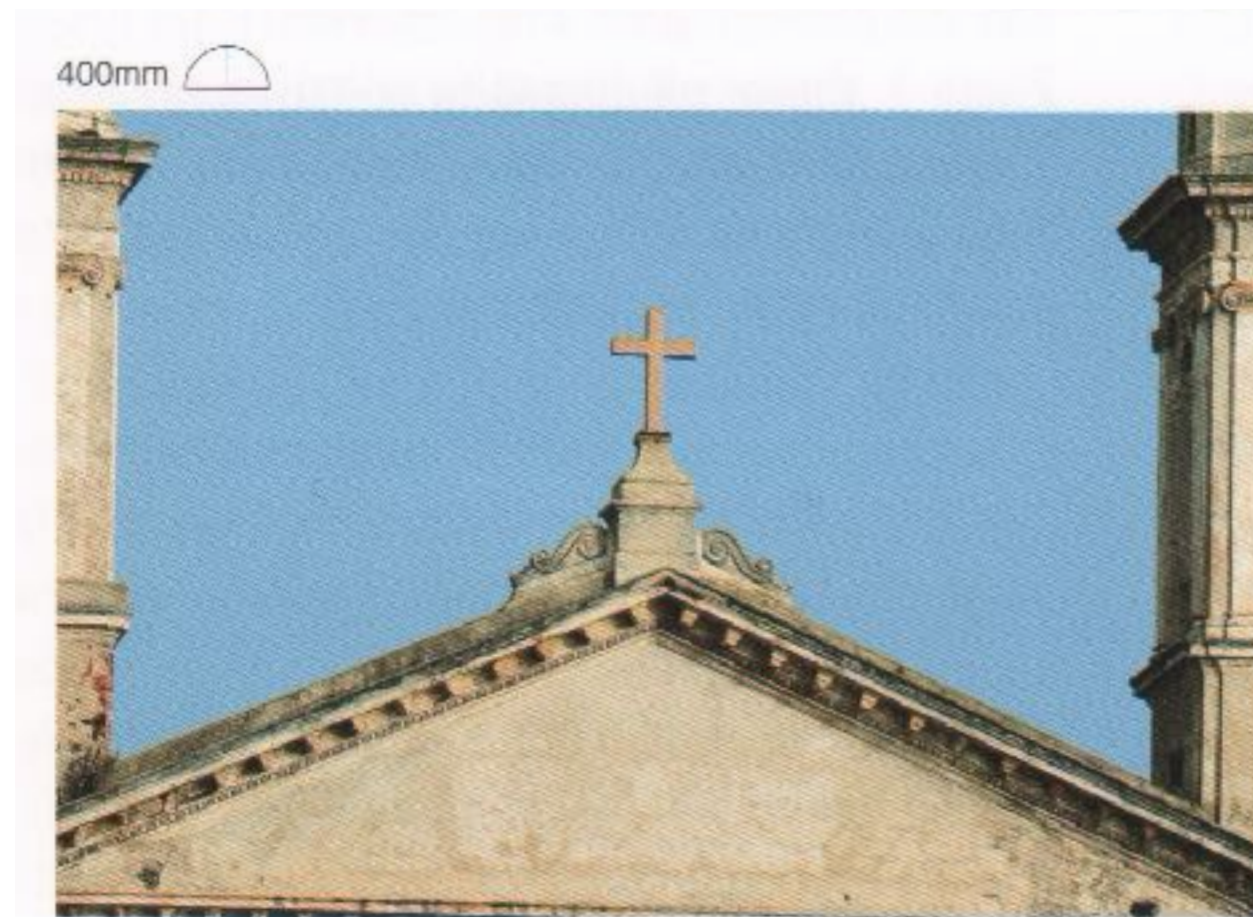
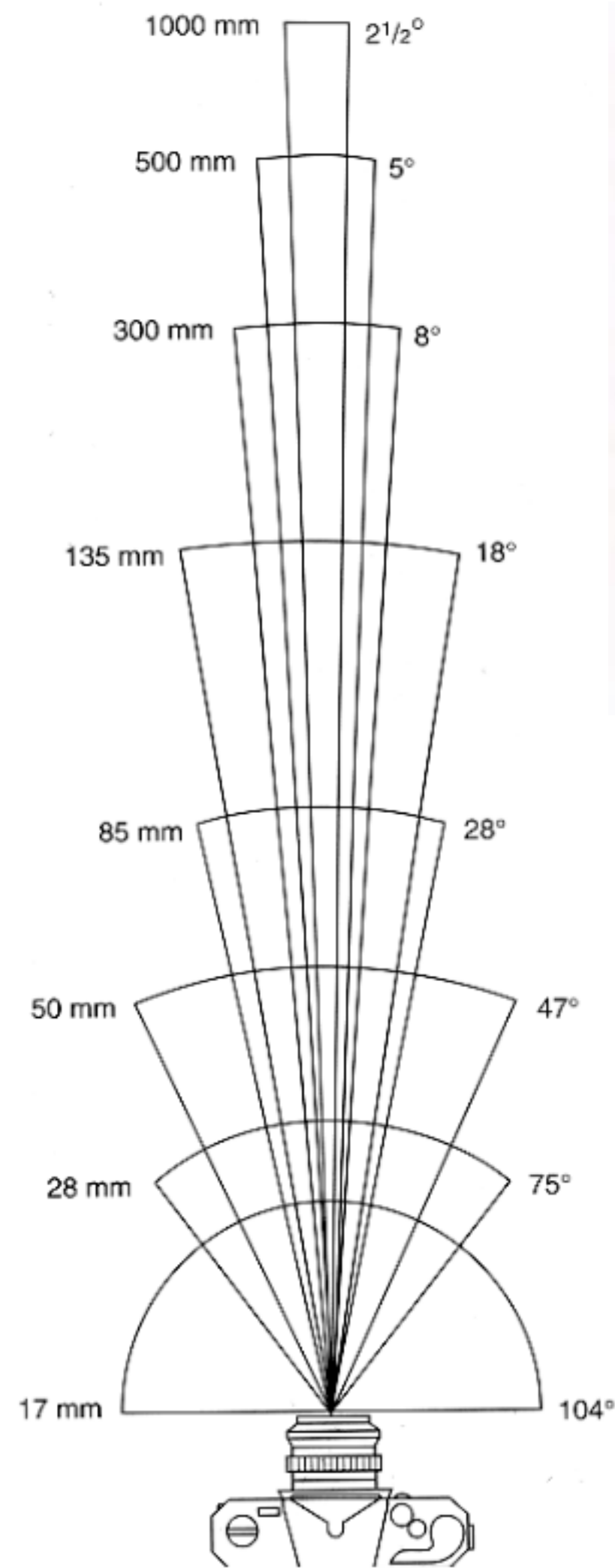
# Focal Length v. Field of View



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





Wide angle: 15mm, f/2.8





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





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





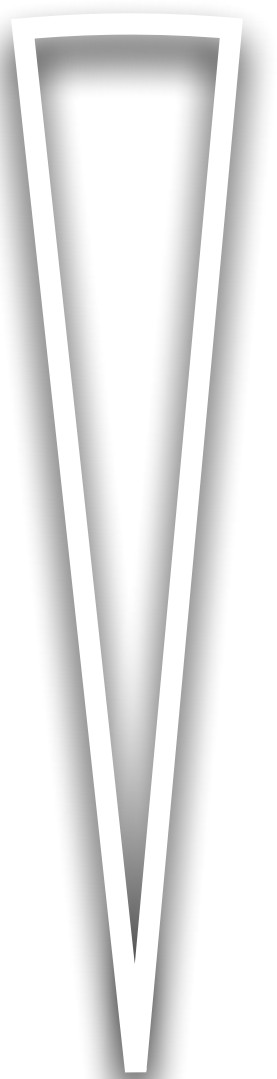
Normal: 64mm, 1/3200, f/2.8





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





Telephoto: 200mm, 1/200, f/2.8





Telephoto: 420mm, 1/1600, f/4





Telephoto: 420mm, 1.0s, f/4





Telephoto: 420mm, 4.0s, f/4



# **Perspective Composition (Photographer's Mindset)**



# Perspective Composition – Camera Position / Focal Length



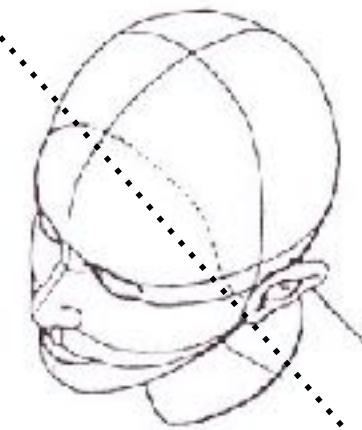
In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

From Canon EF Lens Work III



# Perspective Composition



16 mm (110°)

Up close and zoomed wide  
with short focal length



# Perspective Composition



200 mm (12°)

Walk back and zoom in  
with long focal length



# A Photographer's Mindset



“Choose your perspective before  
you choose your lens.”

— Ming Thein, [mingthein.com](http://mingthein.com)



# Improve Your Own Photography

**Tip 1: Make sure you have a strong subject**

- **Make it prominent, e.g. 1/3 of your image**

**Tip 2: choose a good perspective relationship (relative size) between your subject and background (or foreground)**

- **Complement, don't compete with the subject**

**Tip 3: change the zoom and camera distance to your subject**

- **Implement: actively zoom, and move your camera in/out**
- **Even works with your smartphone!**



# Dolly-Zoom Cinema Technique – “Vertigo Effect”



First used by Alfred Hitchcock in “Vertigo” 1958



# Dolly-Zoom Cinema Technique – a.k.a. “Vertigo Effect”



MOVIECLIPS.COM

By Steven Spielberg in "Jaws" 1975



# Exposure



# **Exposure Duration: Fast and Slow Photography**

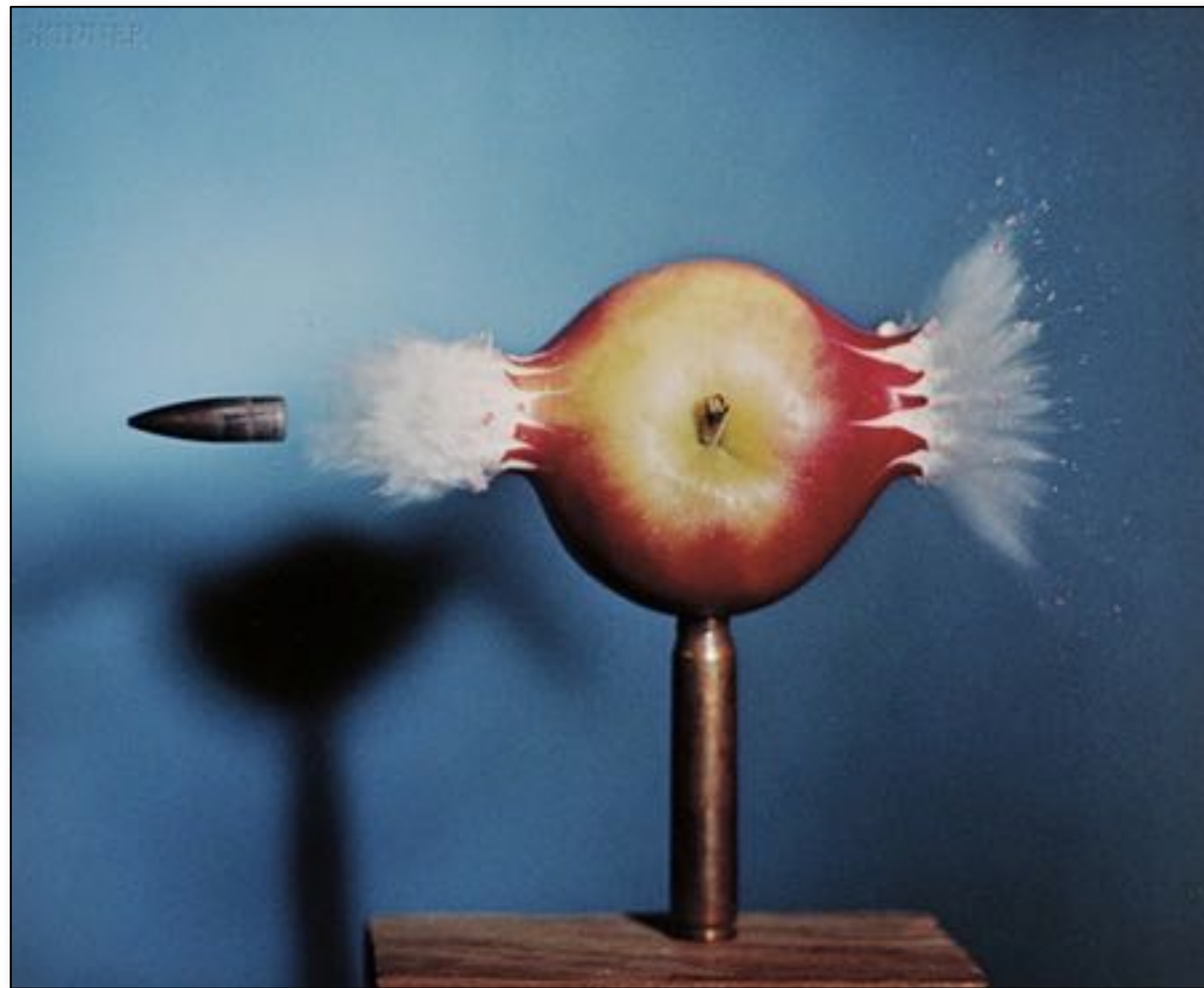


# High-Speed Photography

long exposure

bright strobe illumination

gun synced to camera



Harold Edgerton



Mark Watson

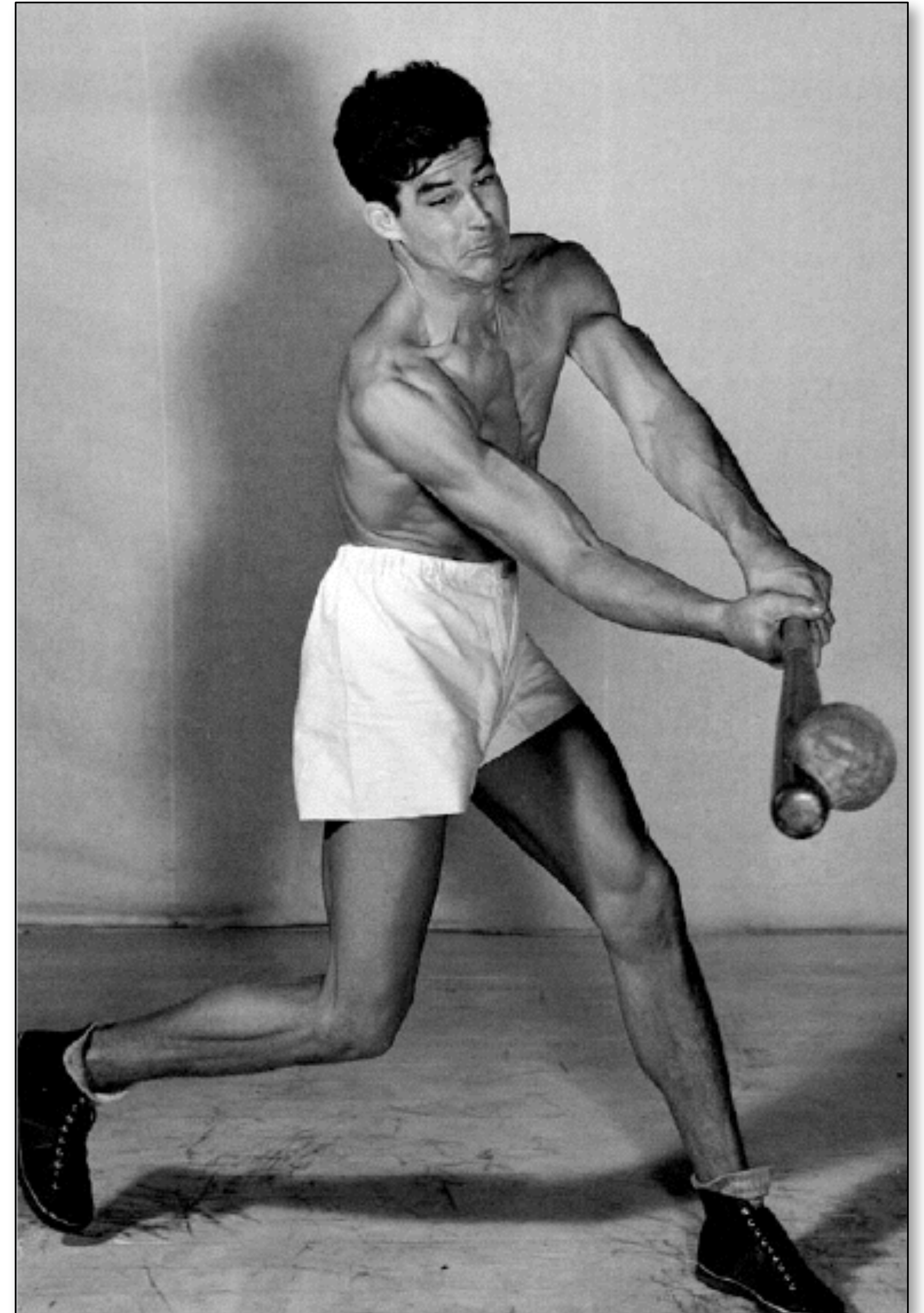
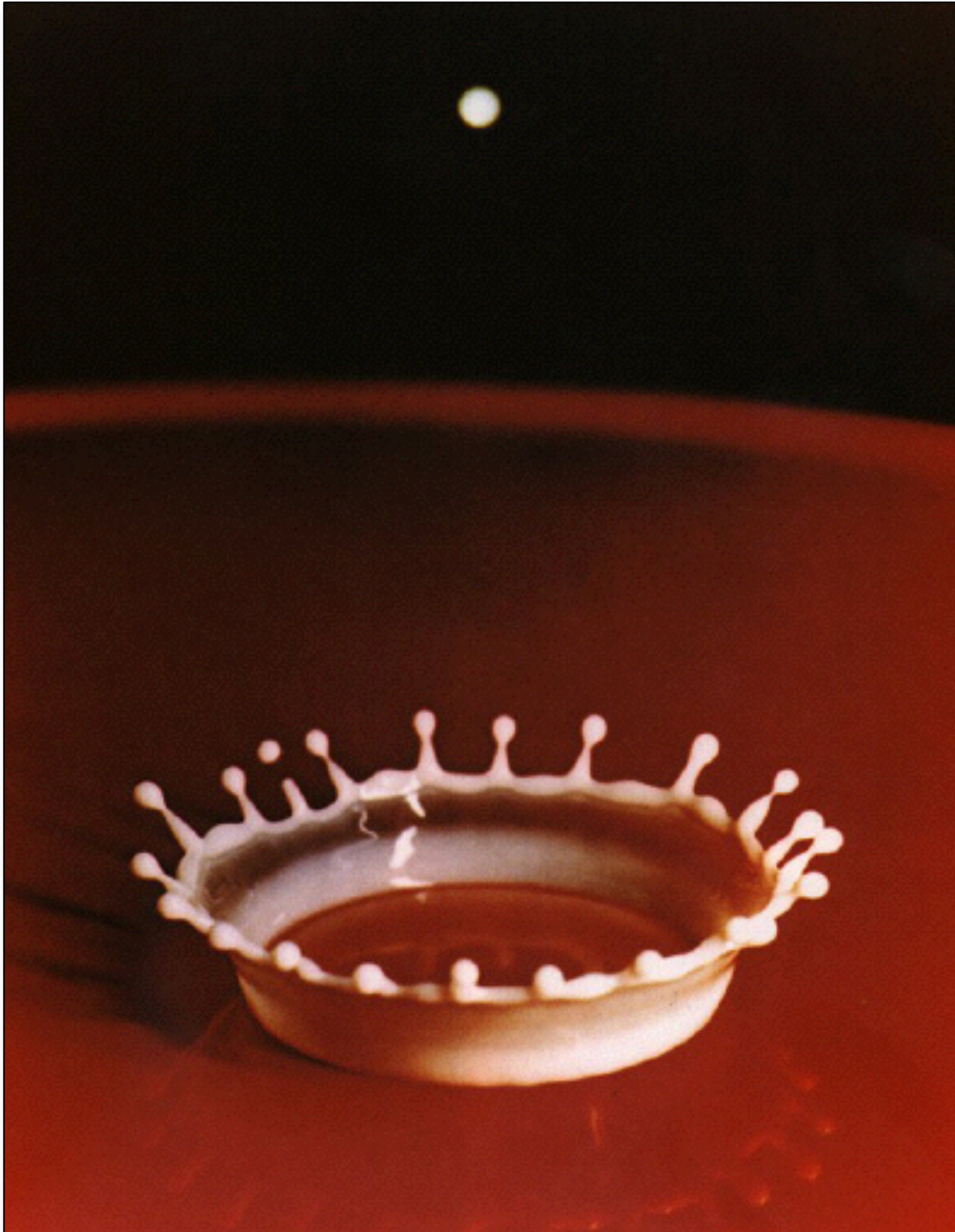
CS184/284A

Slide courtesy L. Waller

Ren Ng

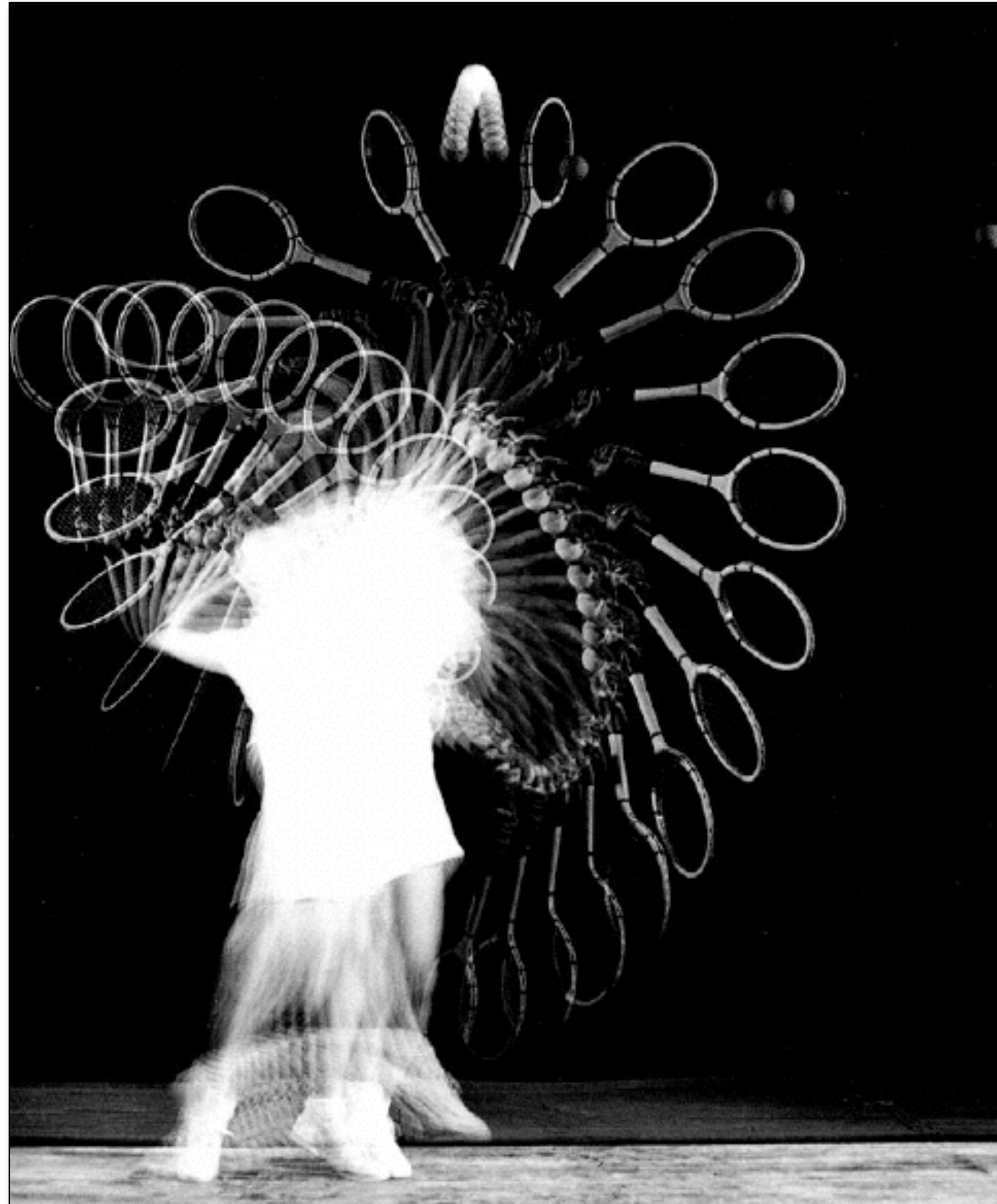


# High-Speed Photography





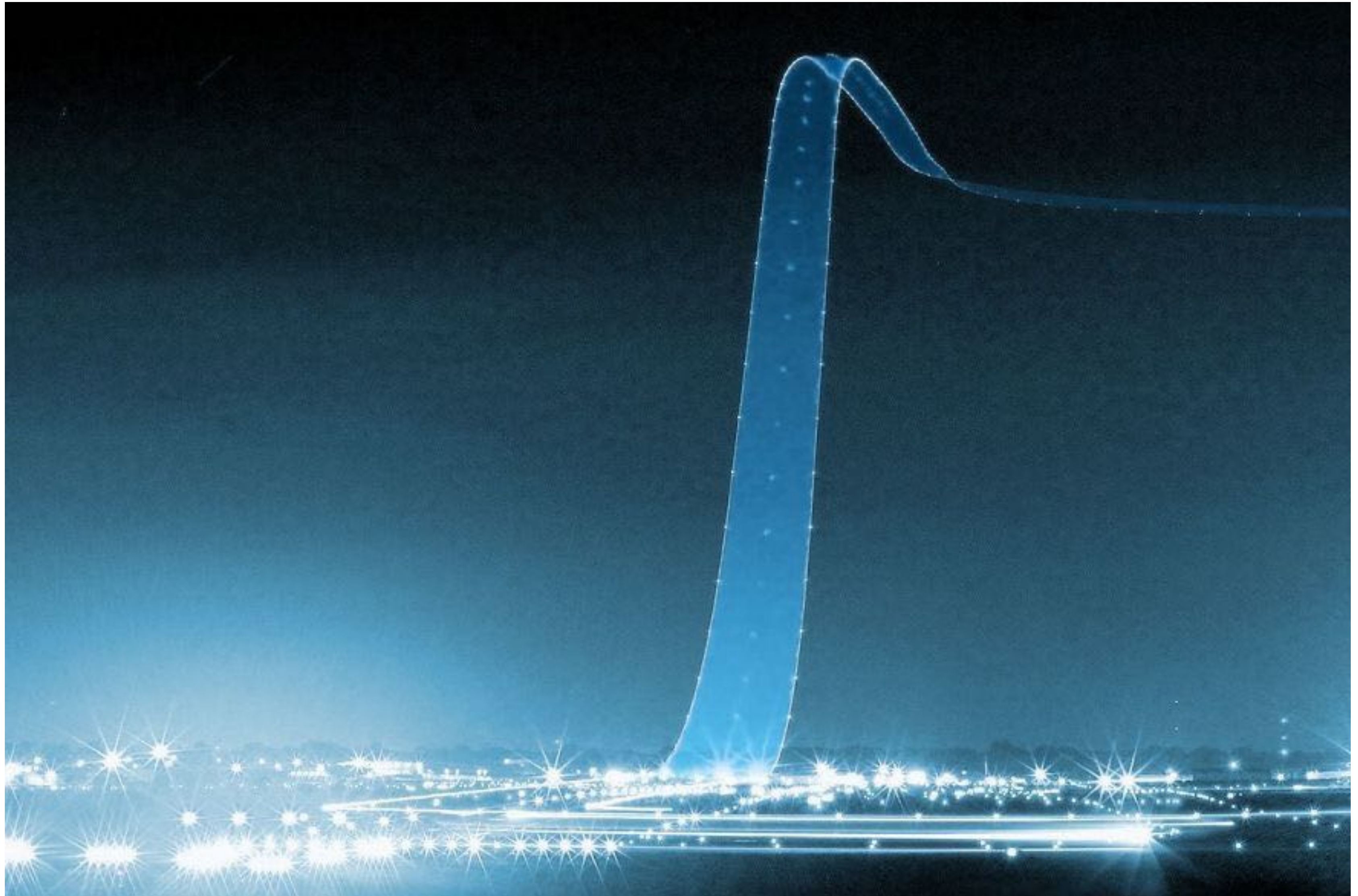
# High-Speed Photography



Harold Edgerton



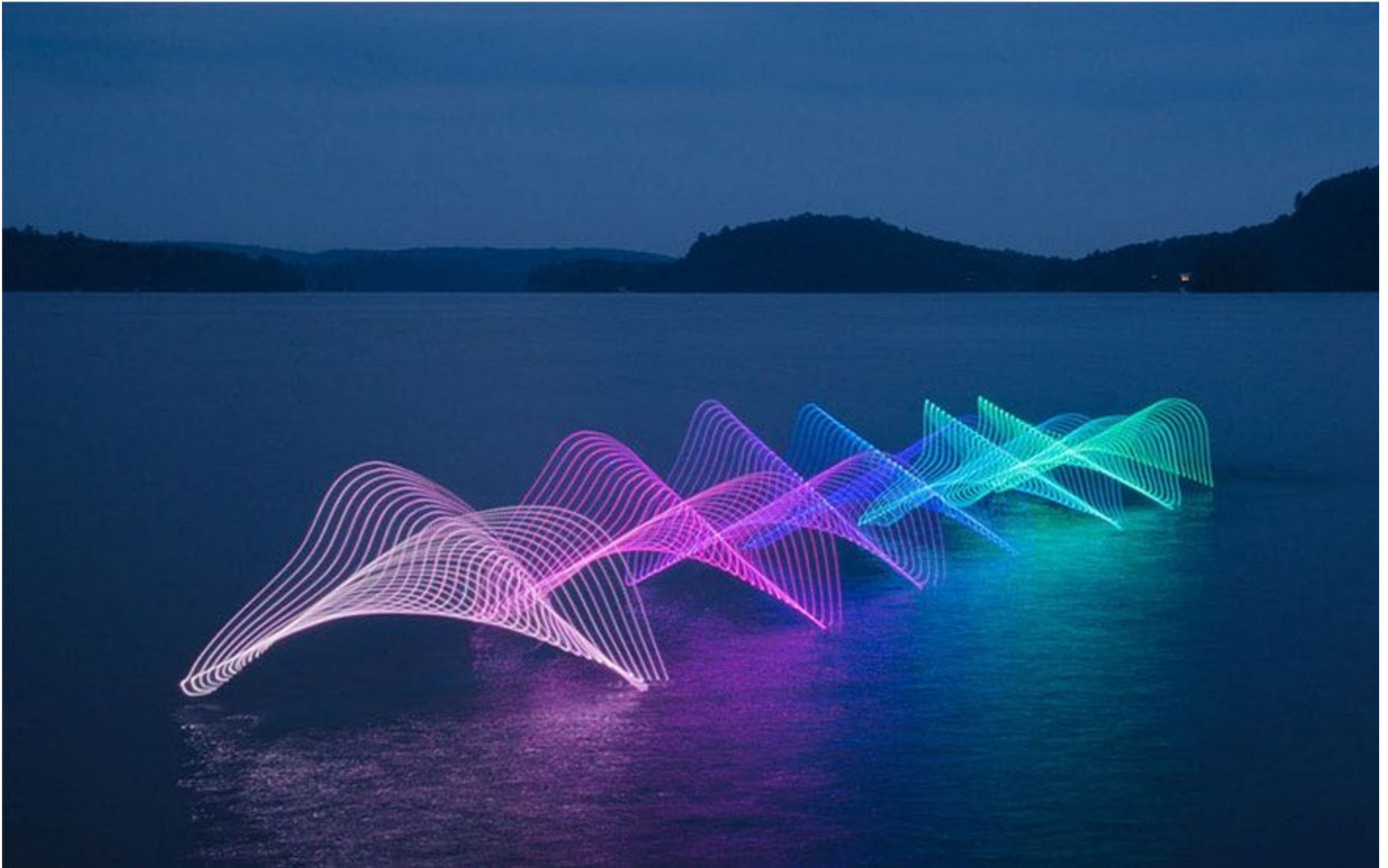
# Long-Exposure Photography



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



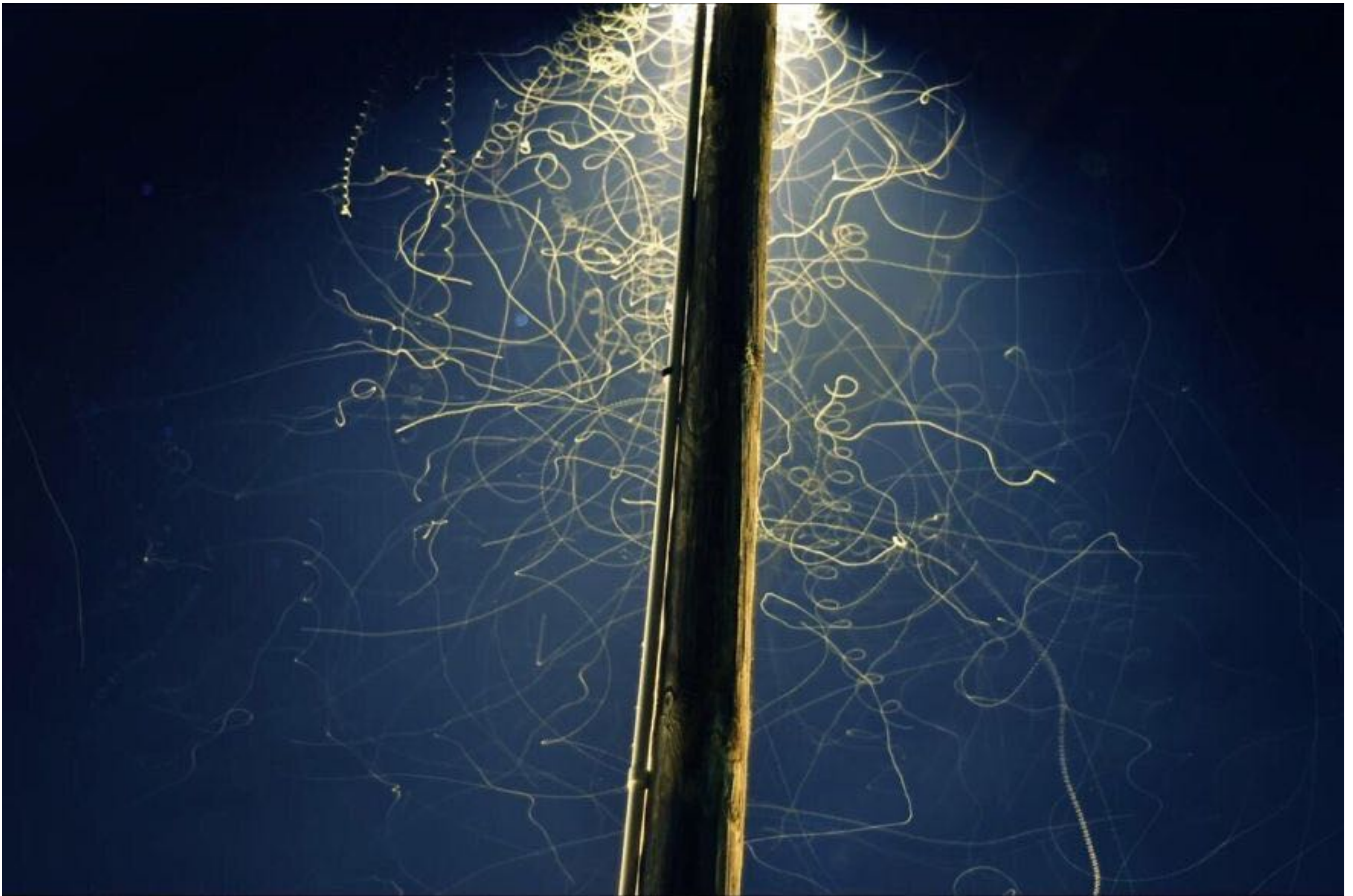
# Long-Exposure Photography



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



# Long-Exposure Photography



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



# Exposure

- $Q = T \times E$
- Exposure = time x irradiance
- Exposure time (T)
  - Controlled by shutter
- Irradiance (E)
  - Power of light falling on a unit area of sensor
  - Controlled by lens aperture and focal length



# Exposure Levels (1 "Stop" = 2x Exposure)

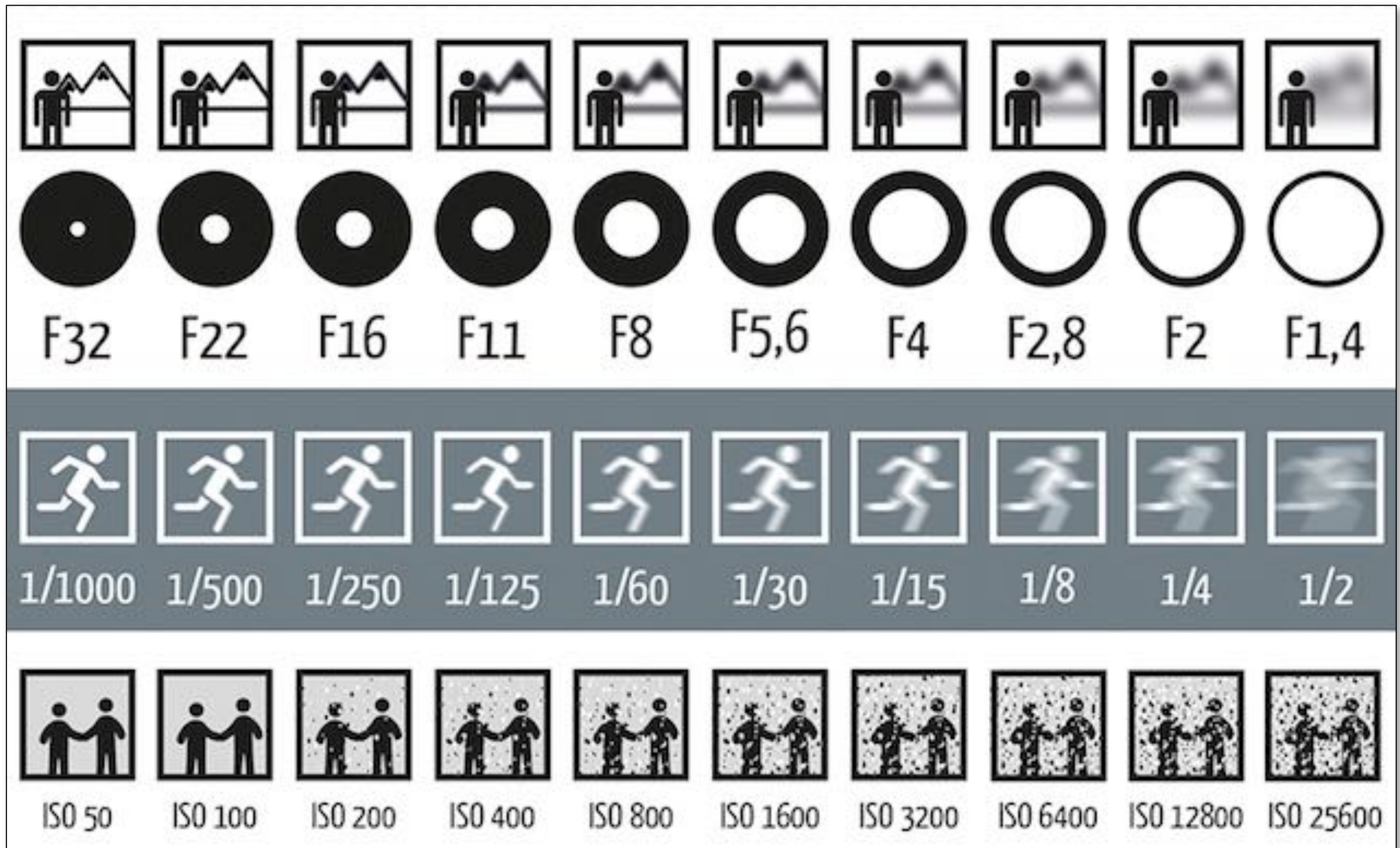


Exposure bracketing with +/- 1 stop exposure

<https://www.dpmag.com/how-to/tip-of-the-week/how-and-why-to-use-auto-exposure-bracketing/>



# Exposure Controls: Aperture, Shutter, Gain (ISO)





# Definition: F-Number of a Lens

- The F-Number of a lens is defined as the focal length divided by the diameter of the aperture
- Common F-stops on real lenses: 1.4, 2, 2.8, 4.0, 5.6, 8, 11, 16, 22, 32
- 1 stop doubles exposure
- Notation: an f-stop of, e.g. 2 is sometimes written  $f/2$ , or  $F:2$



# **Exposure Controls: Aperture, Shutter, Gain (ISO)**

## **Aperture size**

- **Change the f-stop by opening / closing the aperture (if camera has iris control)**

## **Shutter speed**

- **Change the duration the sensor pixels integrate light**

## **ISO gain**

- **Change the amplification (analog and/or digital) between sensor values and digital image values**



# Constant Exposure: F-Stop vs Shutter Speed

Example: these pairs of aperture and shutter speed give equivalent exposure

F-Stop	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0	22.0	32.0
Shutter	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1

If the exposure is too bright/dark, may need to adjust f-stop and/or shutter up/down.



# ISO (Gain)

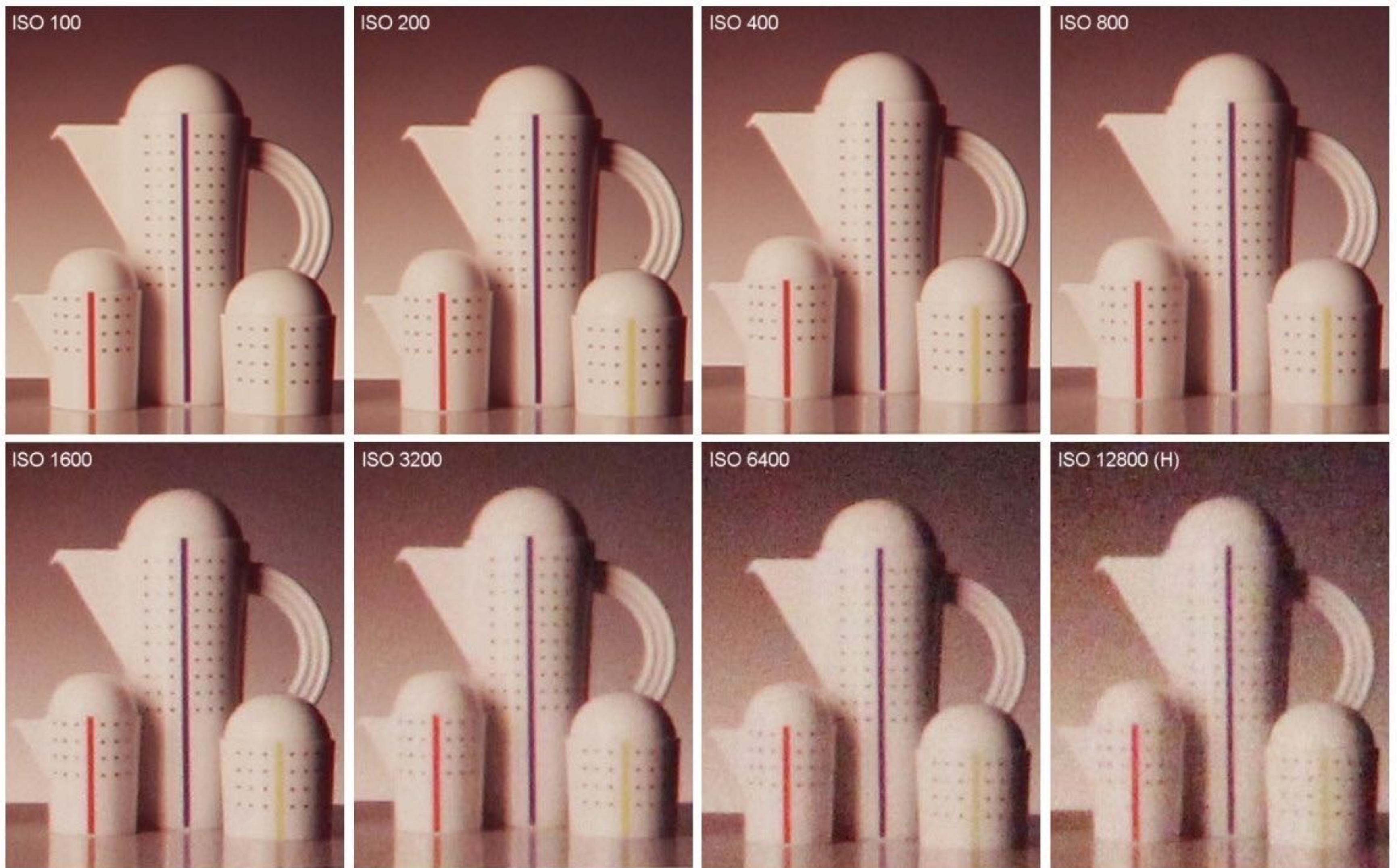
Third variable for exposure

Image sensor: trade sensitivity for noise

- Multiply signal before analog-to-digital conversion
- Linear effect (ISO 200 needs half the light as ISO 100)



# ISO Gain vs Noise in Canon T2i



Credit: [bobatkings.com](http://bobatkings.com)

**CS184/284A**    **Note: trend is same in current sensors, but much less noise!**

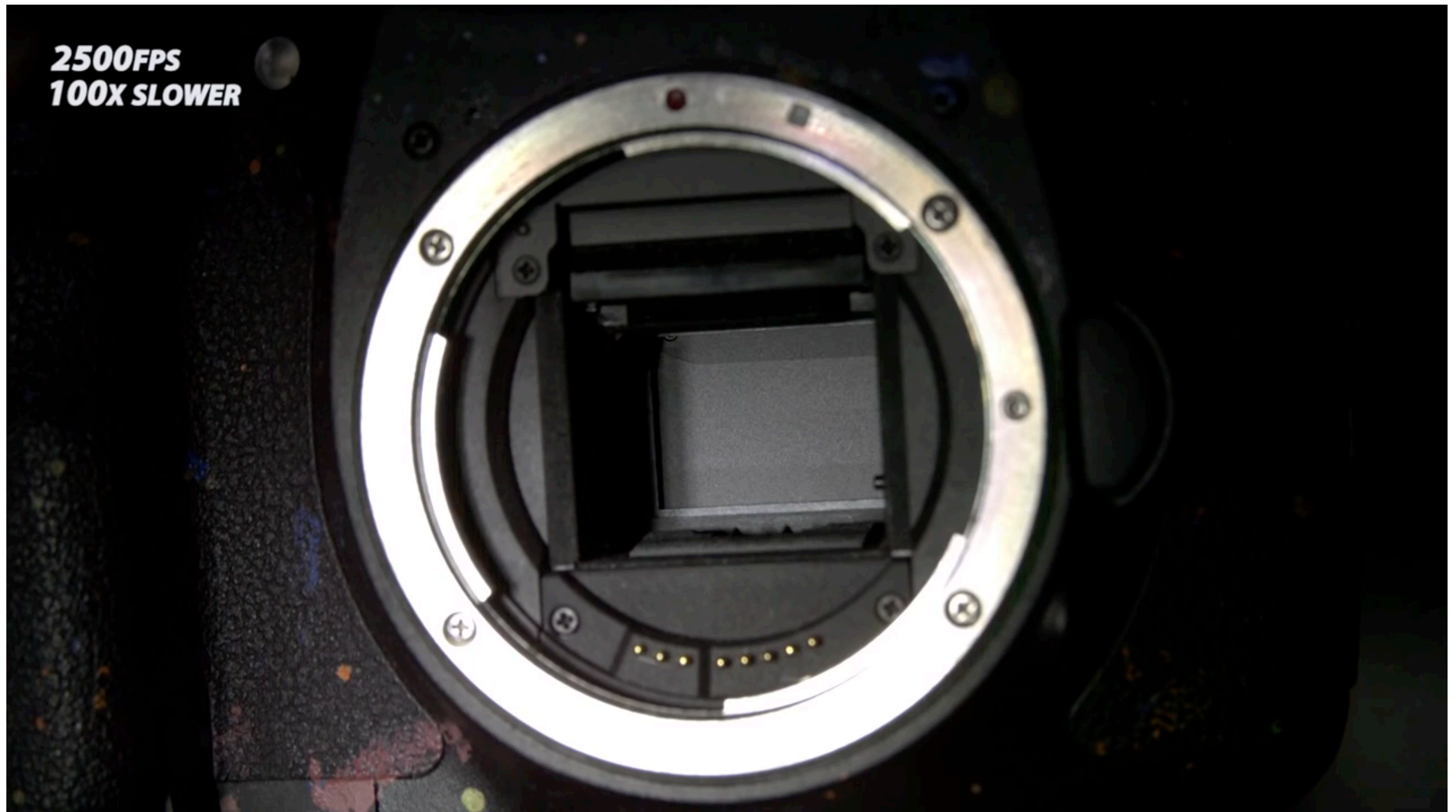
**Ren Ng**



# **Physical & Electronic Shutters**



# Physical Shutter (1/25 Sec Exposure)



The Slow Mo Guys, <https://youtu.be/CmjeCchGRQo>



# Main Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur



<http://www.gavtrain.com/?p=3960>

Gavin Hoey



# Main Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur

Slow shutter speed



Fast shutter speed



London



# Electronic Shutter

- Pixel is electronically reset to start exposure
- Fills with photoelectrons as light falls on sensor
- Reading out pixel electronically “ends” exposure
- Problem: most sensors read out pixels sequentially, takes time (e.g. 1/30 sec) to read entire sensor
  - If reset all pixels at the same time, last pixel read out will have longer exposure
  - So, usually stagger reset of pixels to ensure uniform exposure time
  - Problem: rolling shutter artifact

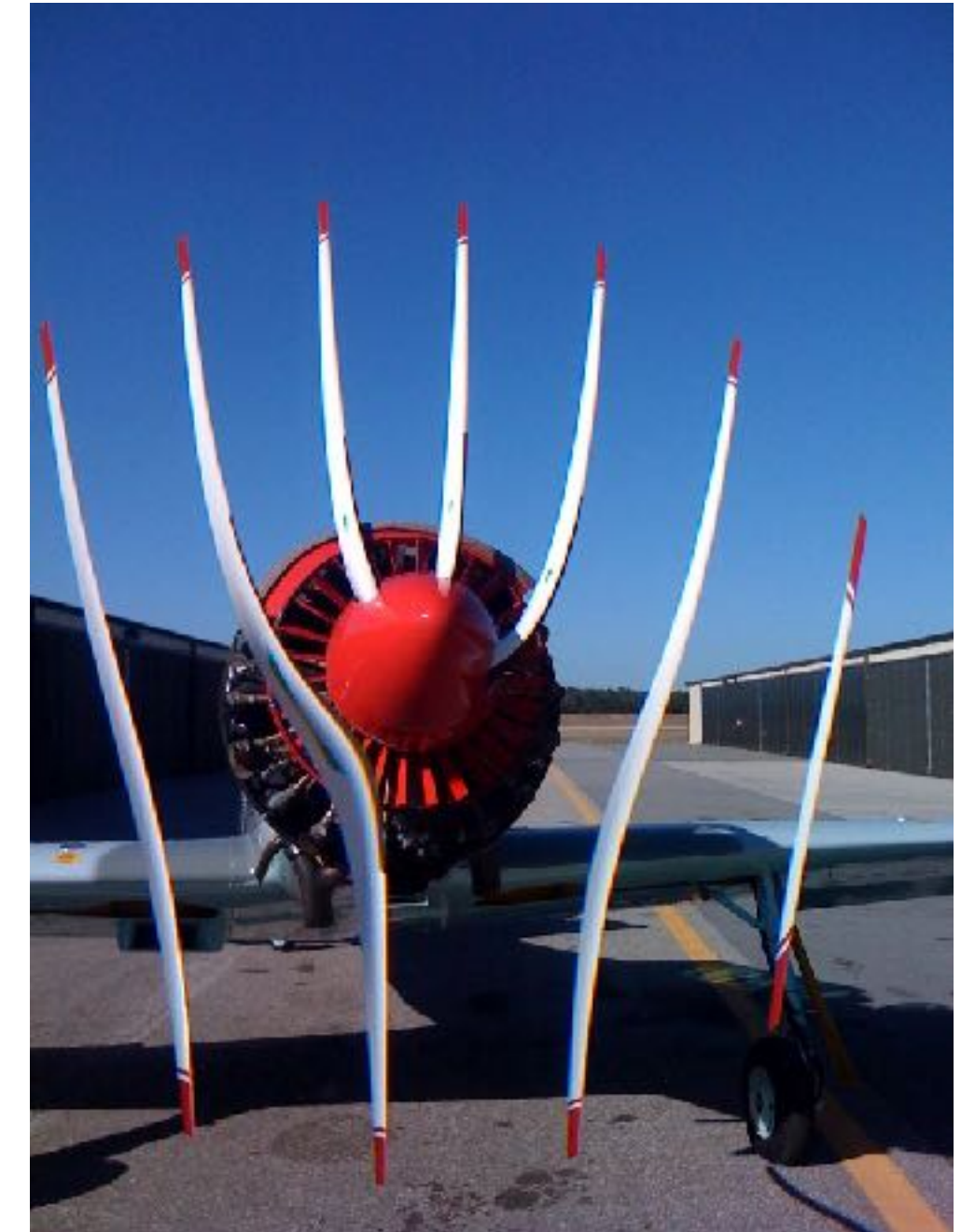


# Electronic Rolling Shutter



Credit: David Adler, B&H Photo Video

<https://www.bhphotovideo.com/explora/video/tips-and-solutions/rolling-shutter-versus-global-shutter>



Credit: Soren Ragsdale

<https://flic.kr/p/5S6rKw>



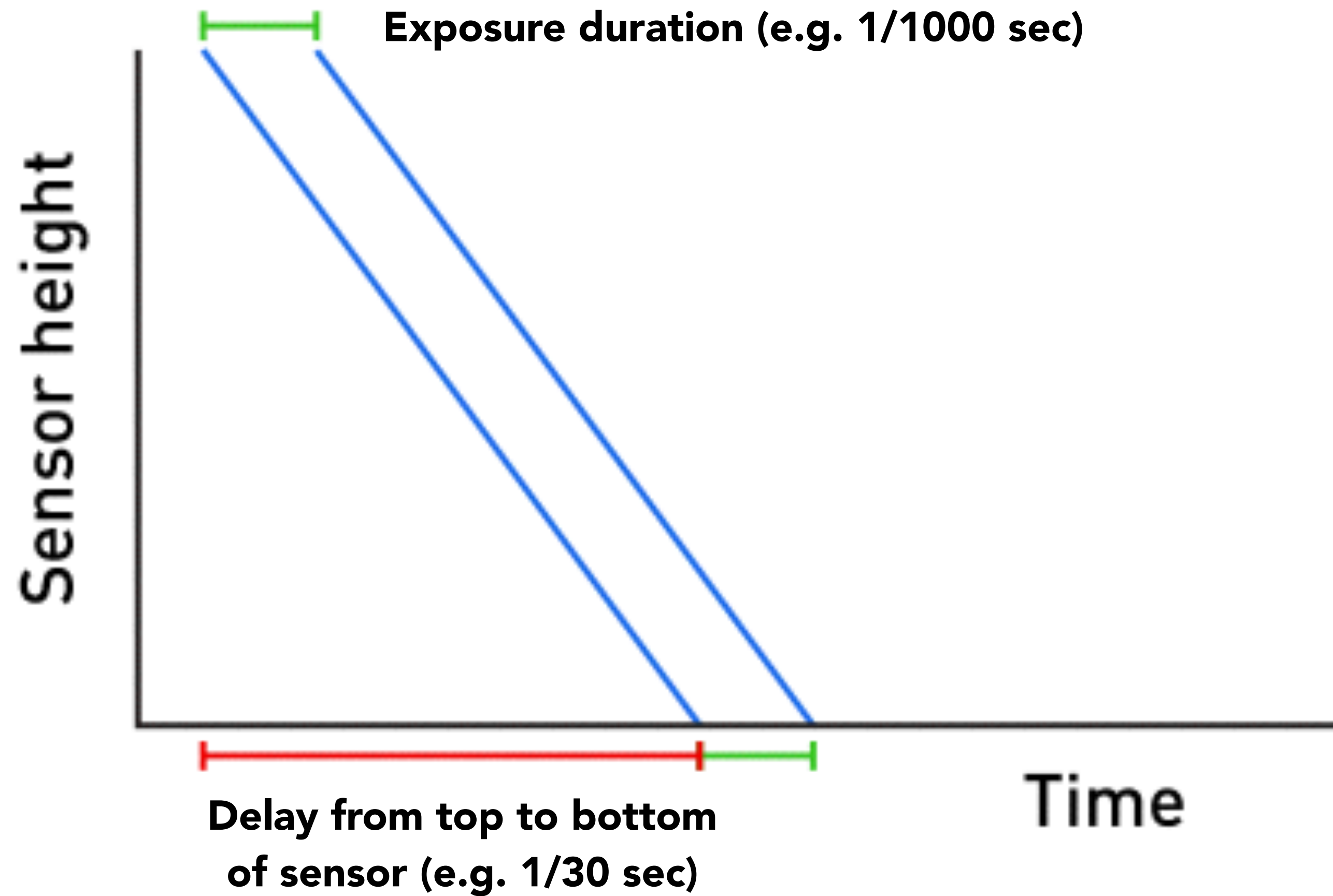
# Electronic Rolling Shutter



The Slow Mo Guys, <https://youtu.be/CmjeCchGRQo>

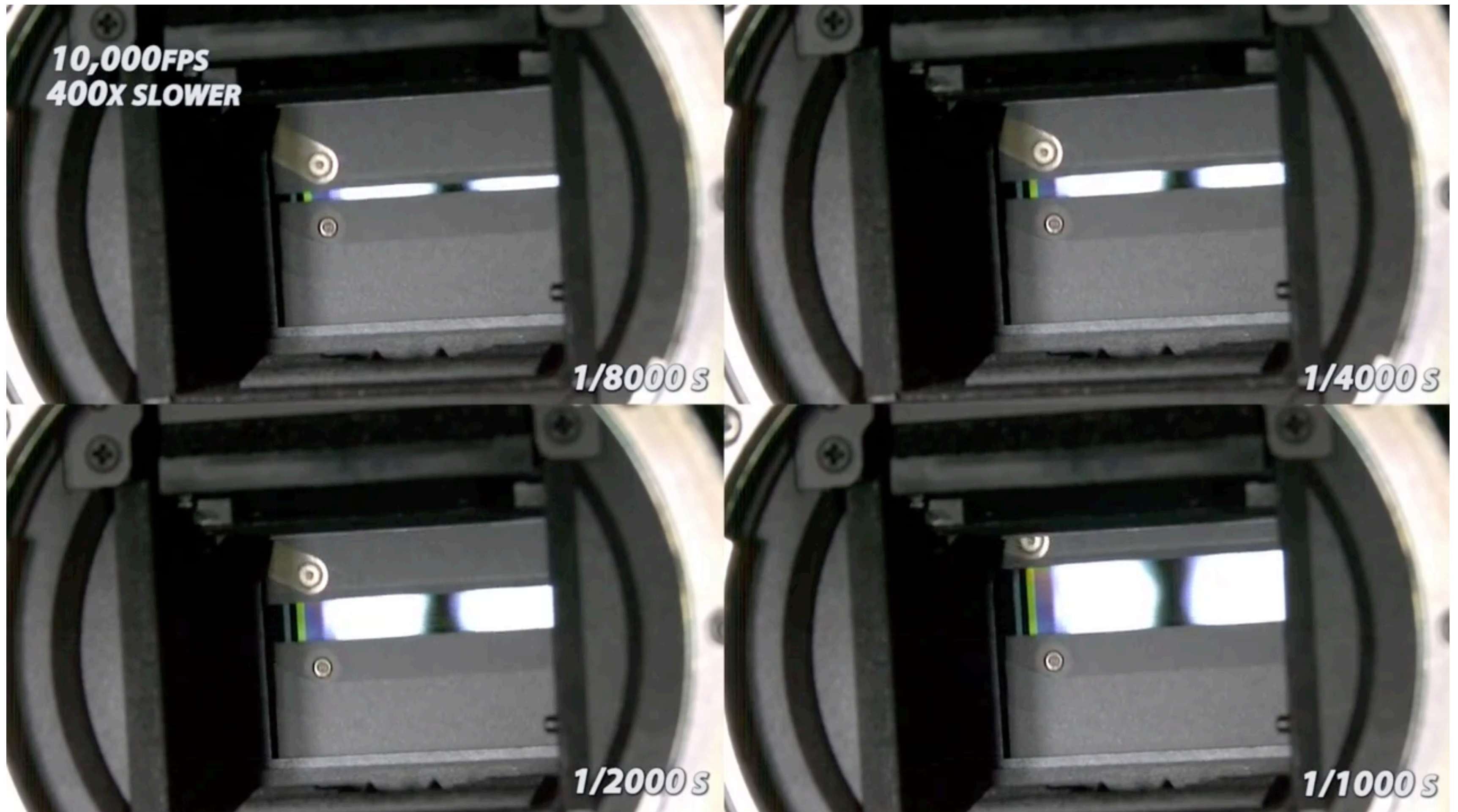


# Electronic Rolling Shutter





# Focal Plane Shutter (Fast Exposures)



The Slow Mo Guys, <https://youtu.be/CmjeCchGRQo>



# Lenses



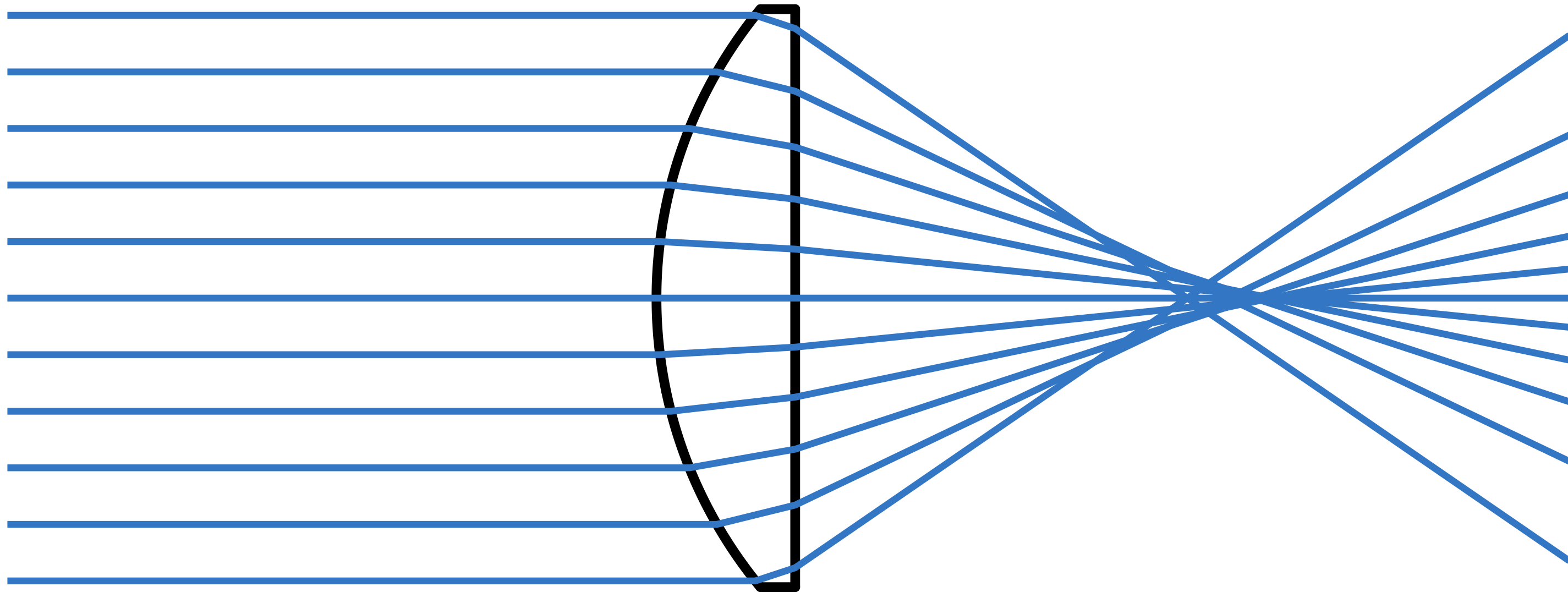
# Real Lens Designs Are Highly Complex



[Apple]



# Real Lens Elements Are Not Ideal – Aberrations



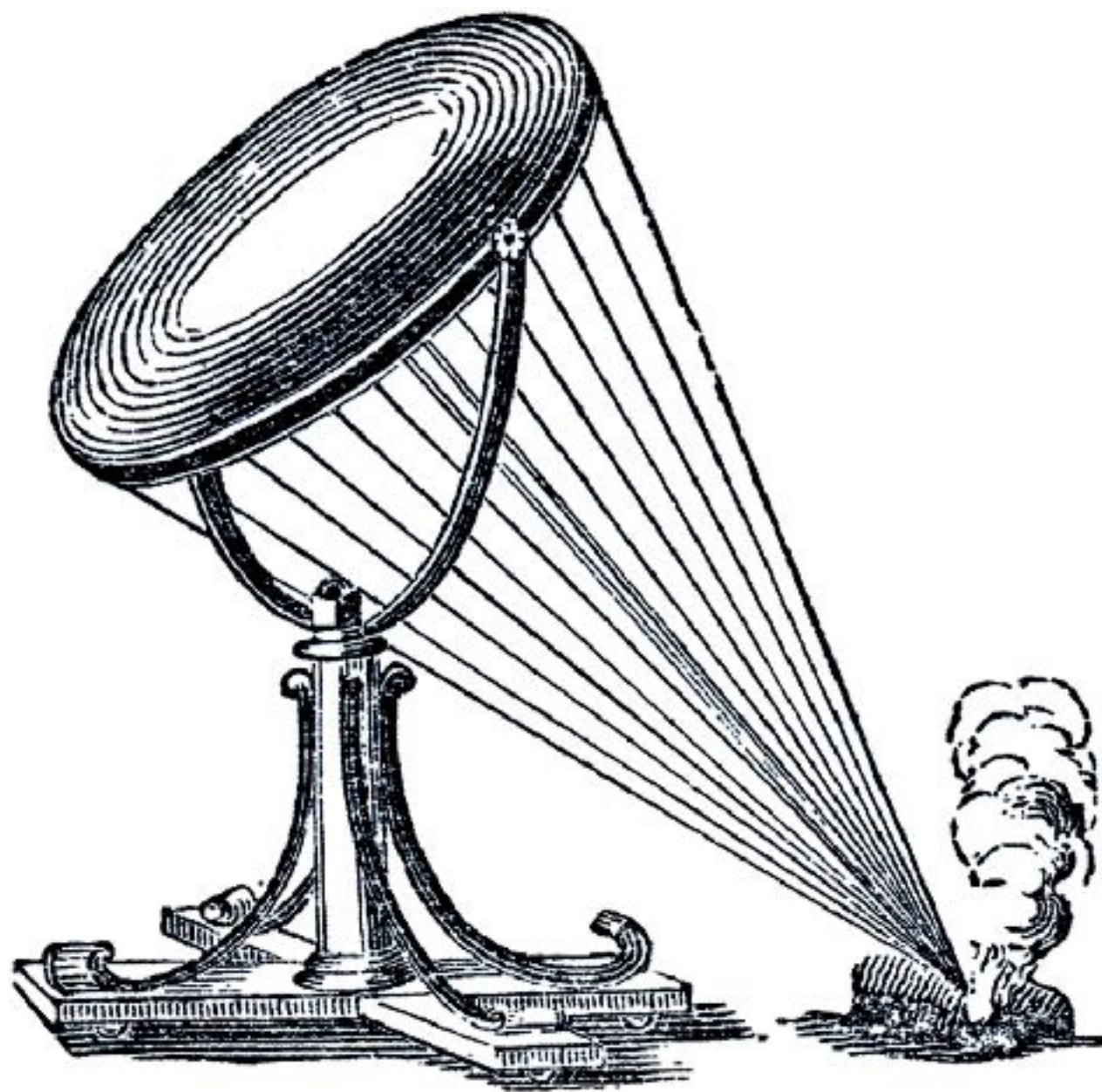
Real plano-convex lens (spherical surface shape).  
Lens does not converge rays to a point anywhere.



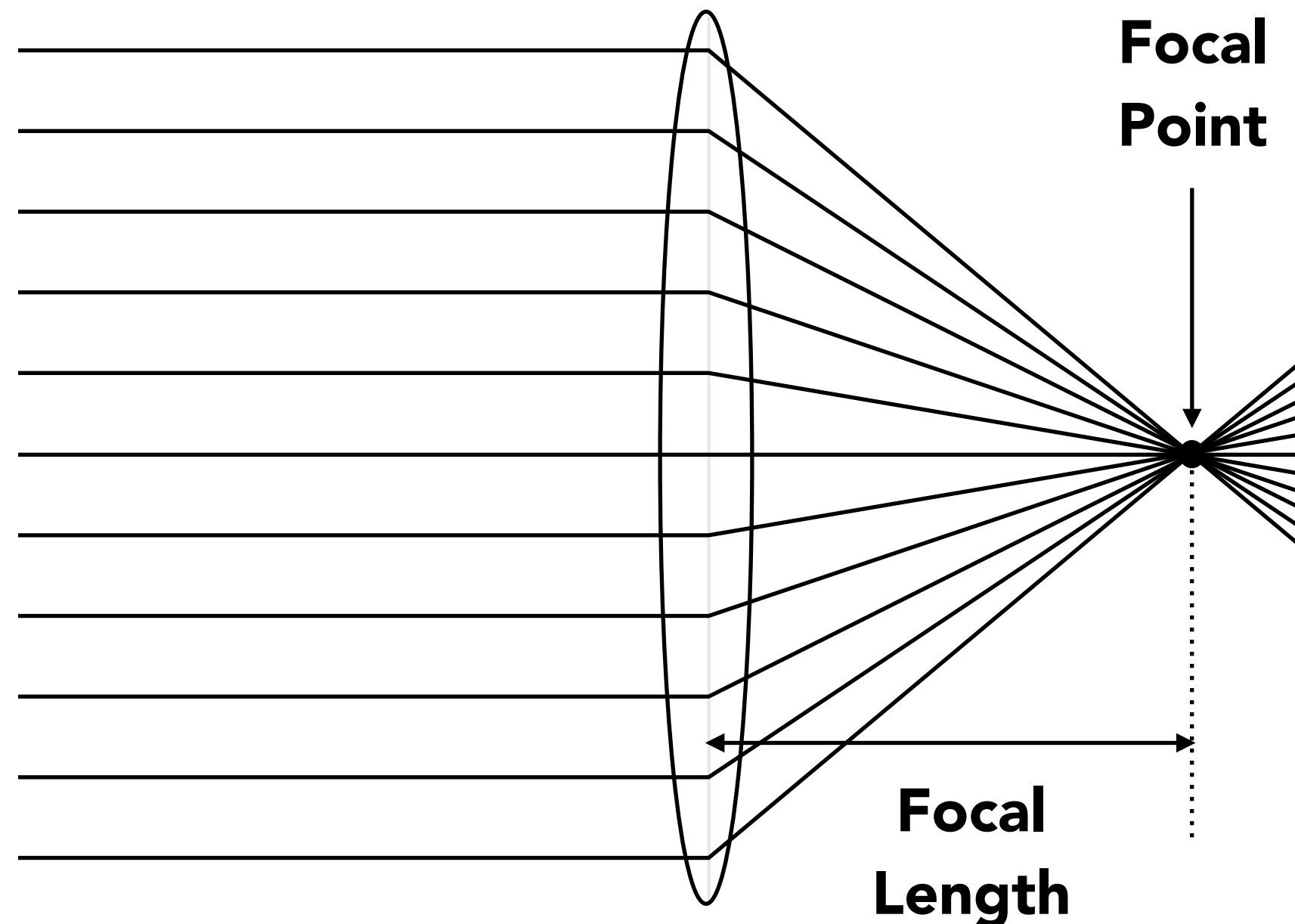
# **First: Thin Lens Approximation**



# Ideal Thin Lens – Focal Point



Credit: Karen Watson



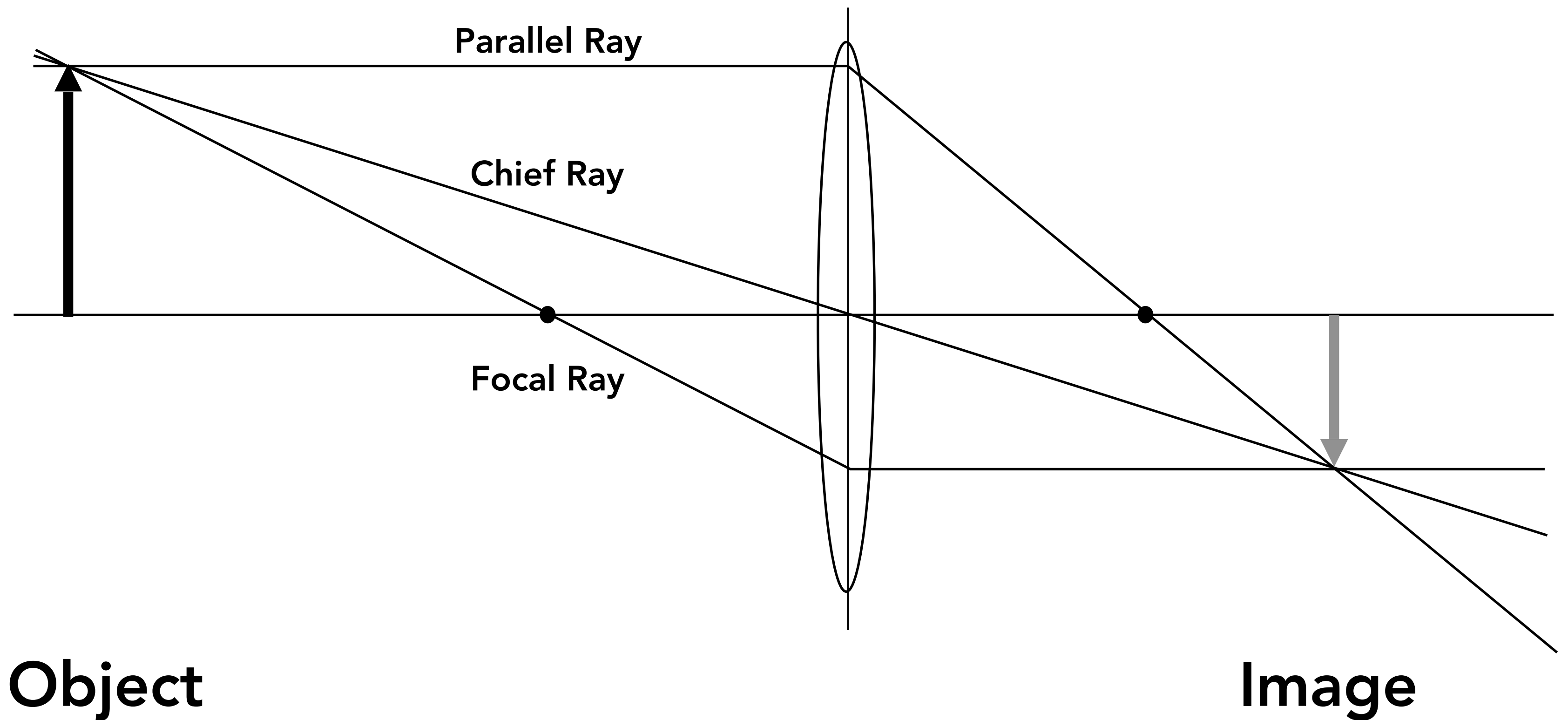
Assume all parallel rays entering a lens pass through its focal point.



# **Gauss' Ray Diagrams**

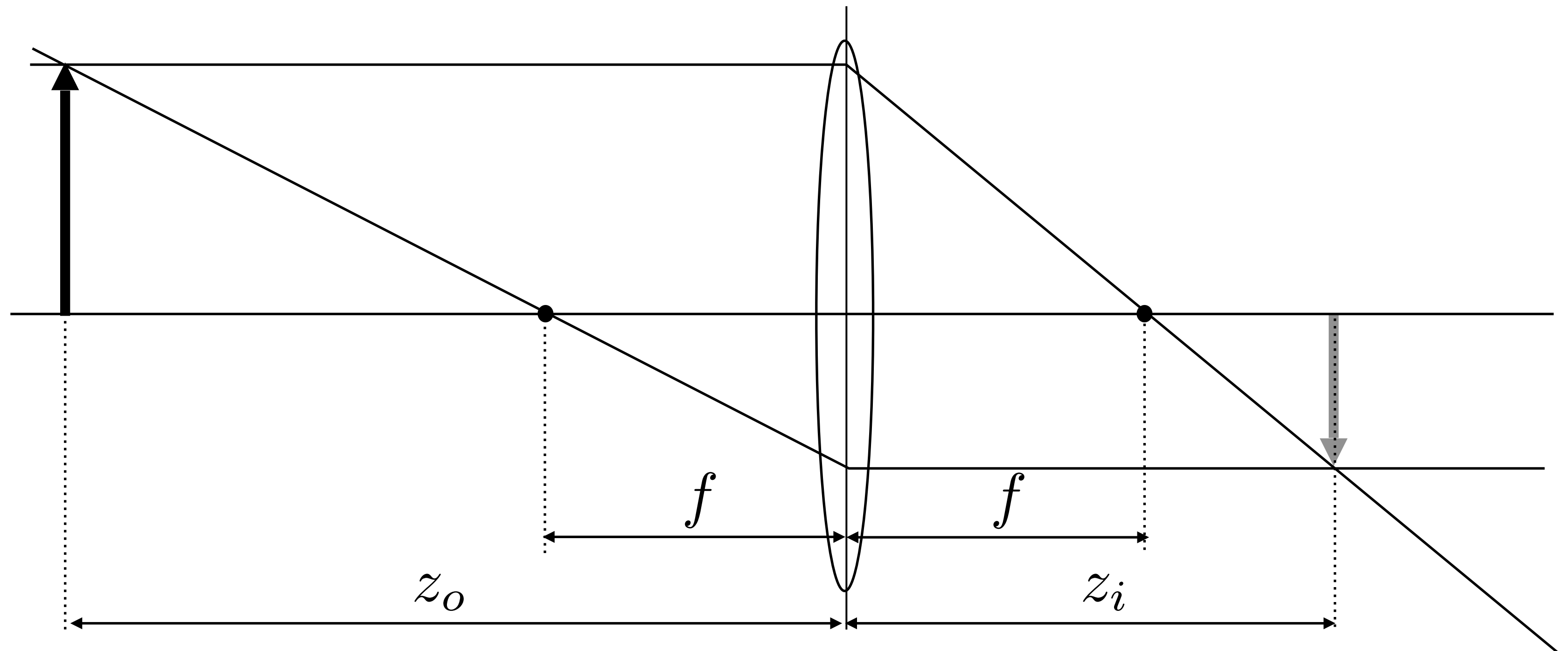


# Gauss' Ray Tracing Construction





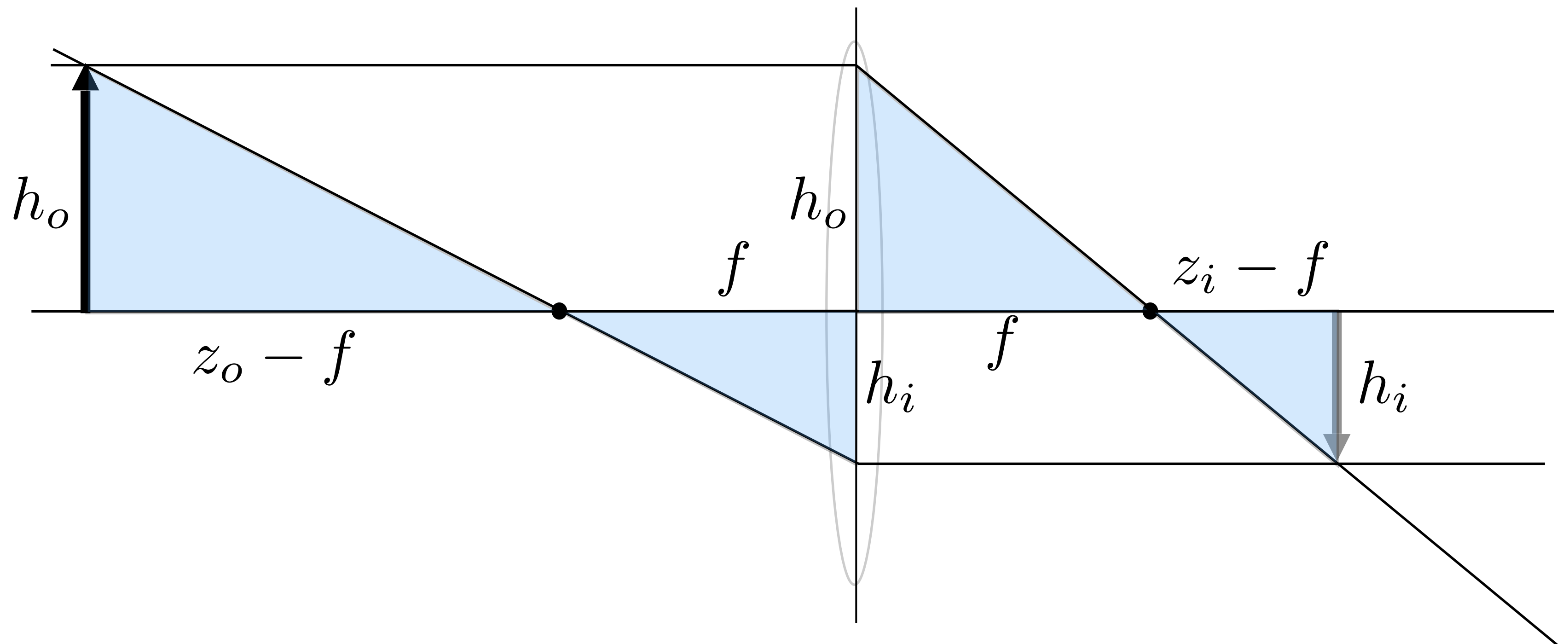
# Gauss' Ray Tracing Construction



What is the relationship between conjugate depths  $z_o, z_i$ ?



# Gauss' Ray Tracing Construction



$$\frac{h_o}{z_o - f} = \frac{h_i}{f}$$

$$\frac{h_o}{f} = \frac{h_i}{z_i - f}$$



# Gauss' Ray Tracing Construction

$$\frac{h_o}{z_o - f} = \frac{h_i}{f} \qquad \frac{h_o}{f} = \frac{h_i}{z_i - f}$$
$$\frac{h_o}{h_i} = \frac{z_o - f}{f} \qquad \frac{h_o}{h_i} = \frac{f}{z_i - f}$$

$$\frac{z_o - f}{f} = \frac{f}{z_i - f}$$

Object / image heights  
factor out - applies to all rays

$$(z_o - f)(z_i - f) = f^2$$

**Newtonian Thin Lens Equation**

$$z_o z_i - (z_o + z_i)f + f^2 = f^2$$

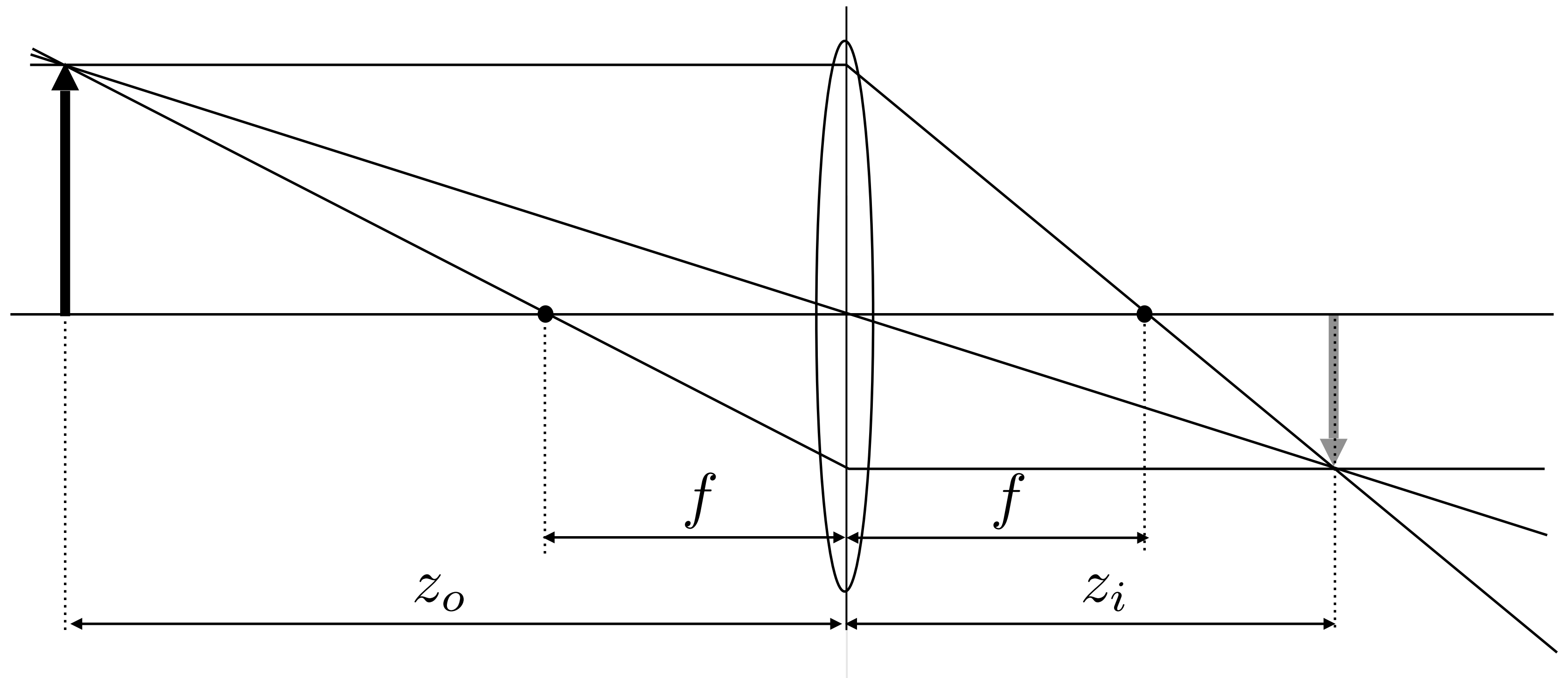
$$z_o z_i = (z_o + z_i)f$$

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

**Gaussian Thin Lens Equation**



# The Thin Lens Equation

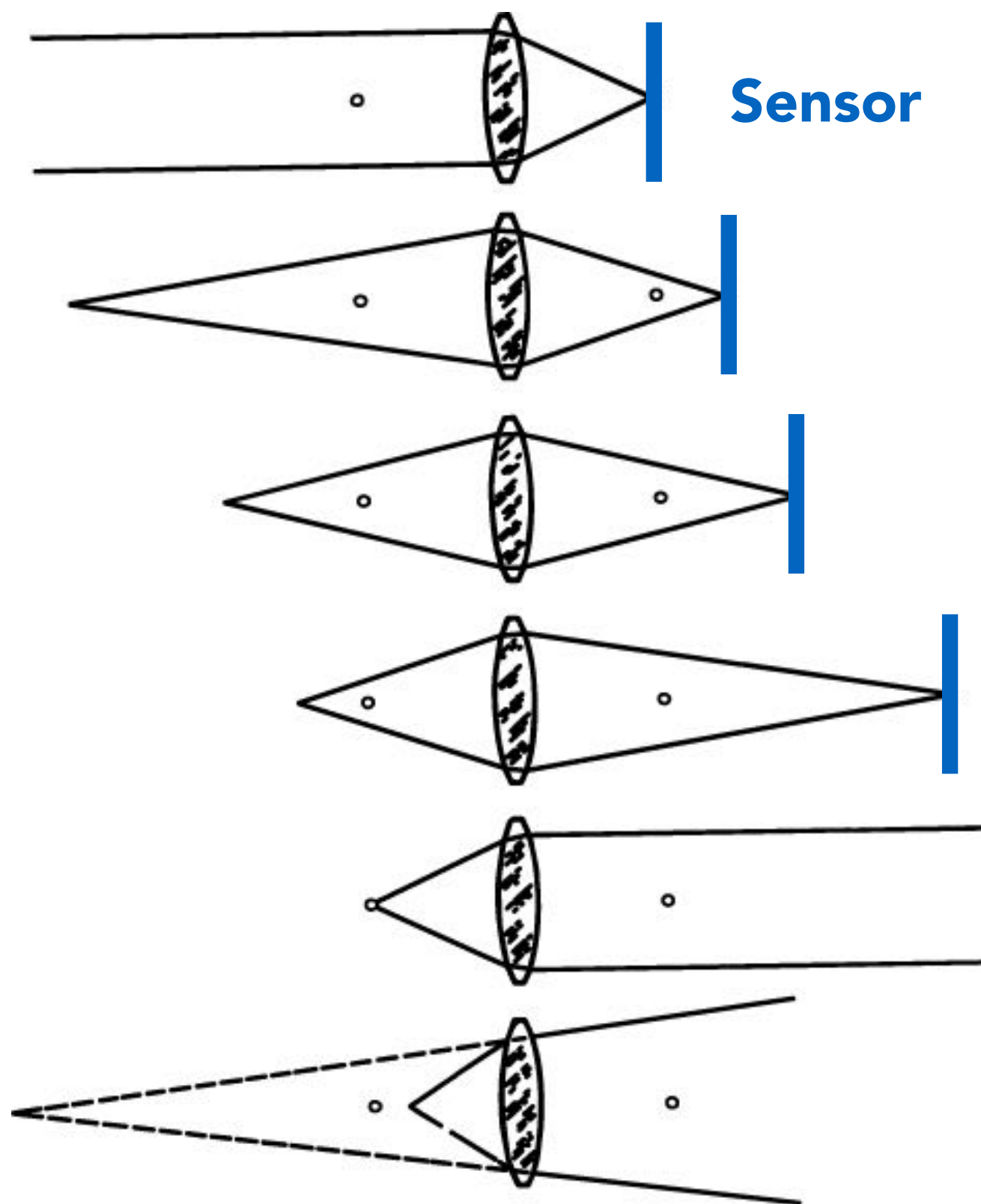


$$\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}$$



# Changing the Focus Distance

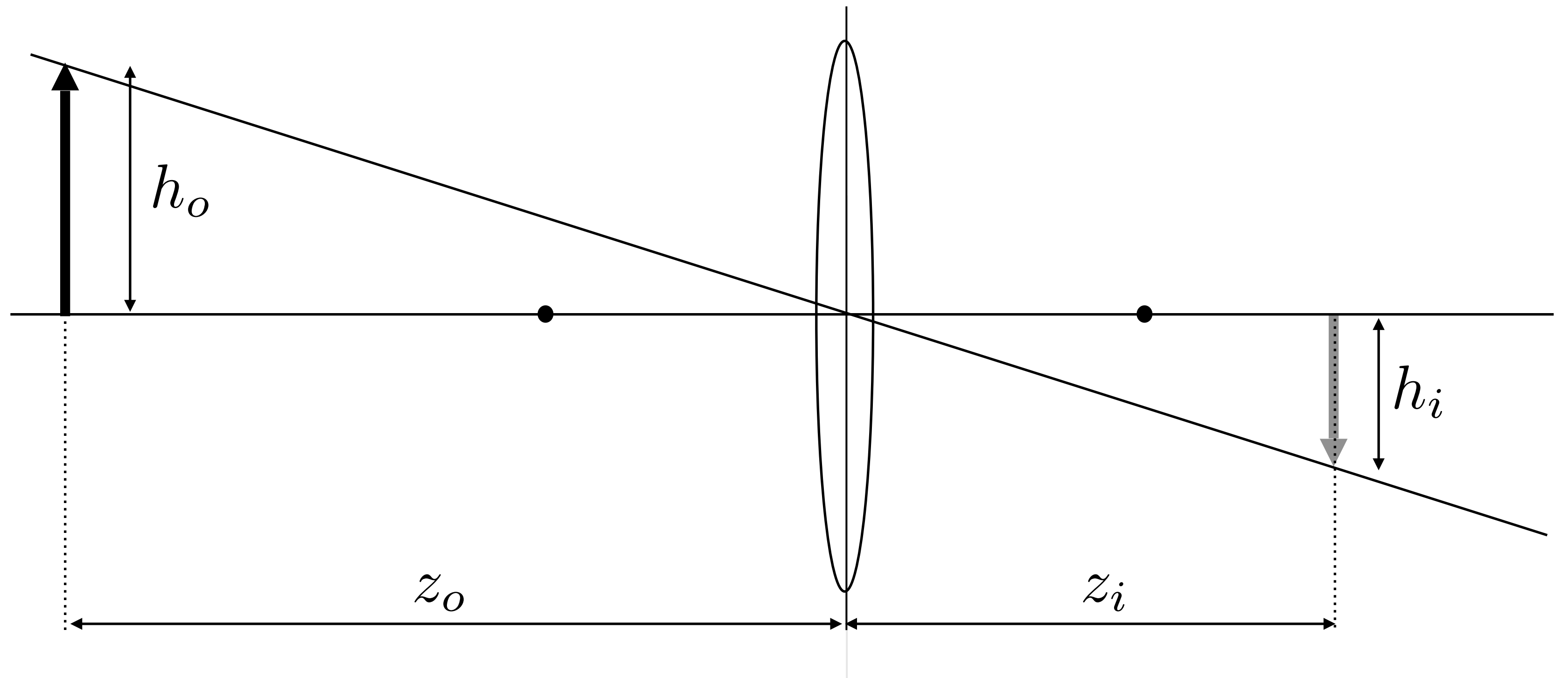
$$\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}$$



- $z_i$  and  $z_o$  are called conjugate points
- To focus on objects at different distances, move the sensor relative to the lens
- For  $z_i < z_o$  the object is larger than the image
- At  $z_i = z_o$  we have 1:1 macro imaging
- For  $z_i > z_o$  the image is larger than the object (magnified)
- Can't focus on objects closer than the lens' focal length



# Magnification



$$m = \frac{h_i}{h_o} = \frac{z_i}{z_o}$$

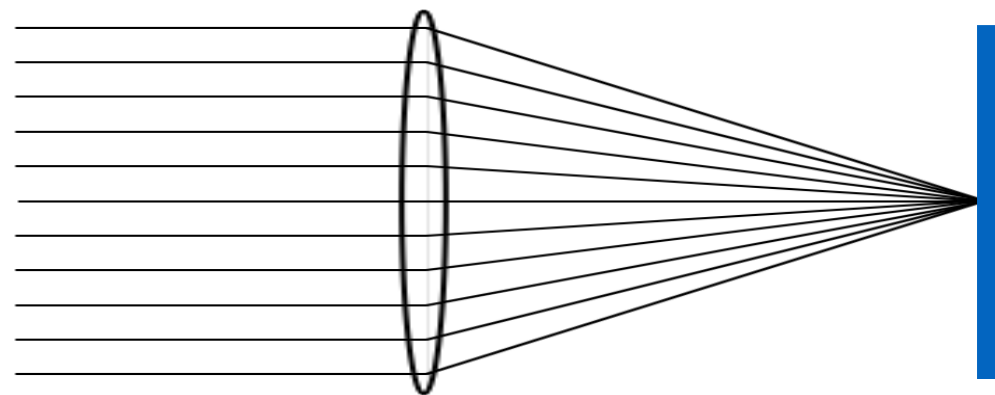


# Magnification Example – Focus at Infinity

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

If focused on a distant mountain

- $z_o \approx \infty$ , so  $z_i = f$
- sensor at focal point
- magnification  $\approx 0$

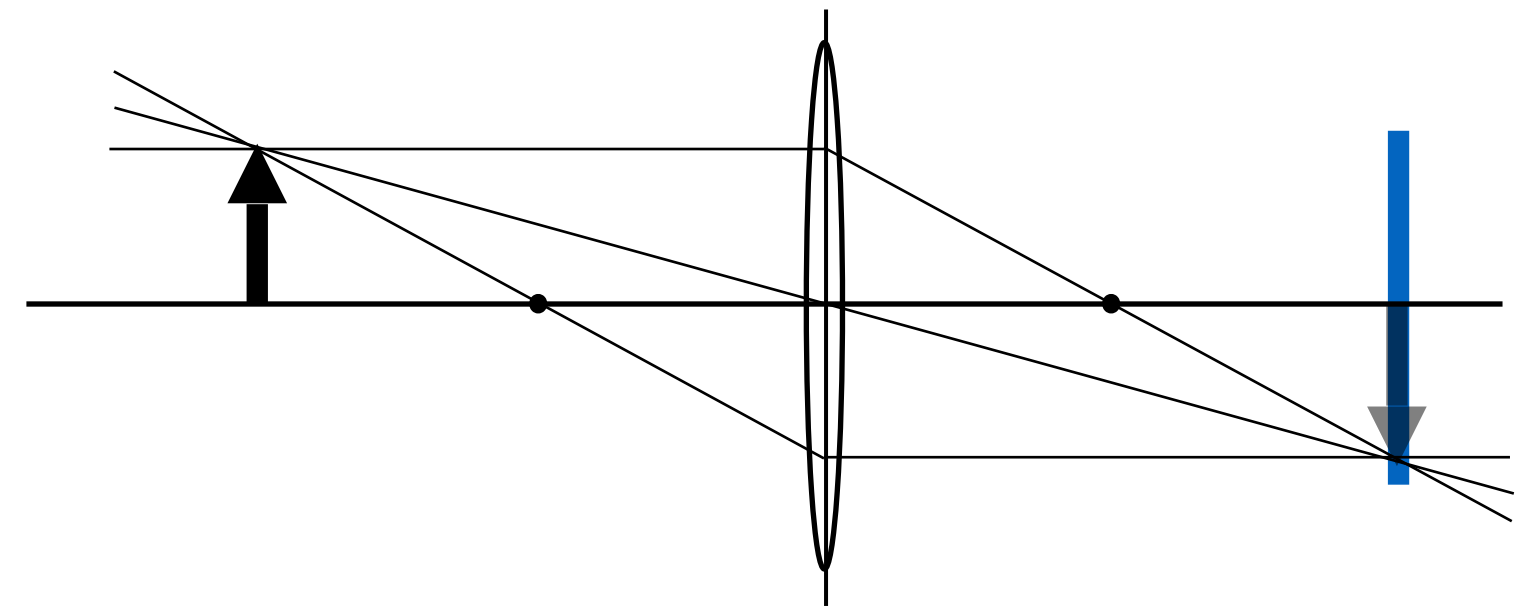




# Magnification Example – Focus at 1:1 Macro



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

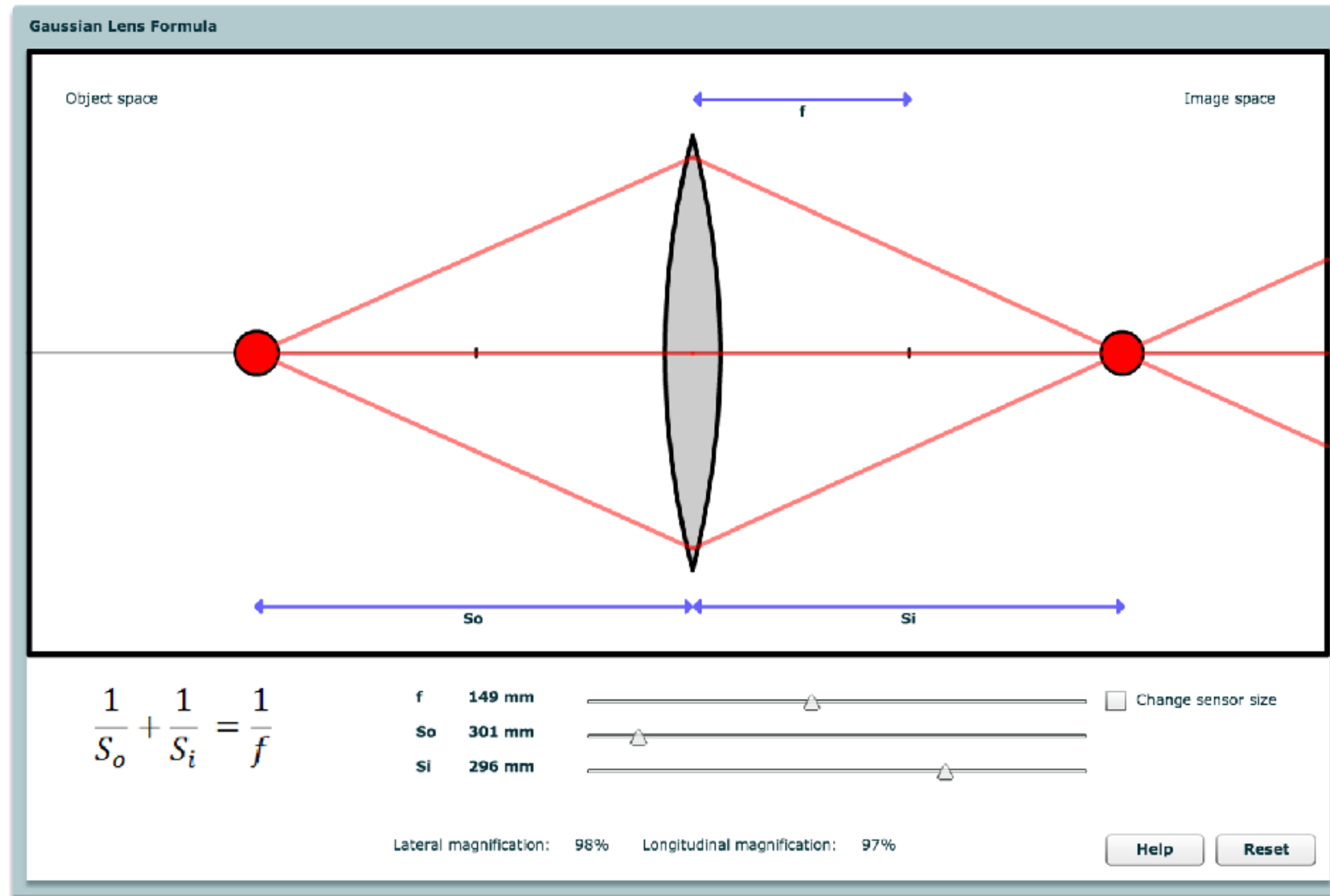


What configuration do we need to achieve a magnification of 1 (i.e. image and object the same size, a.k.a. 1:1 macro)?

- Need  $z_i = z_o$ , so  $z_i = z_o = 2f$  — sensor at twice focal length
- In 1:1 imaging, if the sensor is 36 mm wide, an object 36 mm wide will fill the frame



# Thin Lens Demonstration



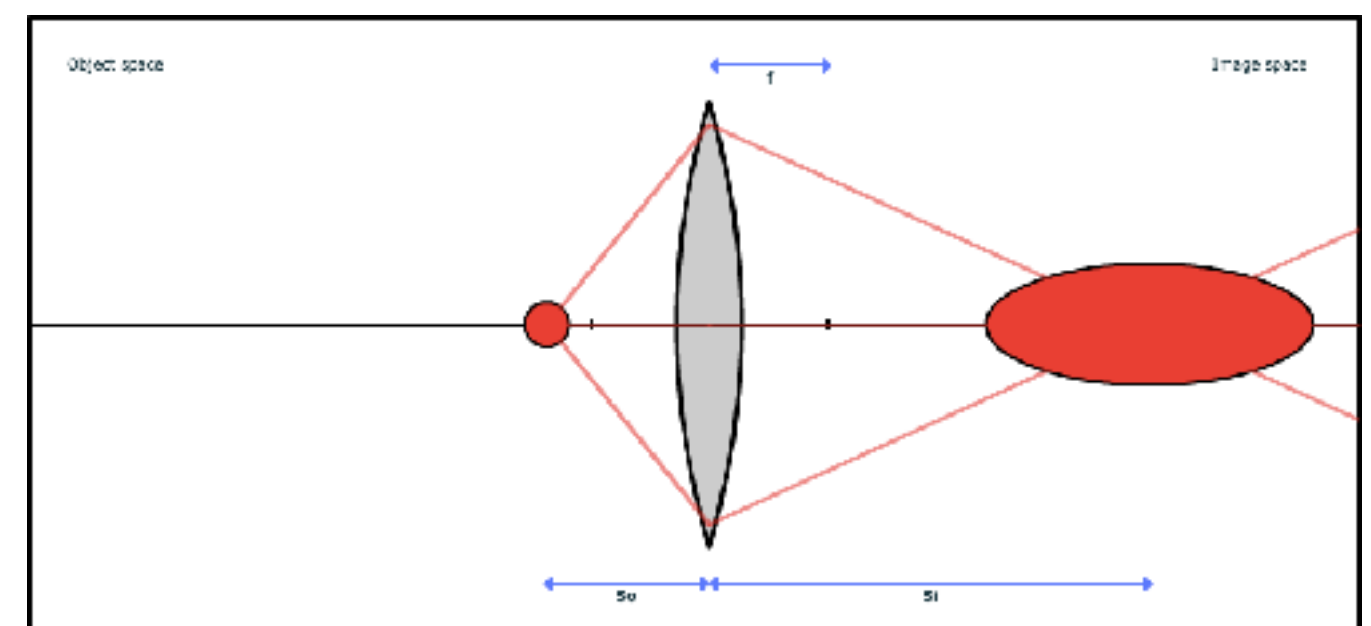
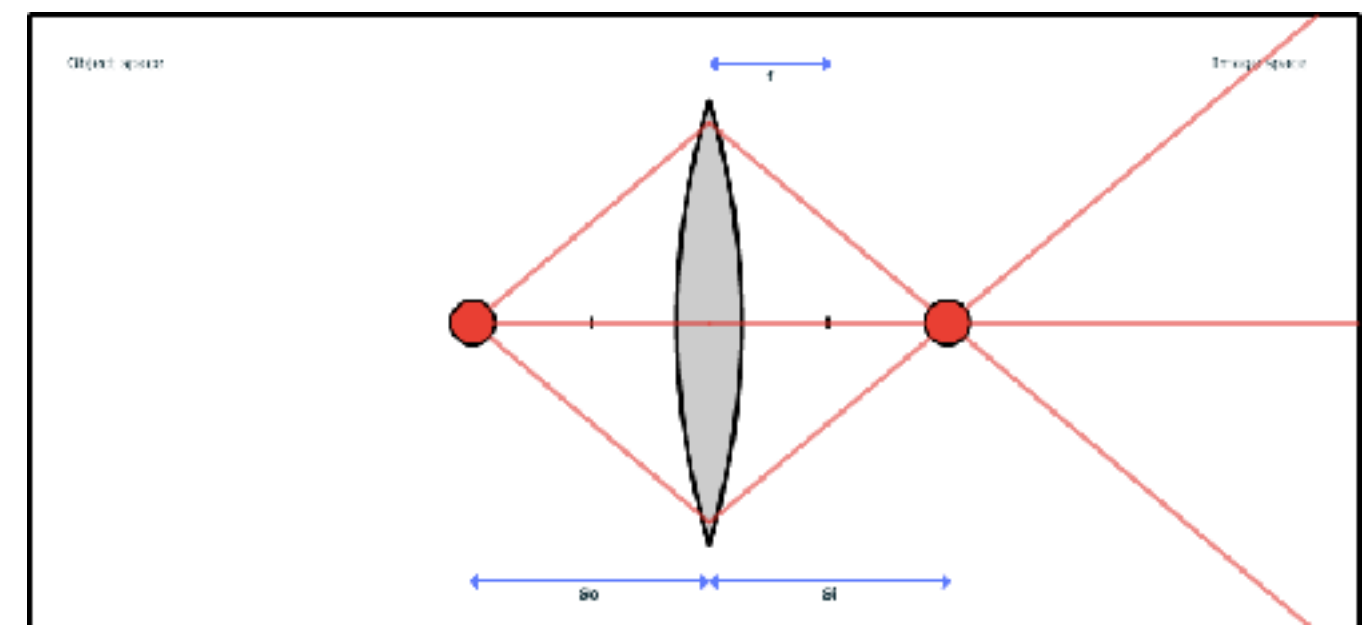
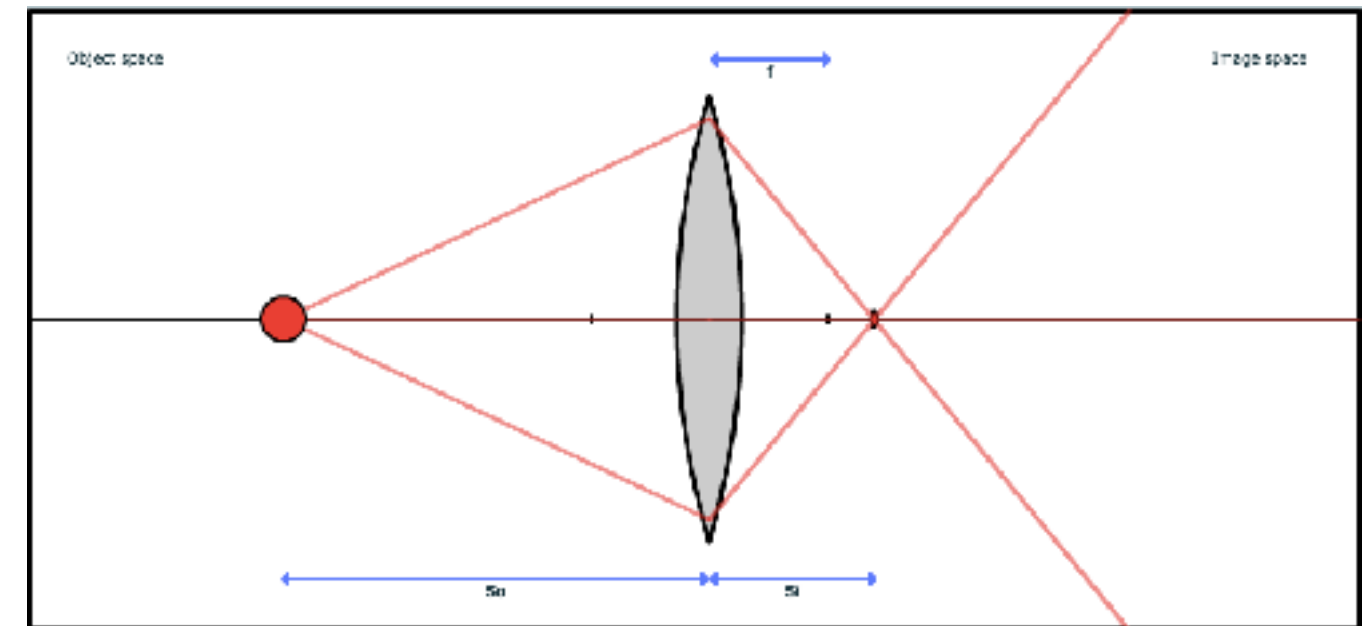
<http://graphics.stanford.edu/courses/cs178-10/applets/gaussian.html>



# Thin Lens Demonstration Observations

3D image of object is:

- Compressed in depth for low magnification
- 1:1 in 3D for unit magnification
- Stretched in depth for high magnification





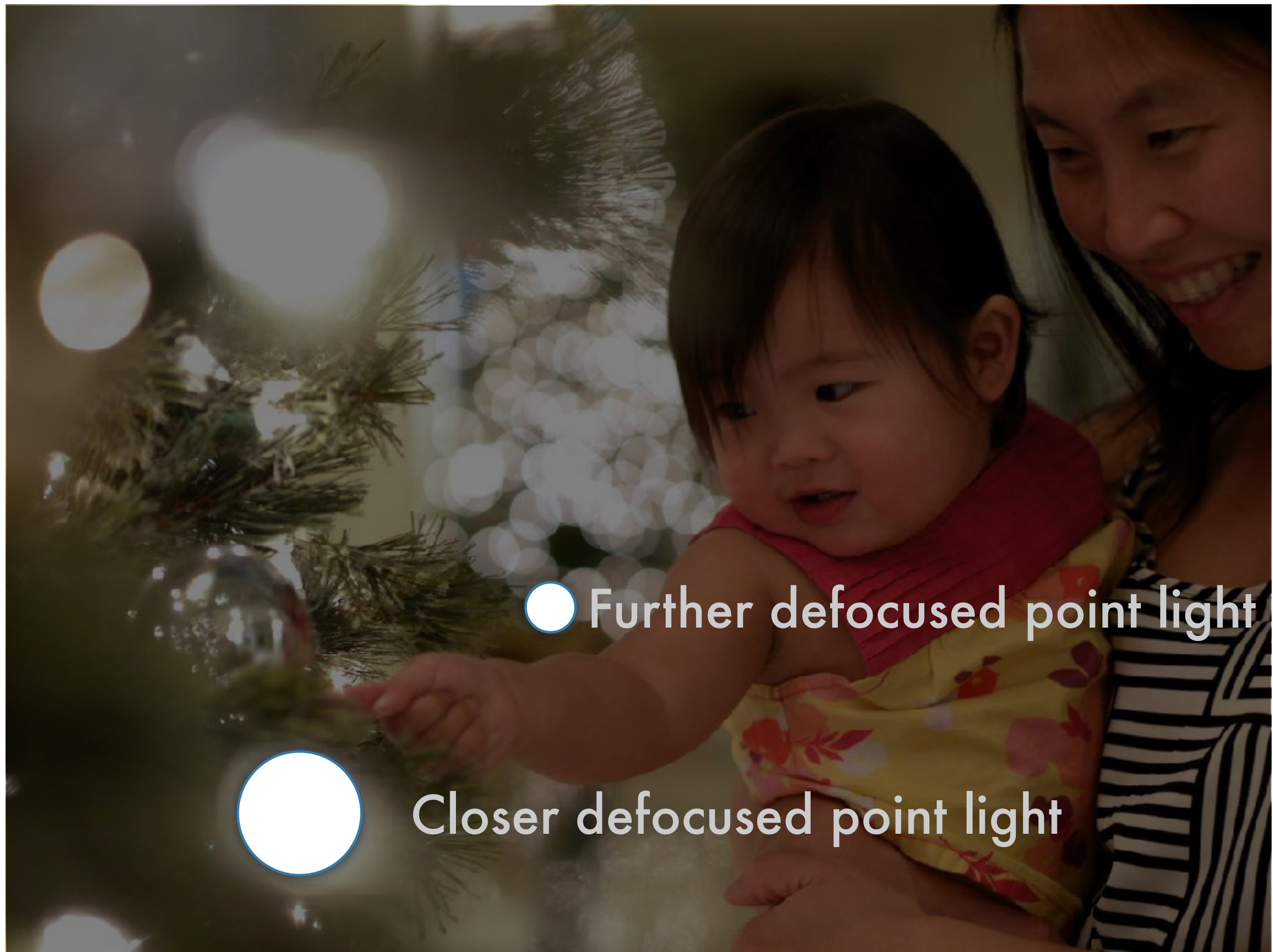
**Defocus Blur**

# Circle of Confusion





# Circle of Confusion





# Circle of Confusion

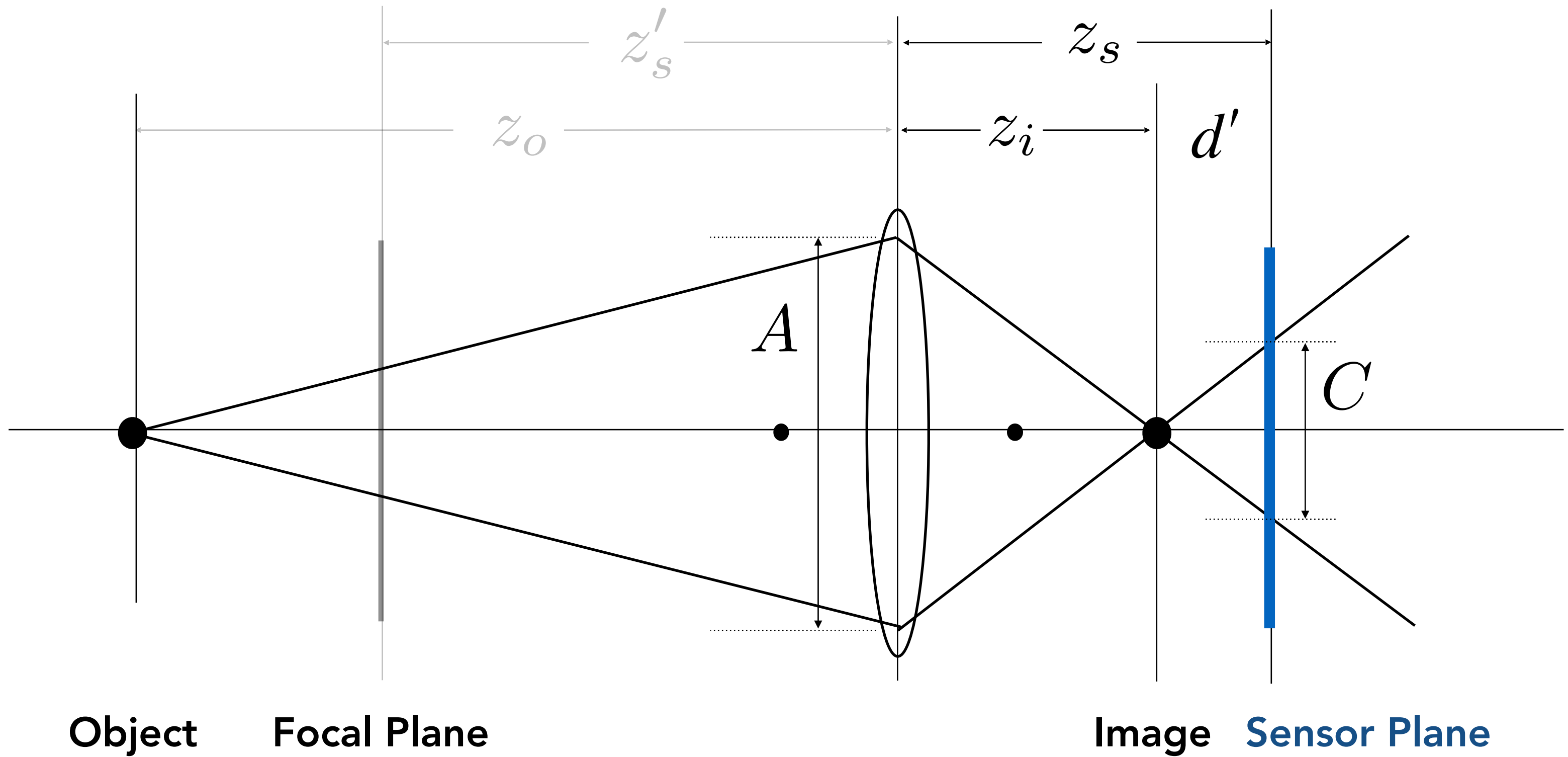




# Circle of Confusion



# Computing Circle of Confusion Diameter (C)



# Circle of confusion is proportional to the size of the aperture

$$\frac{C}{A} = \frac{d'}{z_i} = \frac{|z_s - z_i|}{z_i}$$



# Circle of Confusion – Example

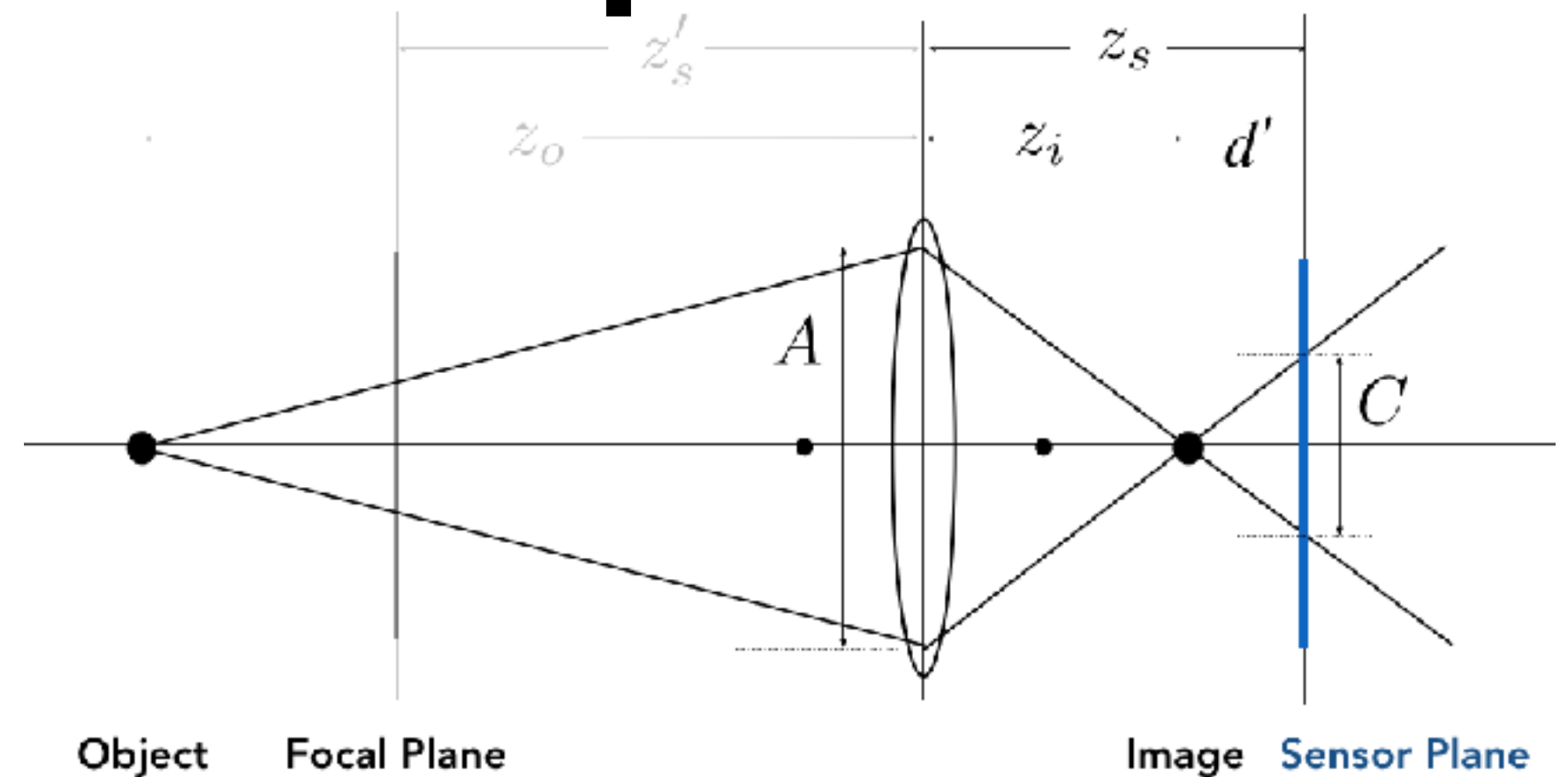
50mm f/2 lens

Full frame sensor (36x24mm)

Focus: 1 meter

Background: 10 meter

Foreground: 0.3 meter



$$A = 50\text{mm}/2 = 25\text{mm}$$

$$z_s = \frac{1}{1/50 - 1/1000} \approx 52.63\text{mm}$$

$$\text{Background: } z_i = \frac{1}{1/50 - 1/10,000} \approx 50.25\text{mm}$$

$$C = A|z_s - z_i|/z_i = 1.18\text{mm} \quad \sim 65 \text{ pixels on HD TV}$$

$$\text{Foreground: } z_i = \frac{1}{1/50 - 1/300} \approx 55.56\text{mm}$$

$$C = A|z_s - z_i|/z_i = 3.07\text{mm} \quad \sim 169 \text{ pixels on HD TV}$$



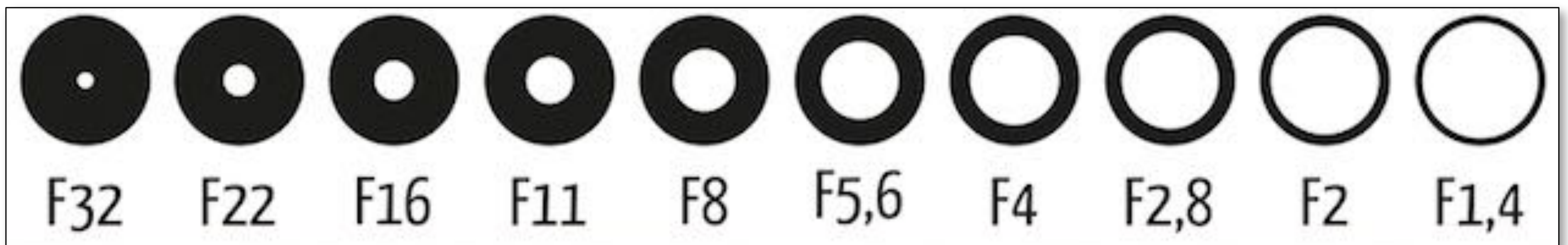
# Lens's F-Number vs F-Number for Photo

A lens's F-Number is the maximum for that lens

- E.g. 50 mm F/1.4 is a high-quality telephoto lens
  - Maximum aperture is  $50/1.4 = 36$  mm diameter

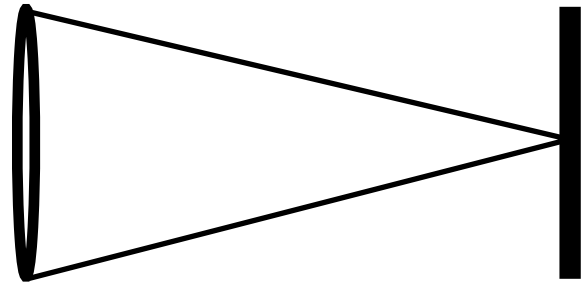
But for an individual photo, the lens aperture may be "stopped down" to a smaller size

- E.g. 50 mm F/1.4 lens stopped down to F/4
  - Aperture is closed down with an iris to  $50/4 = 12.5$  mm





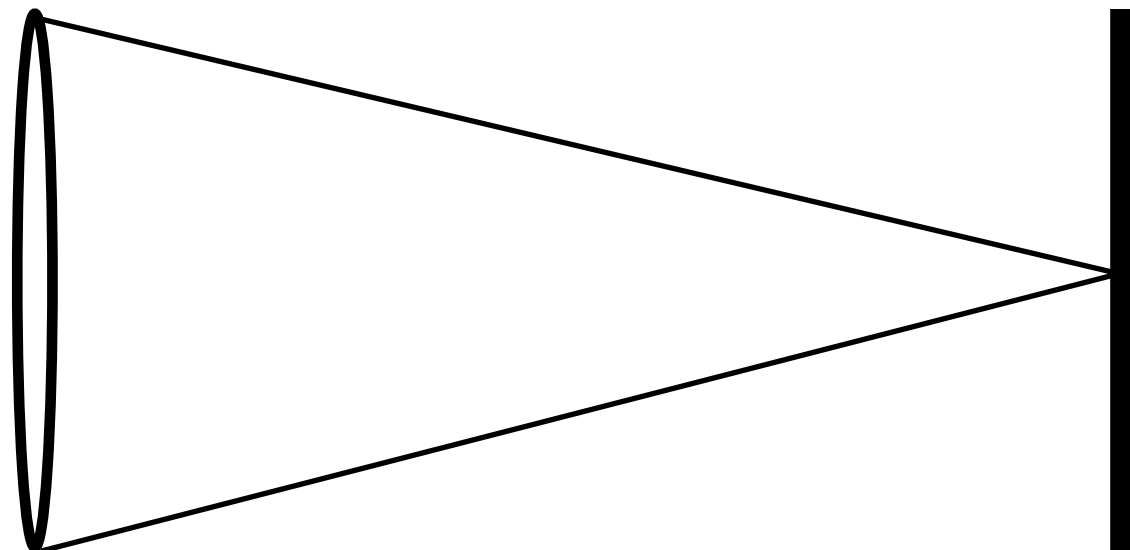
# Example F-Number Calculations



$$D = 50 \text{ mm}$$

$$f = 100 \text{ mm}$$

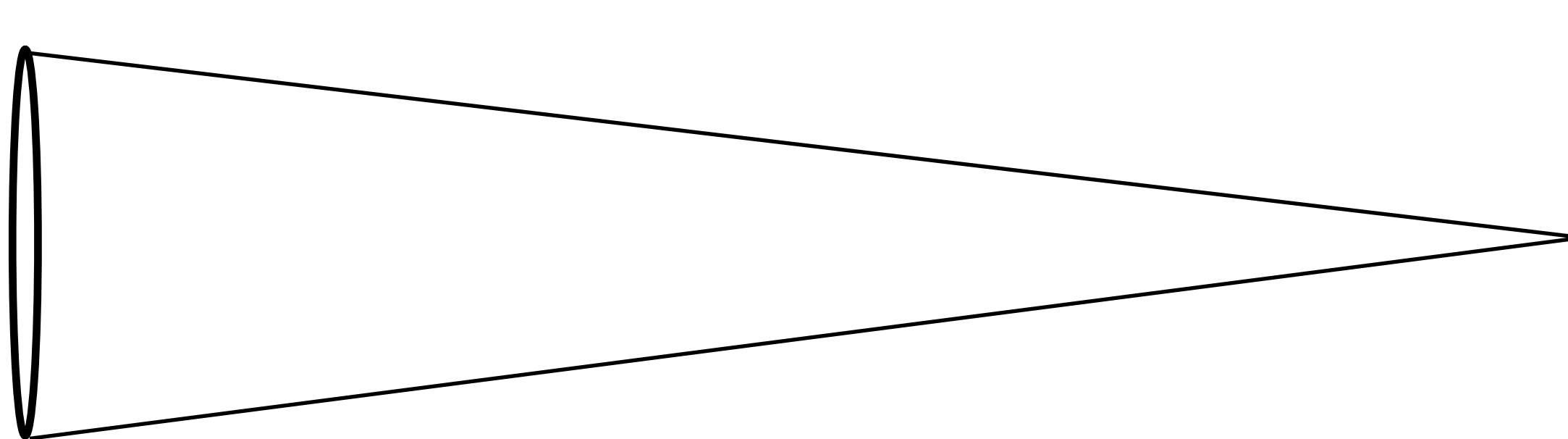
$$N = f/D = 2$$



$$D = 100 \text{ mm}$$

$$f = 200 \text{ mm}$$

$$N = f/D = 2$$



$$D = 100 \text{ mm}$$

$$f = 400 \text{ mm}$$

$$N = f/D = 4$$

# Size of Circle of Confusion is Inversely Proportional to F-Number for Photo



R. Berdan, [canadiannaturephotographer.com](http://canadiannaturephotographer.com)

$$C = A \frac{|z_s - z_i|}{z_i} = \frac{f}{N} \frac{|z_s - z_i|}{z_i}$$



# **Exposure Tradeoffs**

## **Depth of Field vs Motion Blur**

# Constant Exposure: Depth of Field vs Motion Blur



**f / 4**  
**1/125 sec**



**f / 11**  
**1/15 sec**

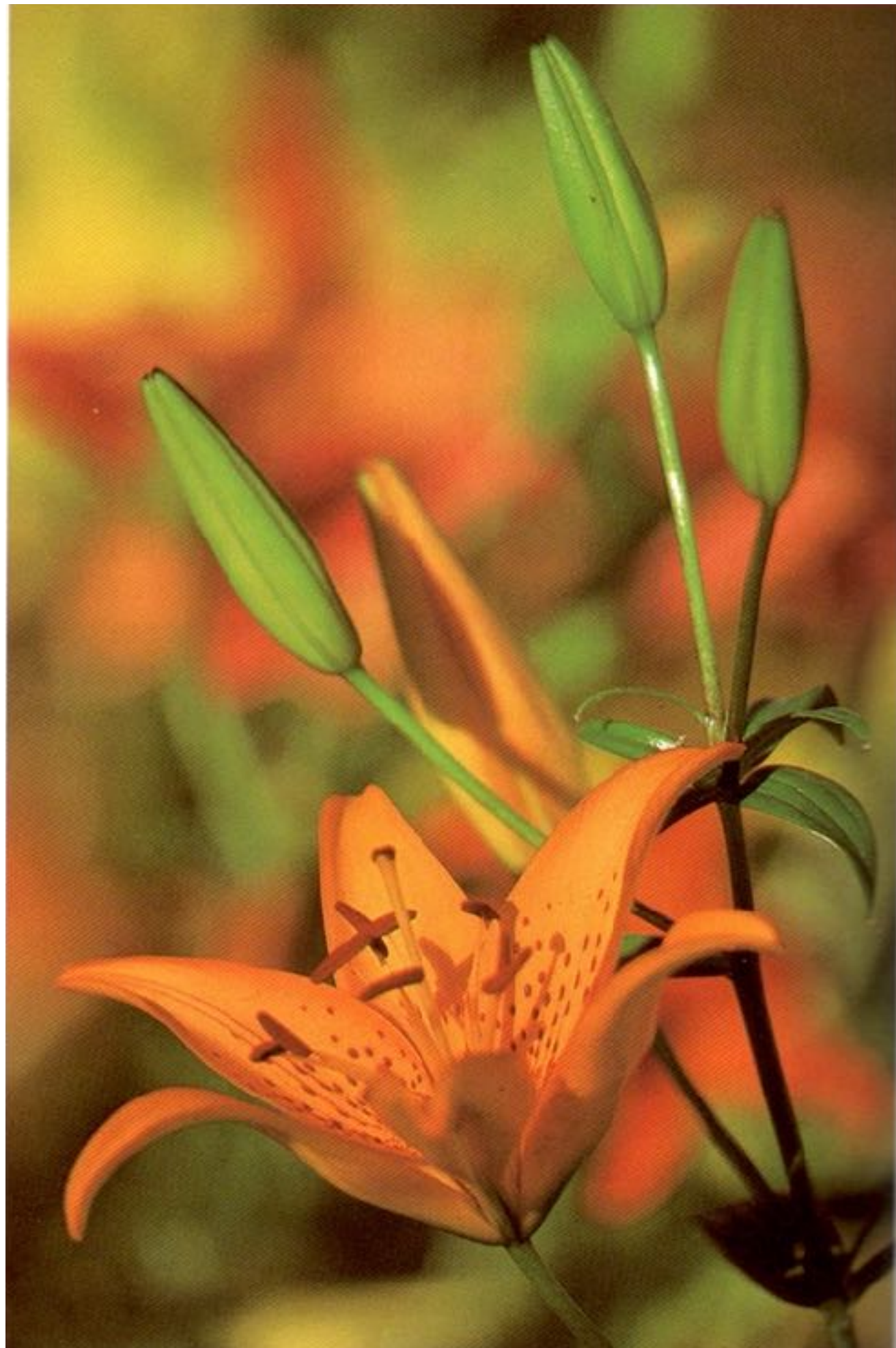


**f / 32**  
**1/2 sec**

- 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



# Depth of Field

# Depth of Field

Large aperture opening



Small aperture opening

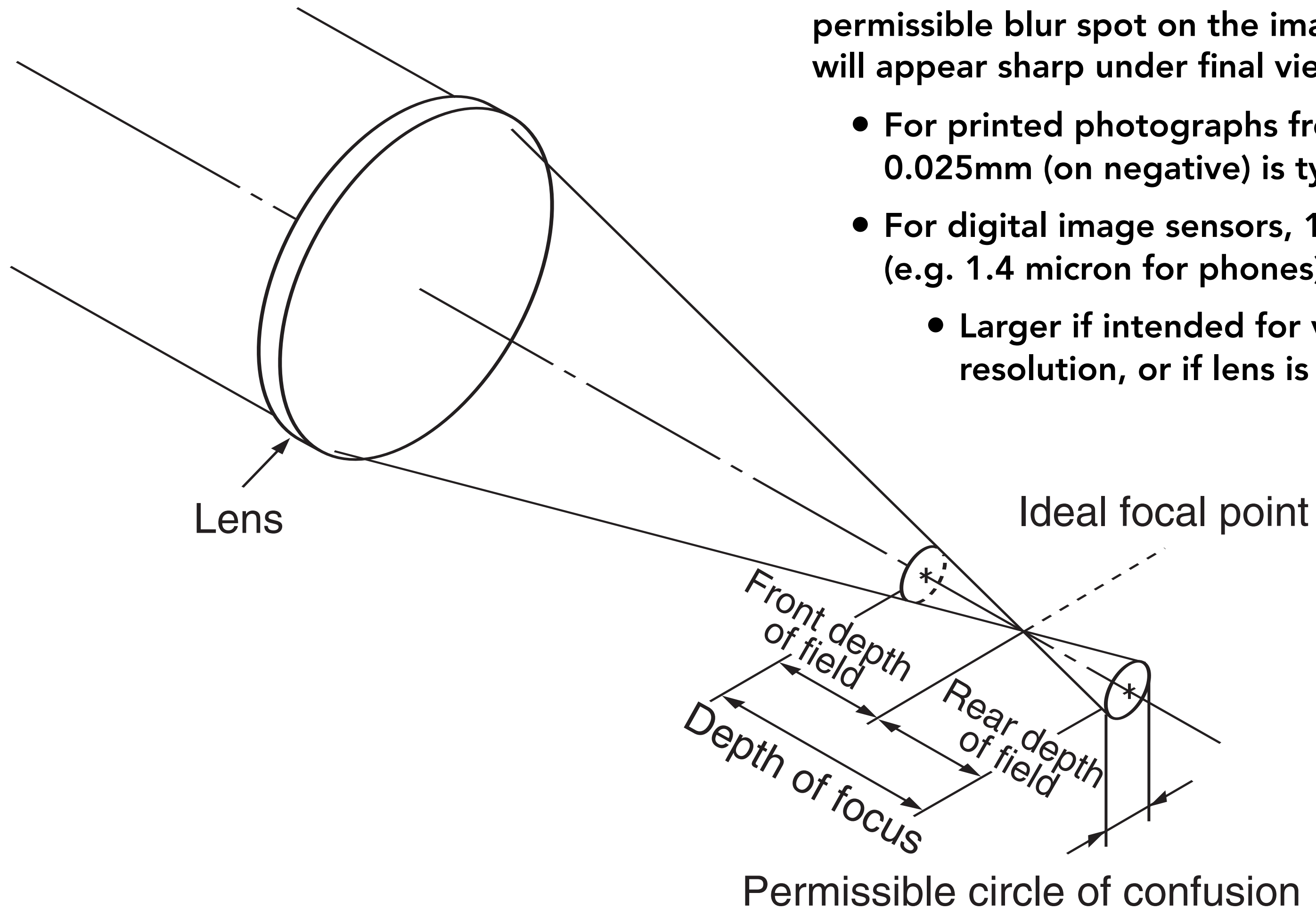


From London and Upton

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



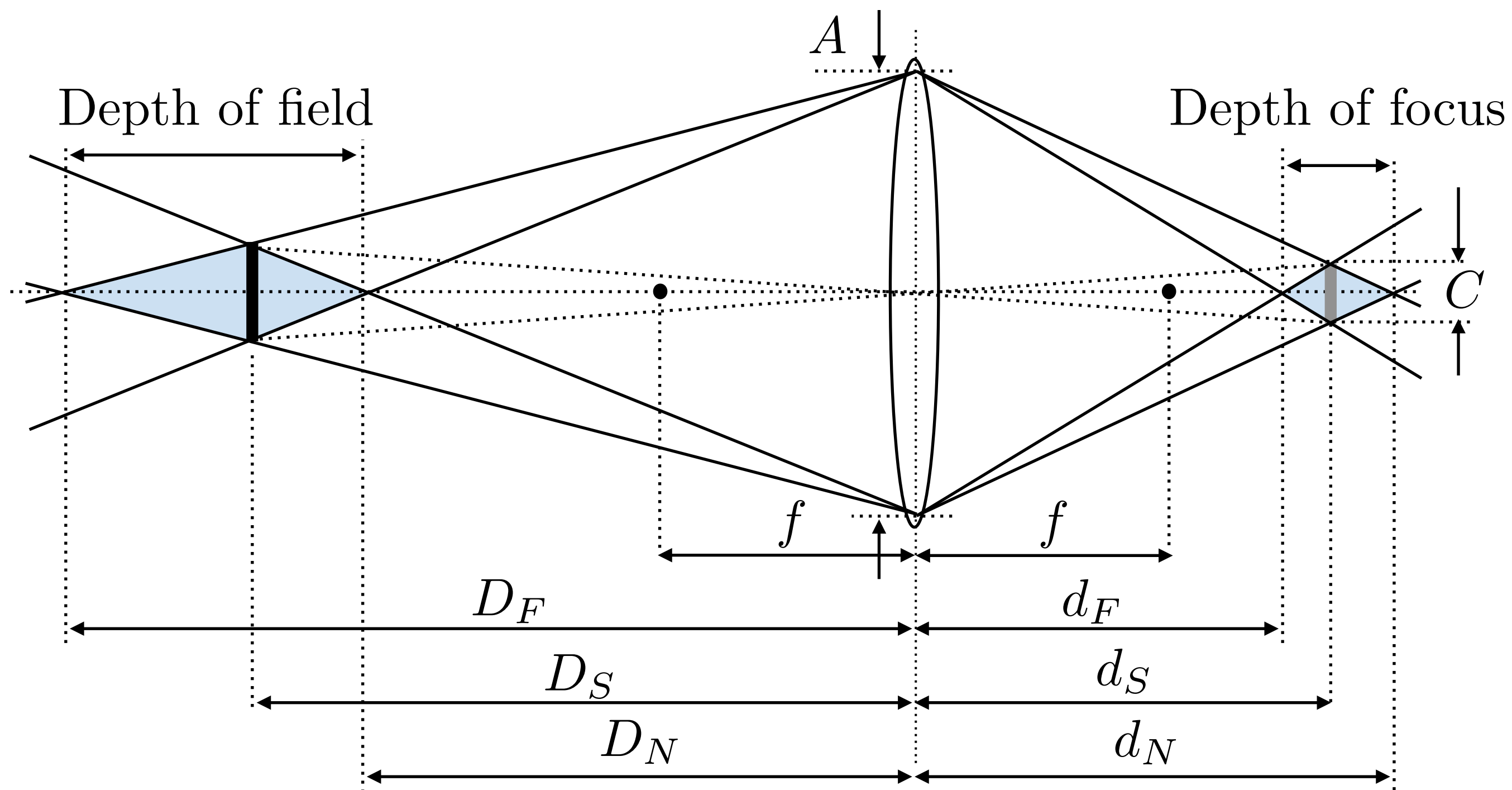
# Circle of Confusion for Depth of Field



Set circle of confusion as the maximum permissible blur spot on the image plane that will appear sharp under final viewing conditions

- For printed photographs from 35mm film, 0.025mm (on negative) is typical
- For digital image sensors, 1 pixel is typical (e.g. 1.4 micron for phones)
  - Larger if intended for viewing at web resolution, or if lens is poor

# Depth of Field



$$\frac{d_N - d_S}{d_N} = \frac{C}{A}$$

$$\frac{d_S - d_F}{d_F} = \frac{C}{A}$$

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

$$\frac{1}{D_F} + \frac{1}{d_F} = \frac{1}{f}$$

$$\frac{1}{D_S} + \frac{1}{d_S} = \frac{1}{f}$$

$$\frac{1}{D_N} + \frac{1}{d_N} = \frac{1}{f}$$

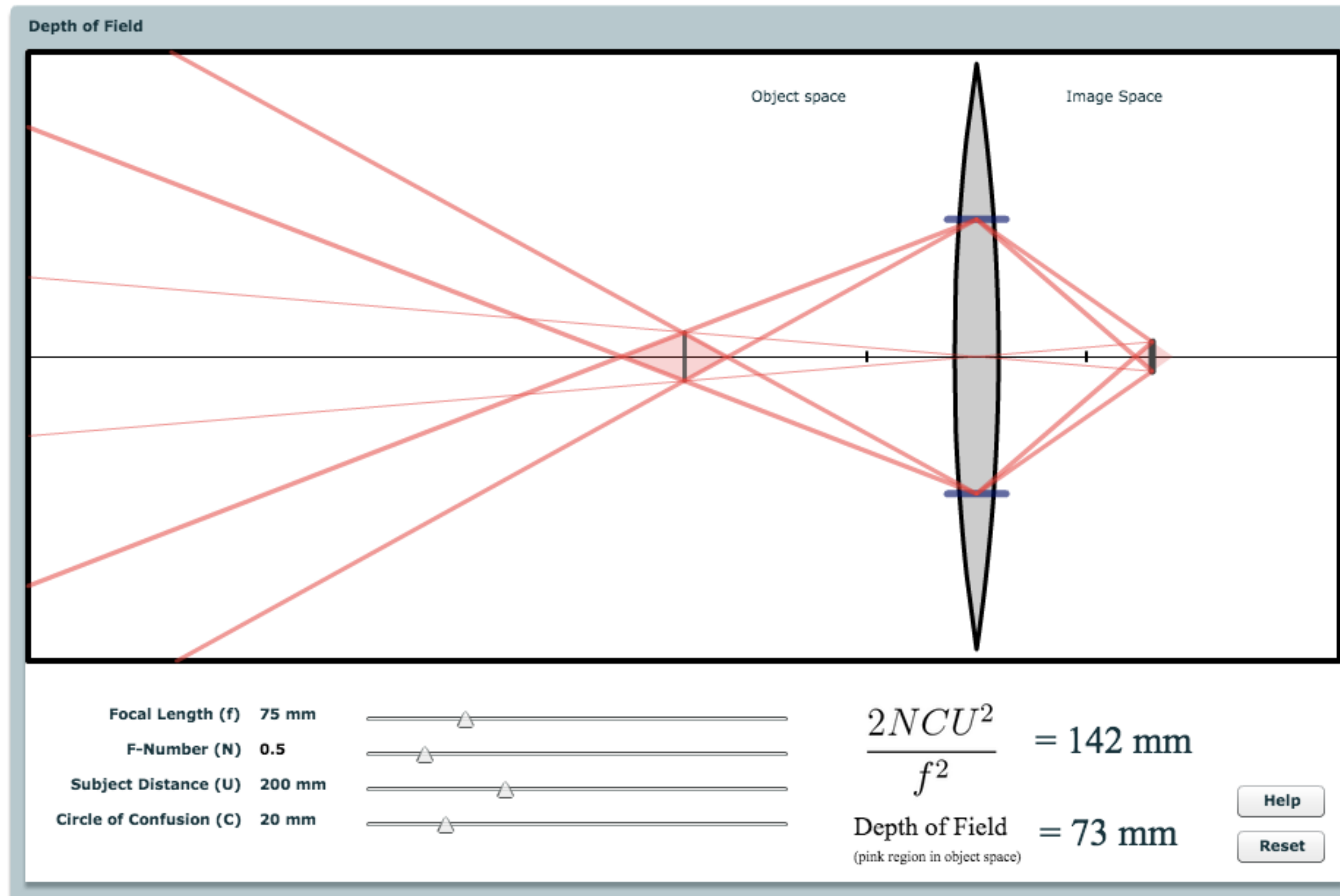
$$\text{DOF} = D_F - D_N$$

$$D_F = \frac{D_S f^2}{f^2 - NC(D_S - f)}$$

$$D_N = \frac{D_S f^2}{f^2 + NC(D_S - f)}$$



# DOF Demonstration



<http://graphics.stanford.edu/courses/cs178/applets/dof.html>

# **Ray Tracing Ideal Thin Lenses**



# Example of Rendering with Lens Focus



**Credit: Bertrand Benoit. "Sweet Feast," 2009. [Blender /VRay]**



# Example of Rendering with Lens Focus



**Credit: Giuseppe Albergo. "Colibri" [Blender]**

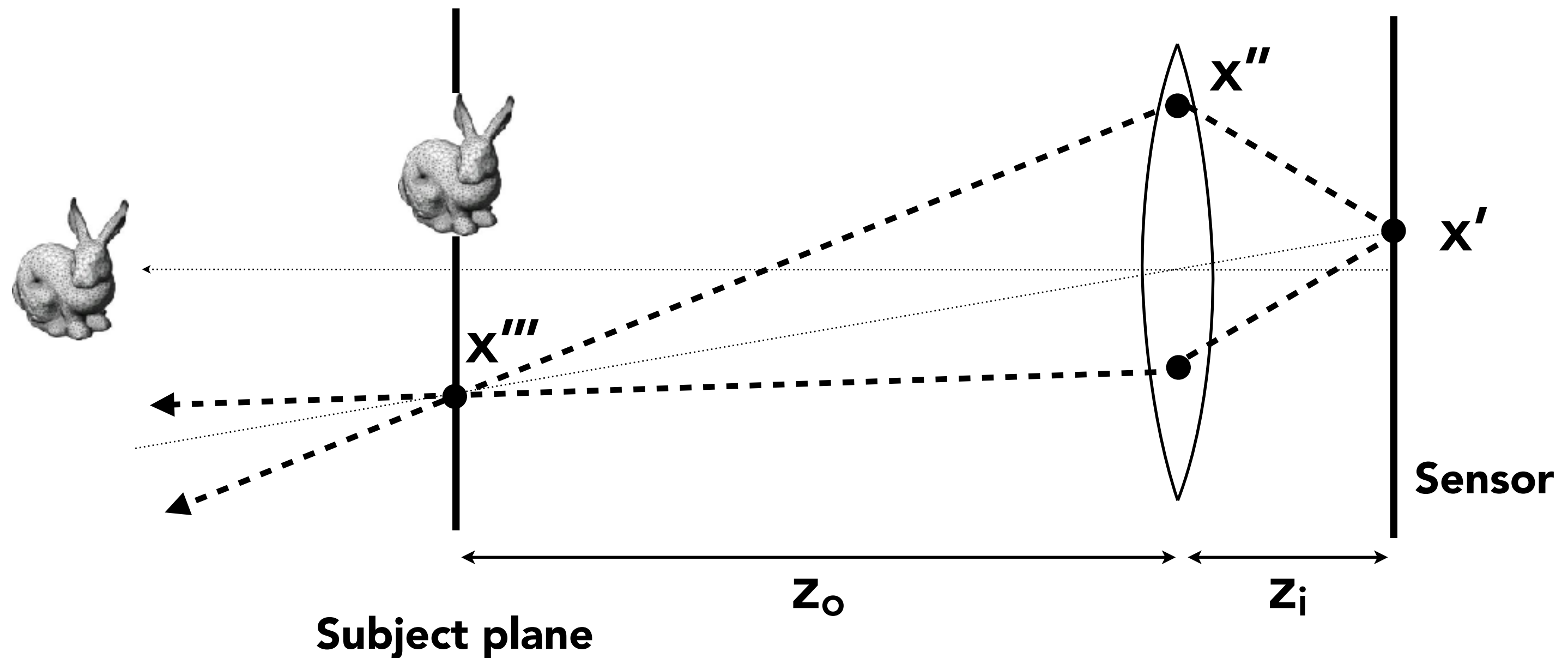


# Example of Rendering with Lens Focus



Pharr and Humphreys

# Ray Tracing for Defocus Blur (Thin Lens)

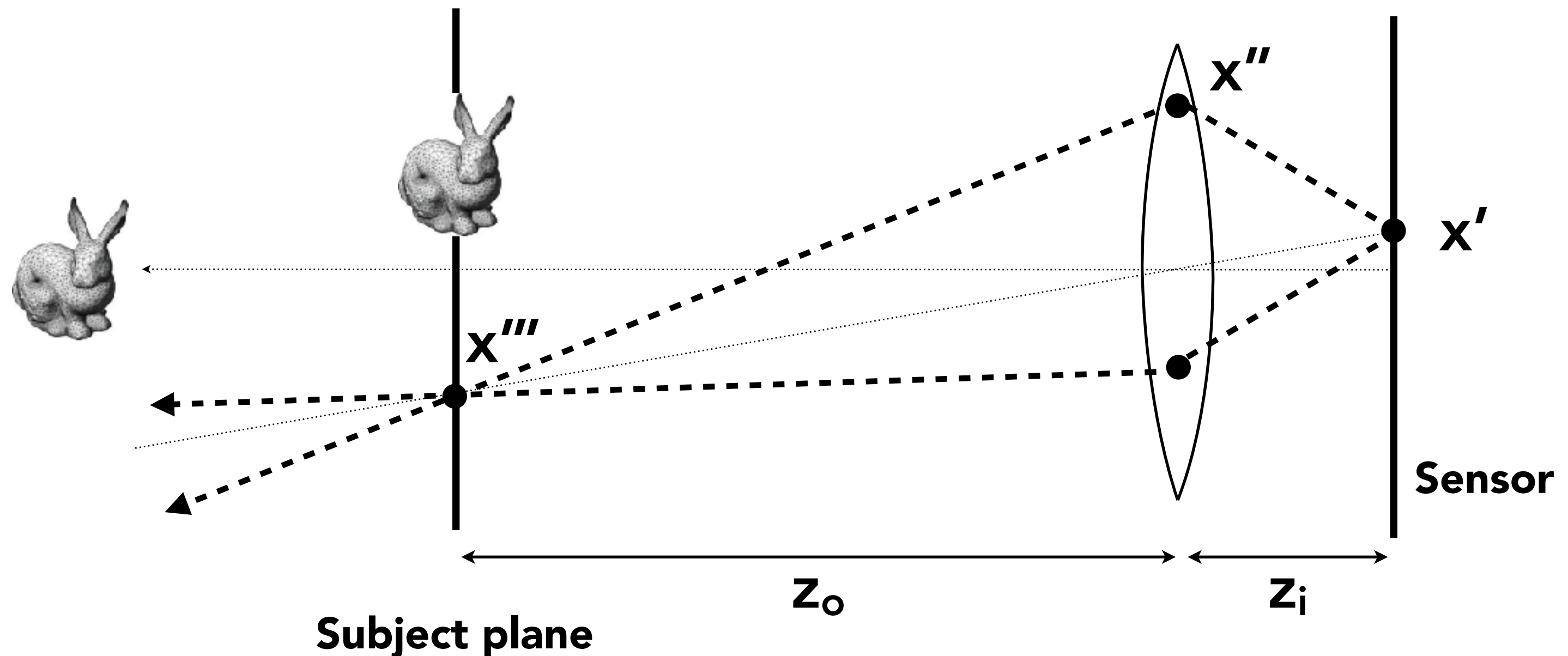


## Setup:

- Choose sensor size, lens focal length and aperture size
- Choose depth of subject of interest  $z_o$ 
  - Calculate corresponding depth of sensor  $z_i$  from thin lens equation (focusing)



# Ray Tracing for Defocus Blur (Thin Lens)



To compute value of pixel at position  $x'$  by Monte Carlo integration:

- Select random points  $x''$  on lens plane
- Rays pass from point  $x'$  on image plane  $z_i$  through points  $x''$  on lens
- Each ray passes through conjugate point  $x'''$  on the plane of focus  $z_o$ 
  - Can determine  $x'''$  from Gauss' ray diagram
  - So just trace ray from  $x''$  to  $x'''$
- Estimate radiance on rays using path-tracing, and sum over all points  $x''$

# Example of Rendering with Lens Focus



Pharr and Humphreys



# Bokeh

# Bokeh

Bokeh is the shape and quality of out-of-focus blur

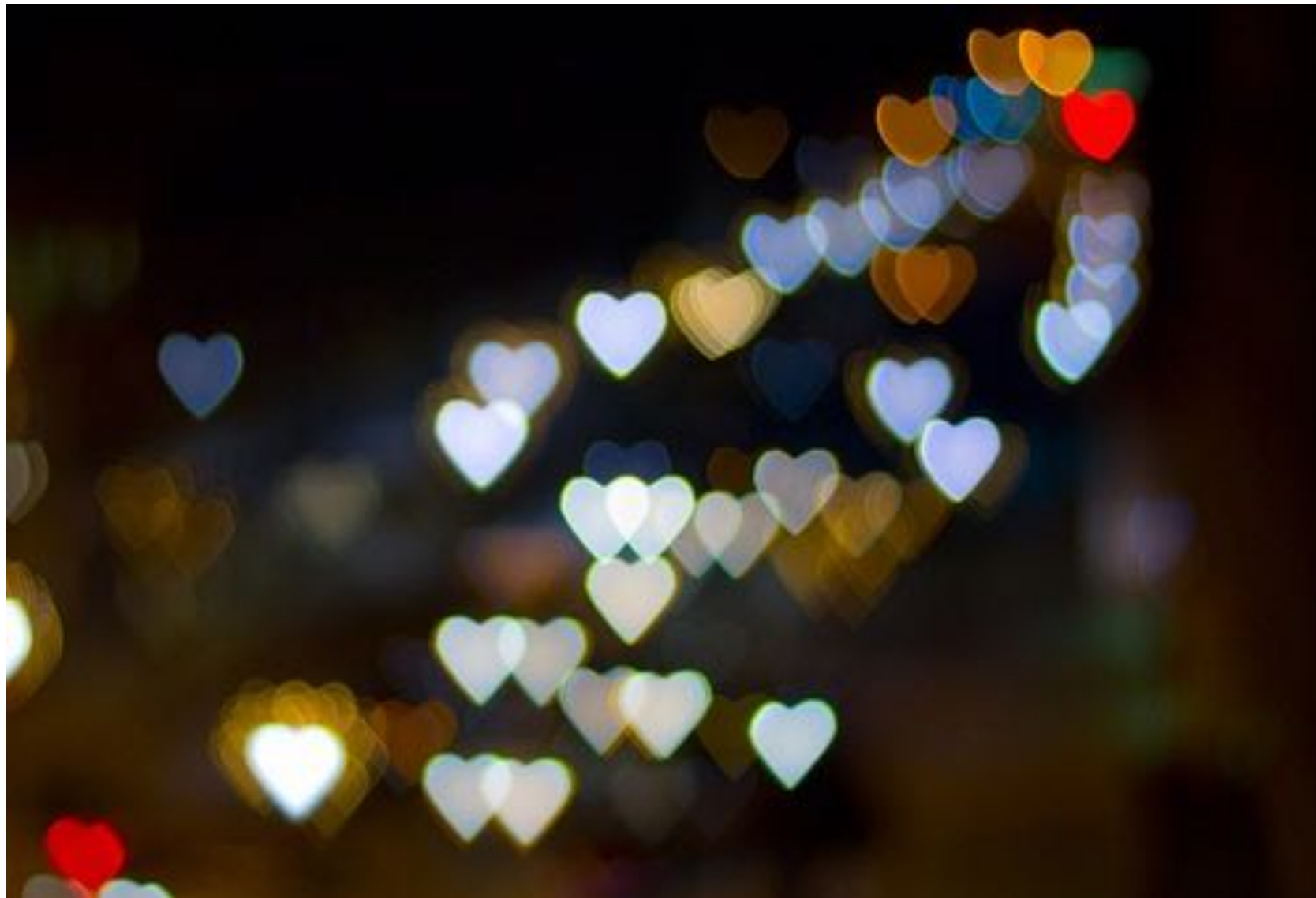
- For small, out-of-focus lights, bokeh takes on the shape of the lens aperture



M Yashna, flickr, 40mm f/3.0



# Bokeh



diyphotography.net

Heart-shaped bokeh?



CS184/284A

Ren Ng



# Bokeh



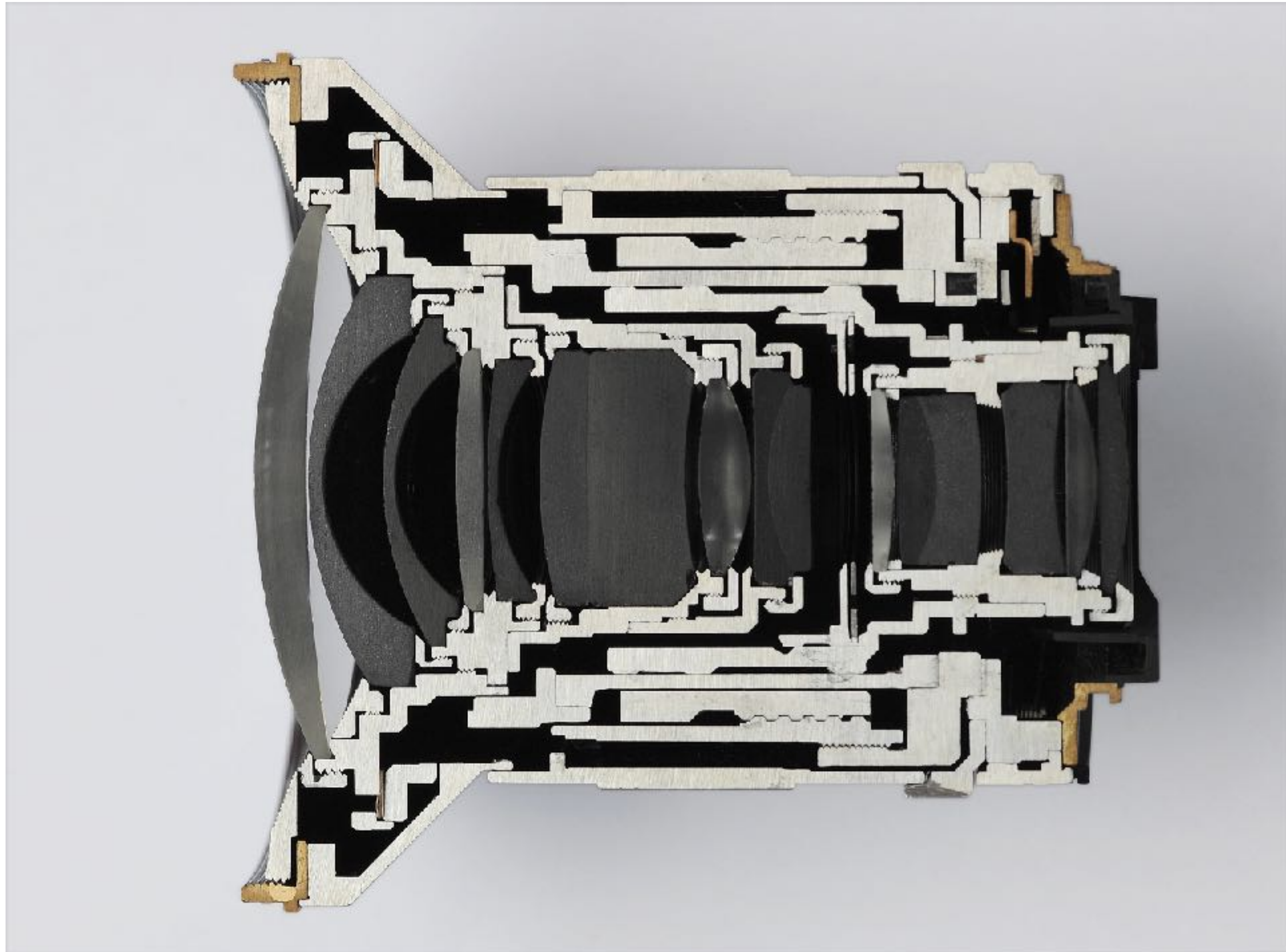
Dino Quinzani, Leica Noctilux 50mm,  $f/0.95$

Why does the bokeh vary across the image?



# **Real Compound Lenses**

# Modern Lens Designs Are Highly Complex

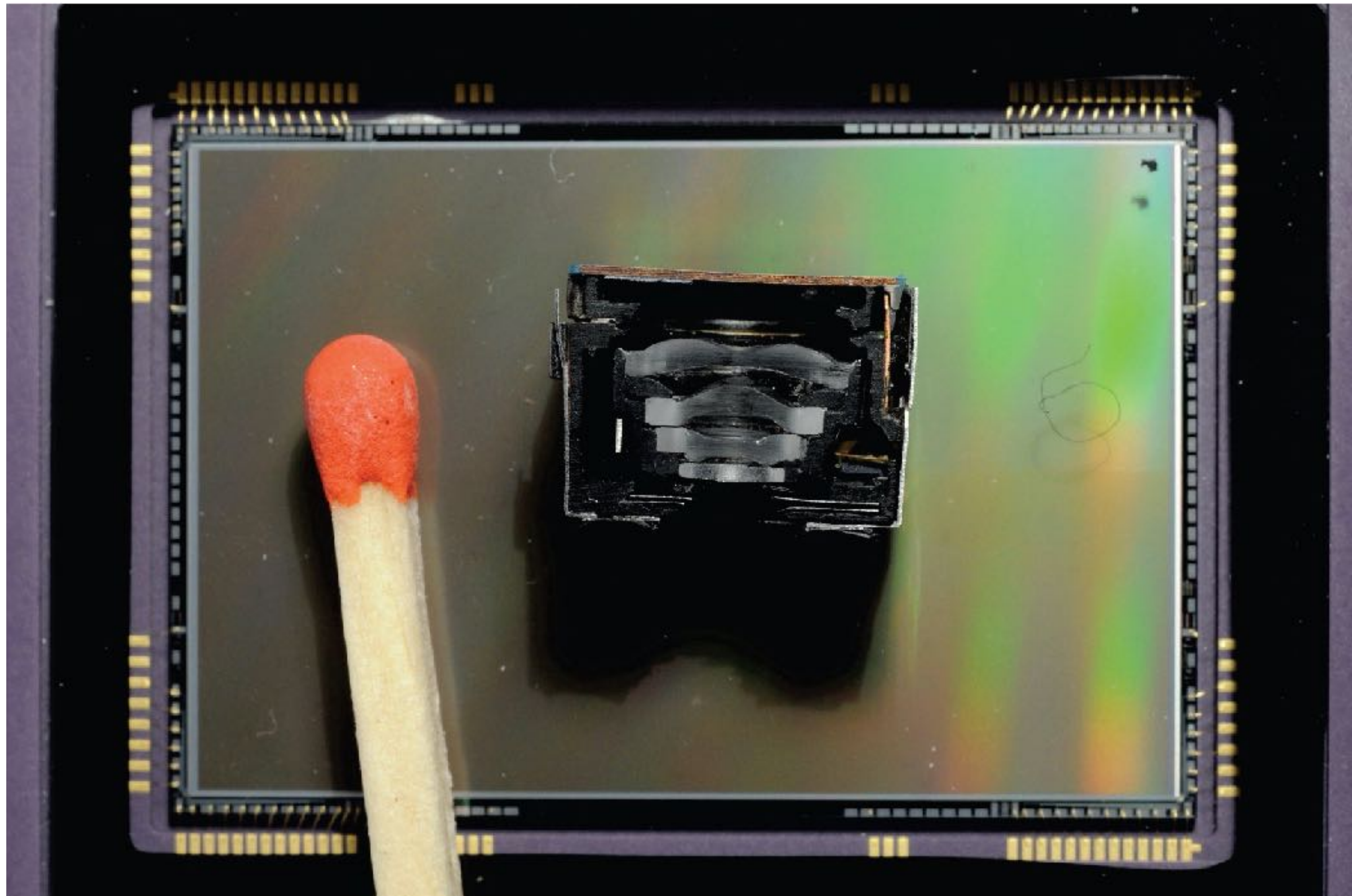


ilovephotography.com

Photographic lens cross section



# Modern Lens Designs Are Highly Complex



ilovehatephoto.com

4 element mobile phone lens (on 24x36mm sensor)

# Modern Lens Designs Are Highly Complex



[Apple]



# Modern Lens Designs Are Highly Complex

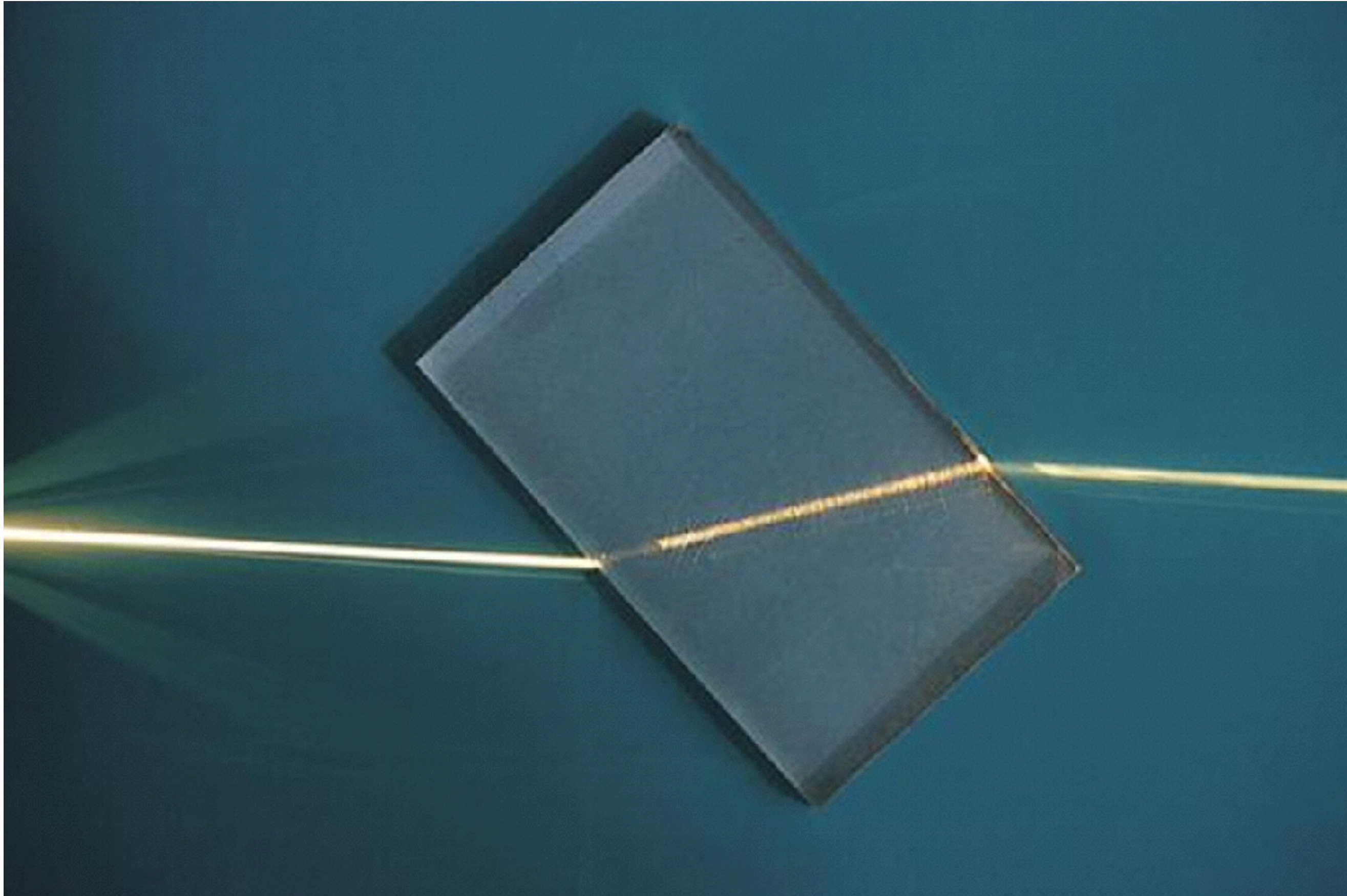


Zeiss flickr.com account

Microscope objective



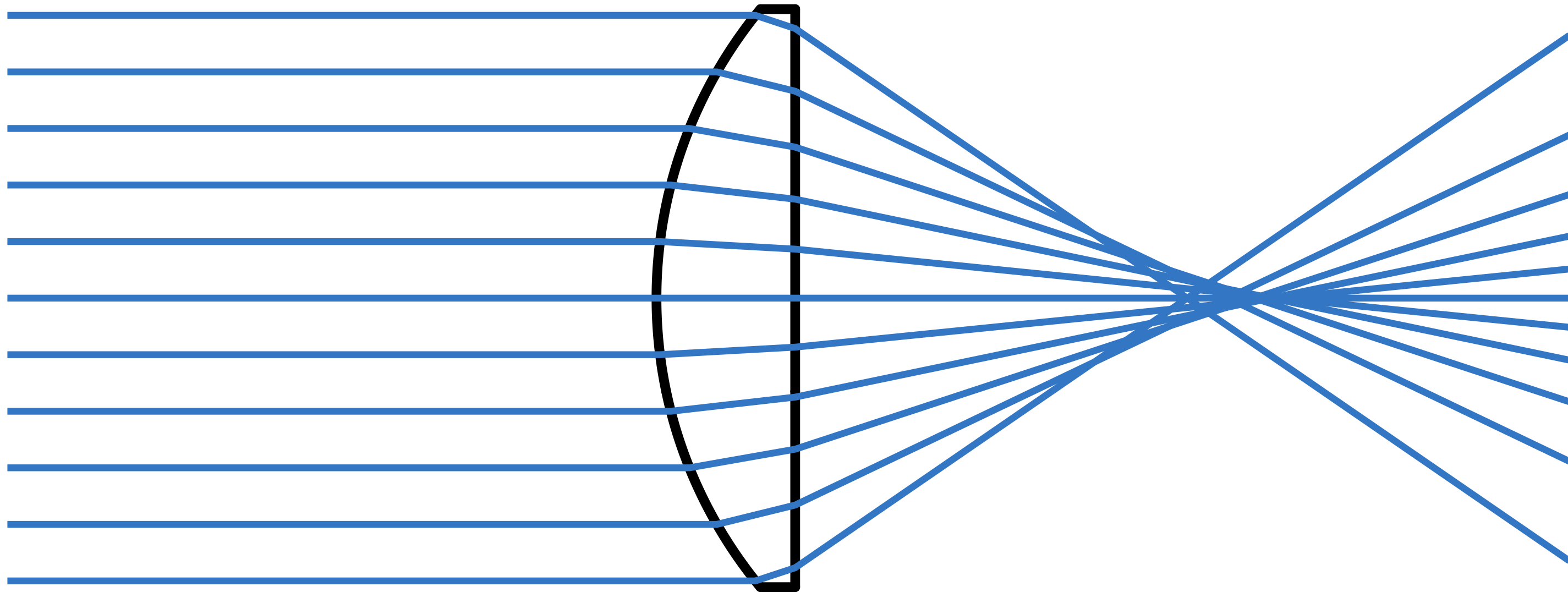
# Recall: Snell's Law of Refraction



$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$

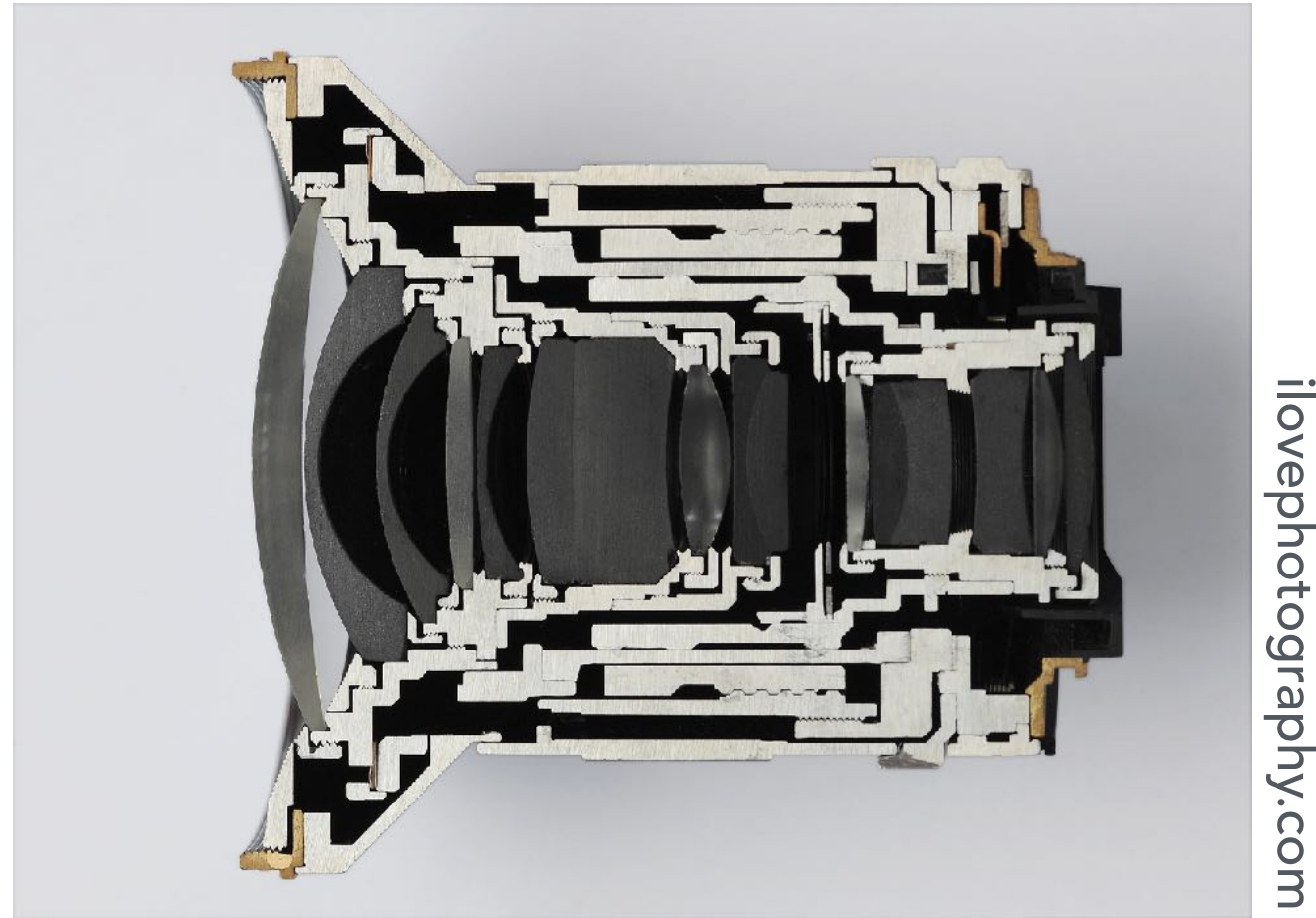


# Real Refraction Through A Lens Is Not Ideal – Aberrations

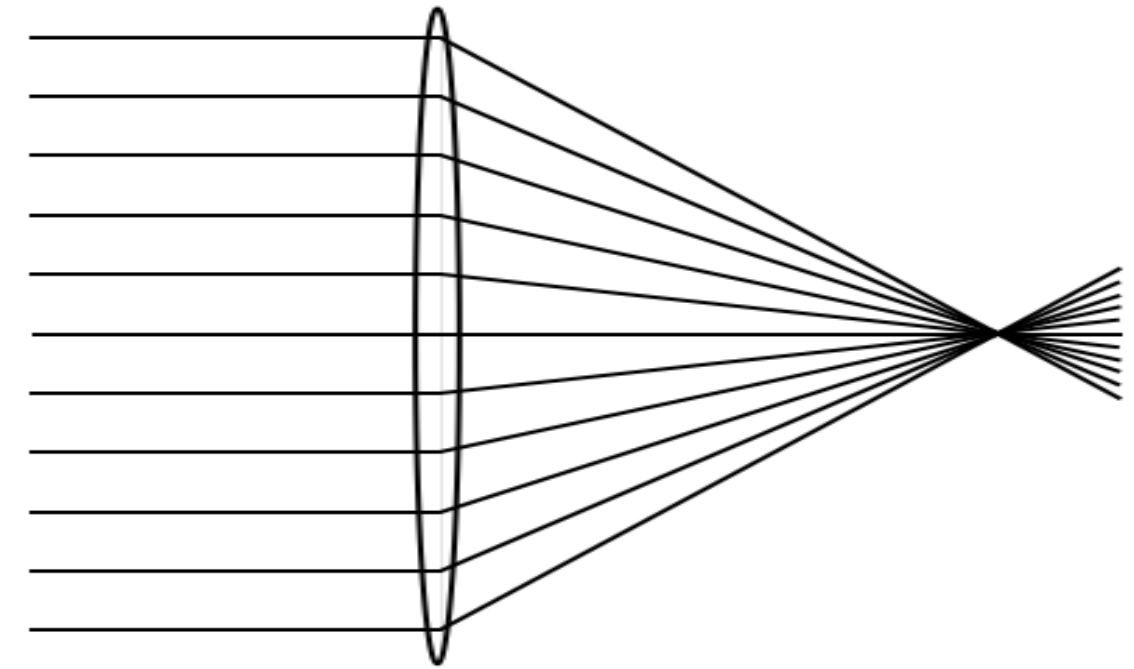


Real plano-convex lens (spherical surface shape).  
Lens does not converge rays to a point anywhere.

# Real Lenses vs Ideal Thin Lenses



- Real optical system
- Multiple physical elements in compound design
- Optical aberrations prevent rays from converging perfectly



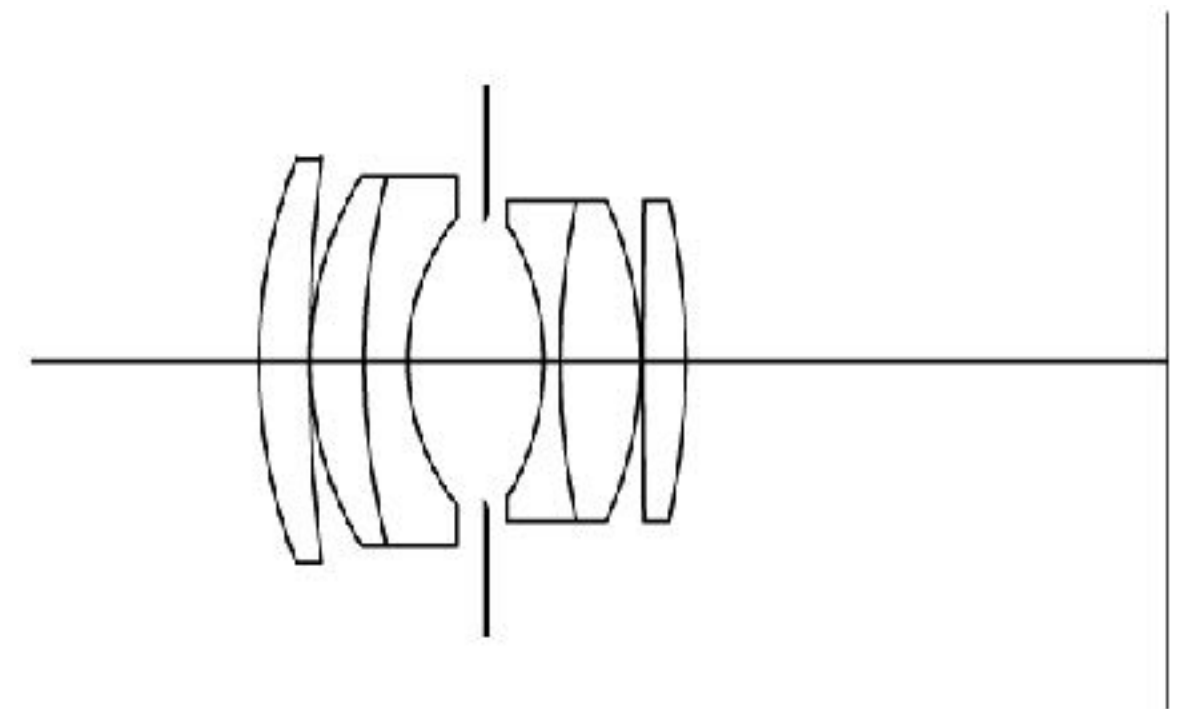
- Theoretical abstraction
- Assume all rays refract at a plane & converge to a point
- Quick and intuitive calculation of main imaging effects



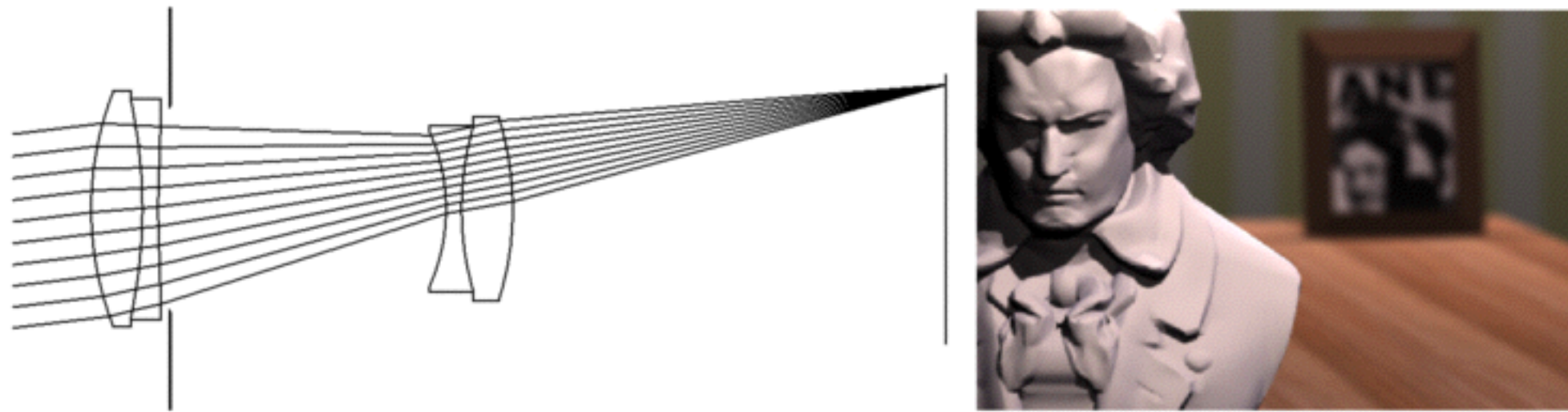
# Example Lens Formula: Double Gauss

**Data from W. Smith,  
Modern Lens Design, p 312**

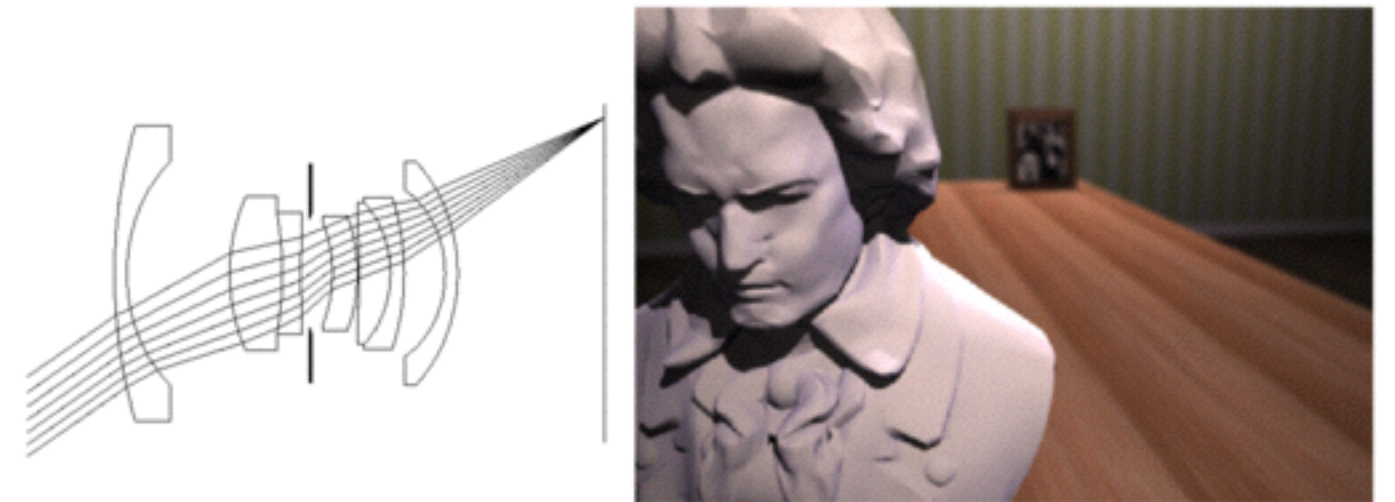
Radius (mm)	Thick (mm)	$n_d$	V-no	Aperture (mm)
58.950	7.520	1.670	47.1	50.4
169.660	0.240			50.4
38.550	8.050	1.670	47.1	46.0
81.540	6.550	1.699	30.1	46.0
25.500	11.410			36.0
	9.000			34.2
-28.990	2.360	1.603	38.0	34.0
81.540	12.130	1.658	57.3	40.0
-40.770	0.380			40.0
874.130	6.440	1.717	48.0	40.0
-79.460	72.228			40.0



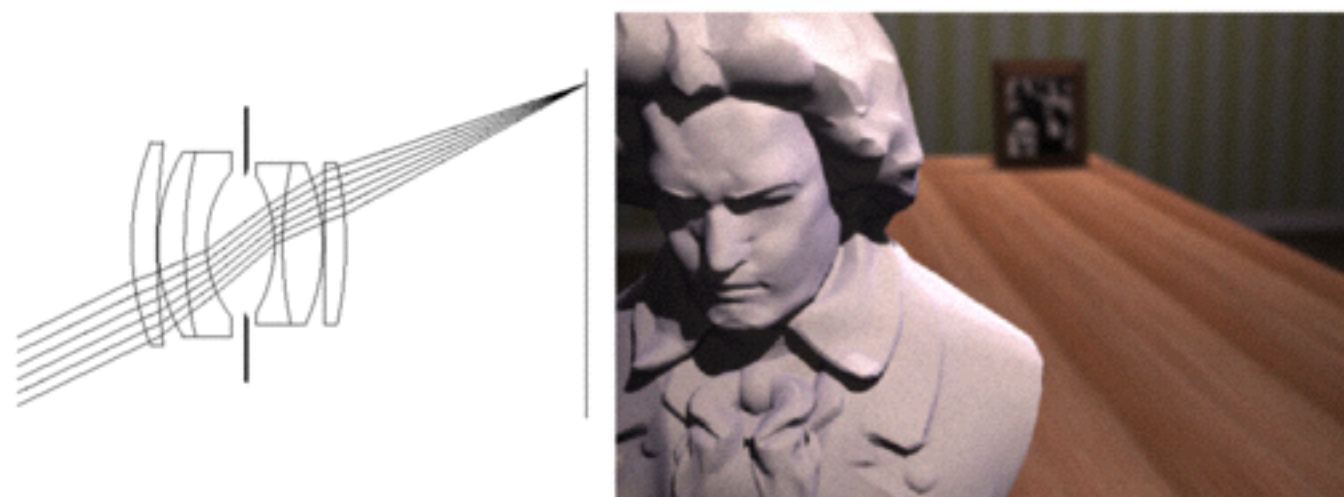
# Ray Tracing Through Real Lens Designs



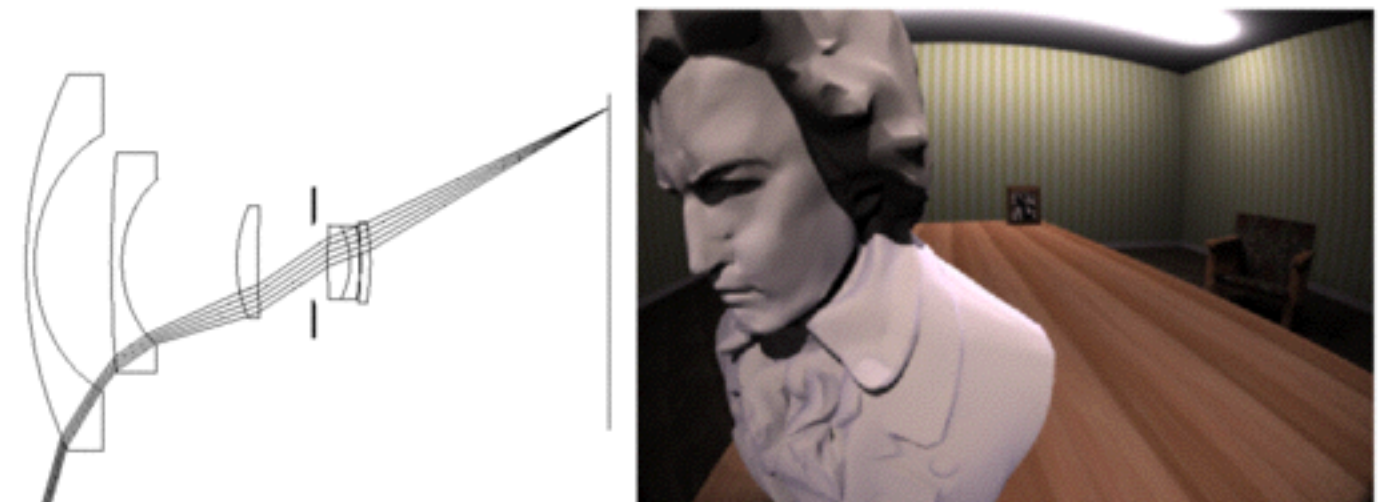
**200 mm telephoto**



**35 mm wide-angle**



**50 mm double-gauss**



**16 mm fisheye**

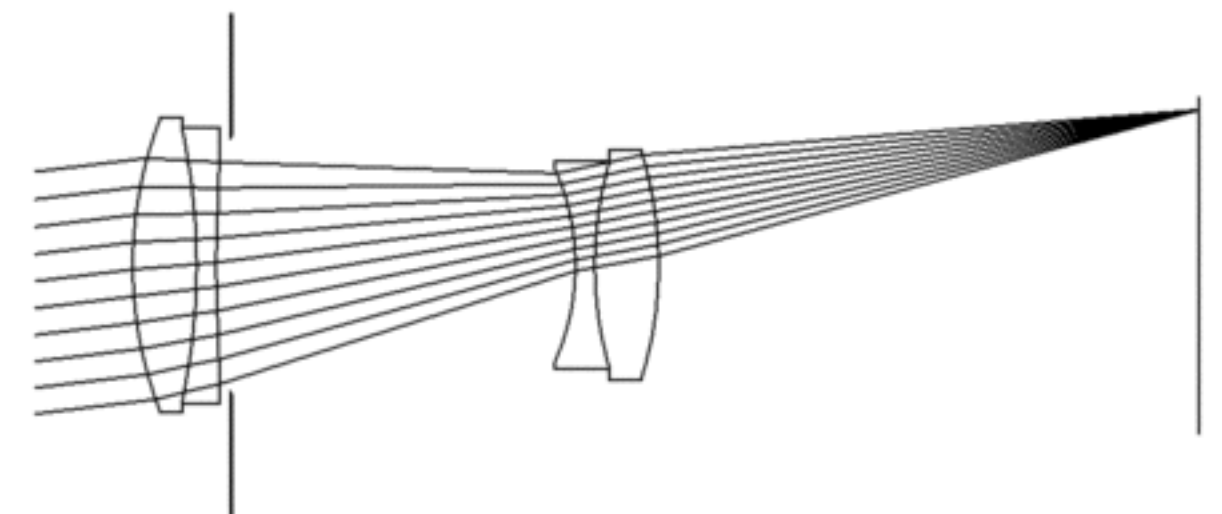
**From Kolb, Mitchell and Hanrahan (1995)**



# Ray Tracing Through Real Lens Designs



200 mm telephoto

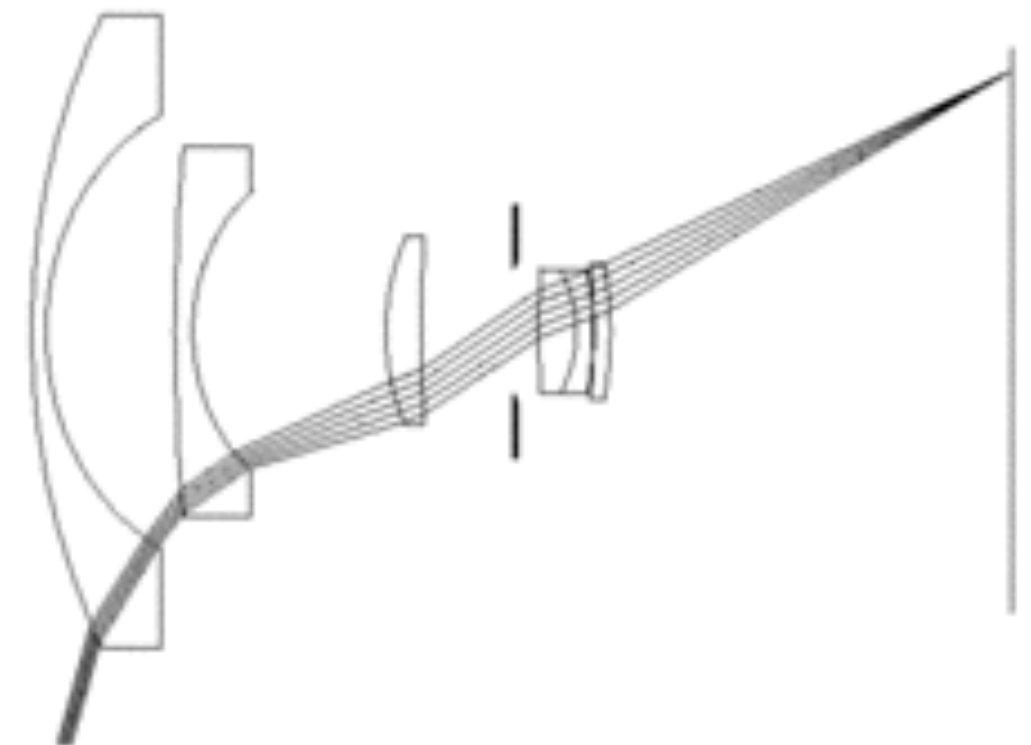


Notice shallow depth of field (out of focus background)

# Ray Tracing Through Real Lens Designs



16 mm fisheye



Notice distortion in the corners (straight lines become curved)



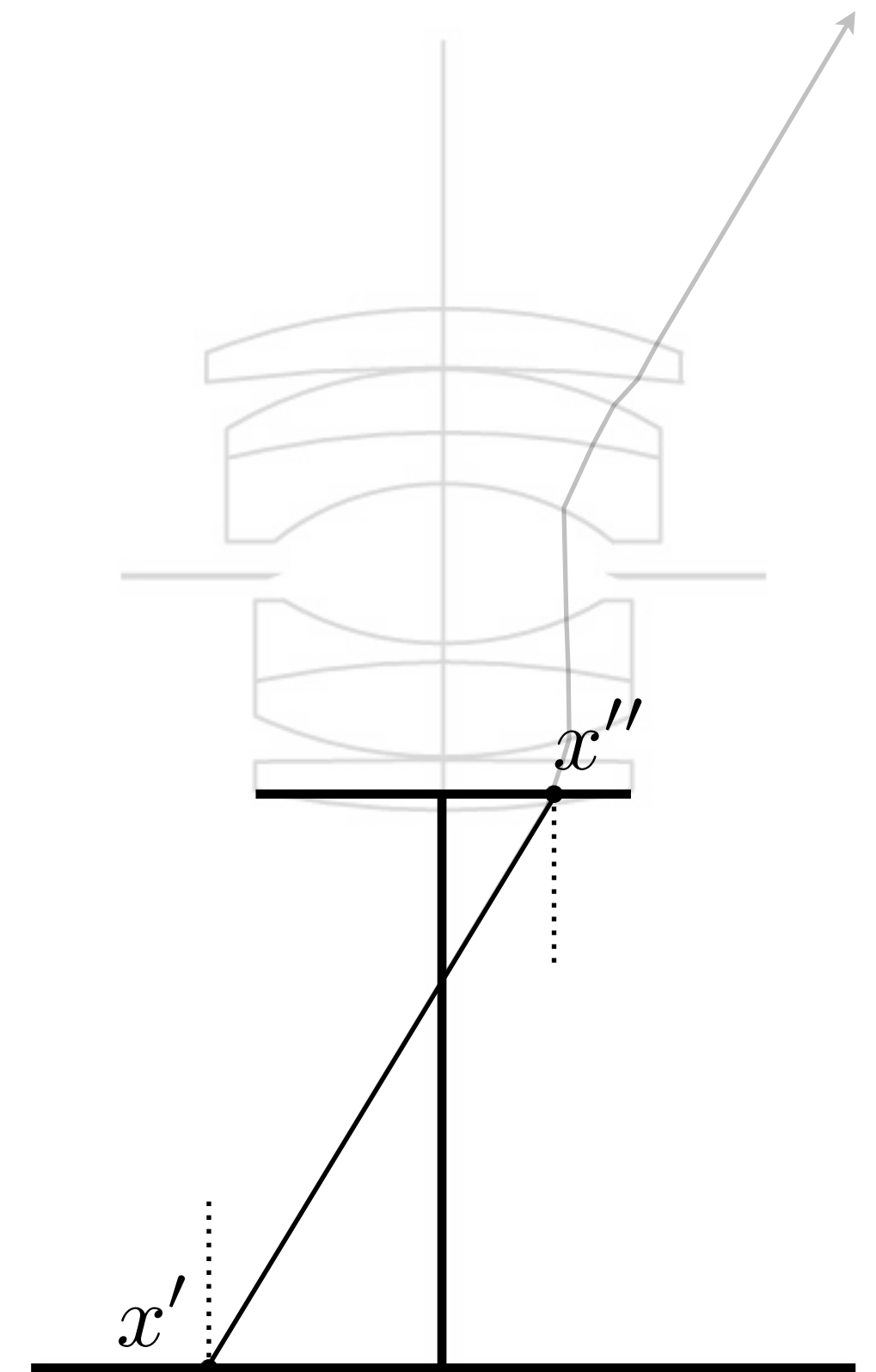
# Ray Tracing Real Lens Designs

## Monte Carlo approach

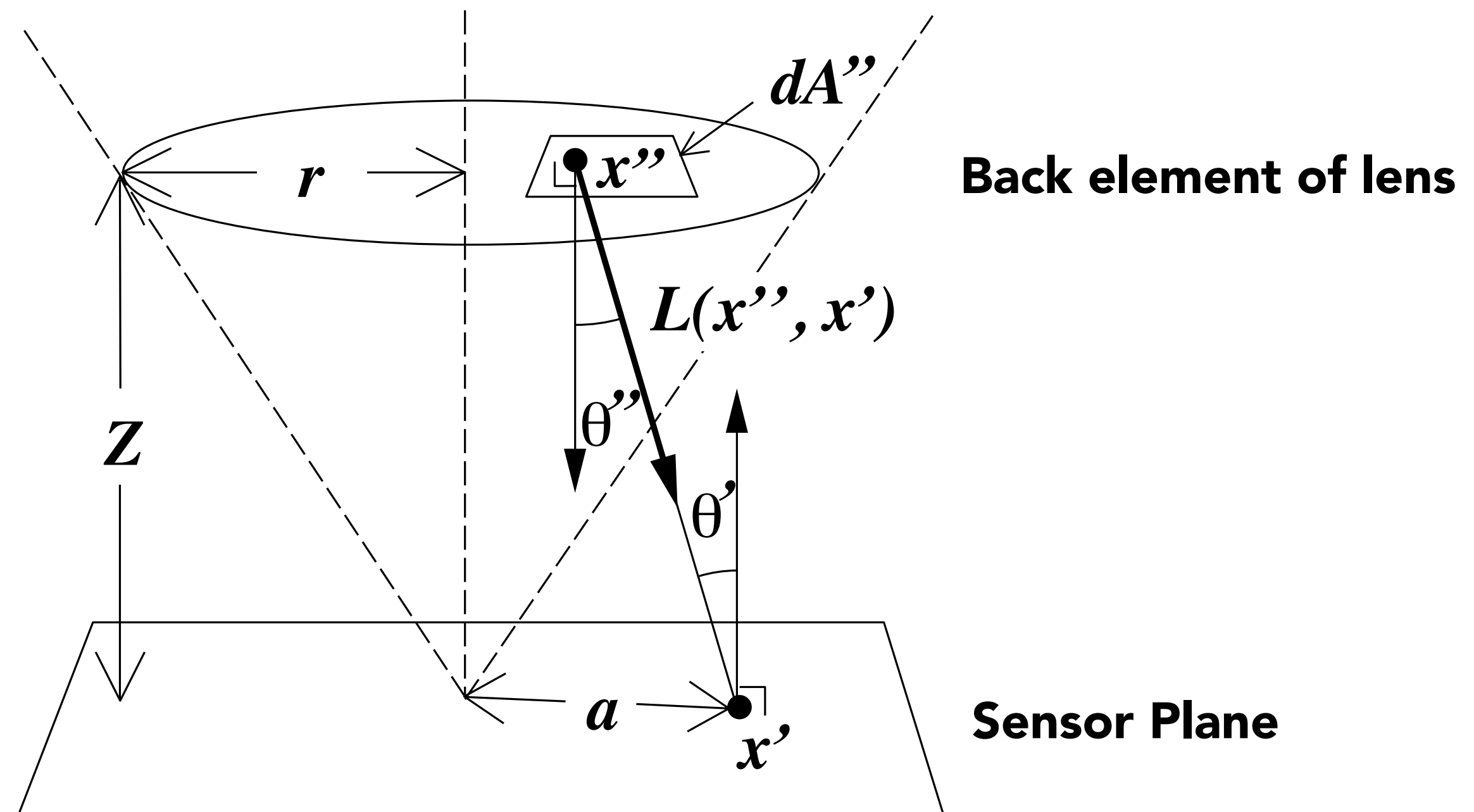
- At every sensor pixel, compute integral of rays incident on pixel area arriving from all paths through the lens

## Algorithm (for a pixel)

- Choose  $N$  random positions in pixel
- For each position  $x'$ , choose a random position on the back element of the lens  $x''$
- Trace a ray through from  $x'$  to  $x''$ , trace refractions through lens elements until it misses the next element (kill ray) or exits the lens (path trace through the scene)
- Weight each ray according to radiometric calculation on next slide to estimate irradiance  $E(x')$



# Radiometry for Tracing Lens Designs



$$\begin{aligned}
 E(x') &= \int_{x'' \in D} L(x'' \rightarrow x') \frac{\cos \theta' \cos \theta''}{||x'' - x'||^2} dA'' \\
 &= \frac{1}{Z^2} \int_{x'' \in D} L(x'' \rightarrow x') \cos^4 \theta dA''
 \end{aligned}$$



# Things to Remember

## Effect

## Cause

Field of view

Sensor size, focal length

Depth of field

Aperture, focal length, object dist.

Exposure

Aperture, shutter, ISO

Motion blur

Shutter

Grain/noise

ISO

Pinholes and lenses form perspective images

Perspective composition, dolly zoom

# Acknowledgments

Many thanks to Marc Levoy, who created many of these slides, and Pat Hanrahan.

- London, Stone, and Upton, Photography (9th ed.), Prentice Hall, 2008.
- Peterson, Understanding Exposure, AMPHOTO 1990.
- The Slow Mo Guys
- [bobatkins.com](http://bobatkins.com)
- Hari Subramanyan
- Canon EF Lens Work III



**Extra**

# **Auto Focus**



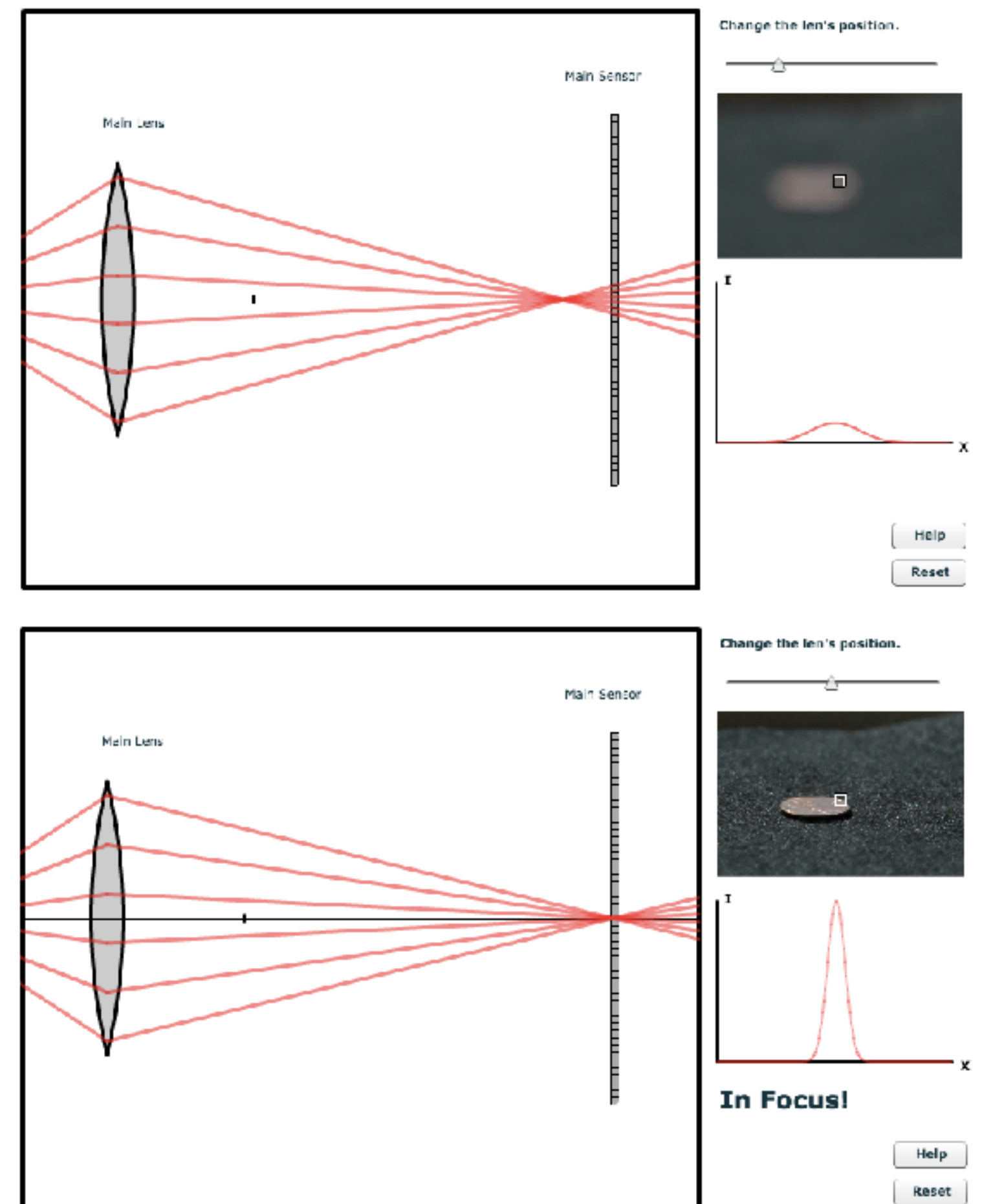
# Contrast Detection Autofocus

A target object is imaged through the lens to an image patch on the sensor.

The contrast of this image patch is high if the object is in focus, low otherwise.

The physical focus of the lens is adjusted until the contrast of this image patch is maximized.

Many ways to estimate how in-focus the image patch is: gradient, Sum Modified Laplacian (Nayar), variance...



**Demo (Levoy, Willet, Adams)**

<https://graphics.stanford.edu/courses/cs178-10/applets/autofocusCD.html>

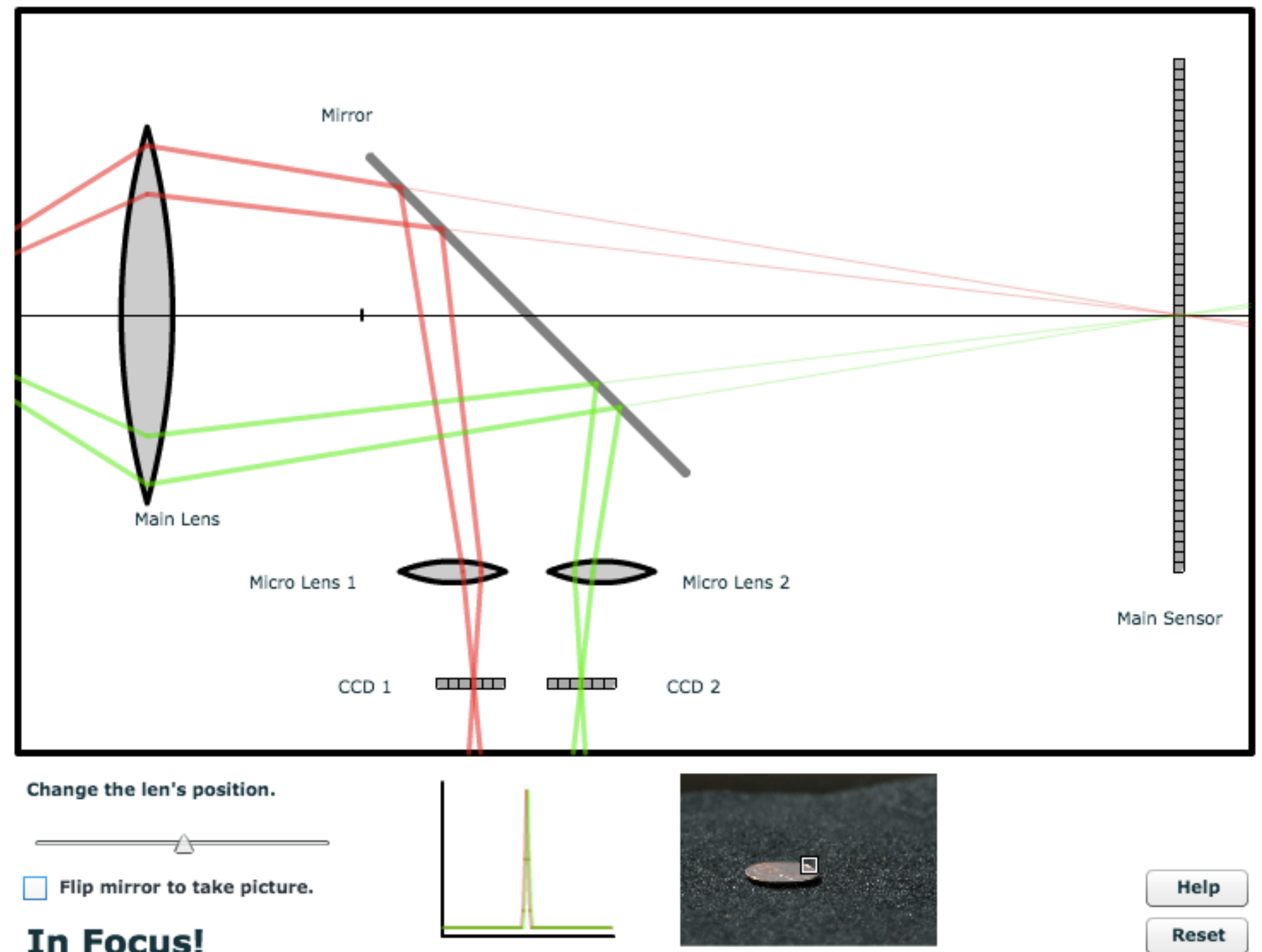
# Phase Detection Autofocus

Ray bundles from a target object converge to points at different depths in the camera depending on the lens focus.

In a phase detection AF system ray bundles passing through different portions of the lens (red and green shown) are brought to focus on separate lenslets with separate AF sensors.

Depending on depth of focus point, the ray bundles converge to different positions on their respective AF sensors (see interactive demo).

A certain spacing (disparity) between these images is "in focus"

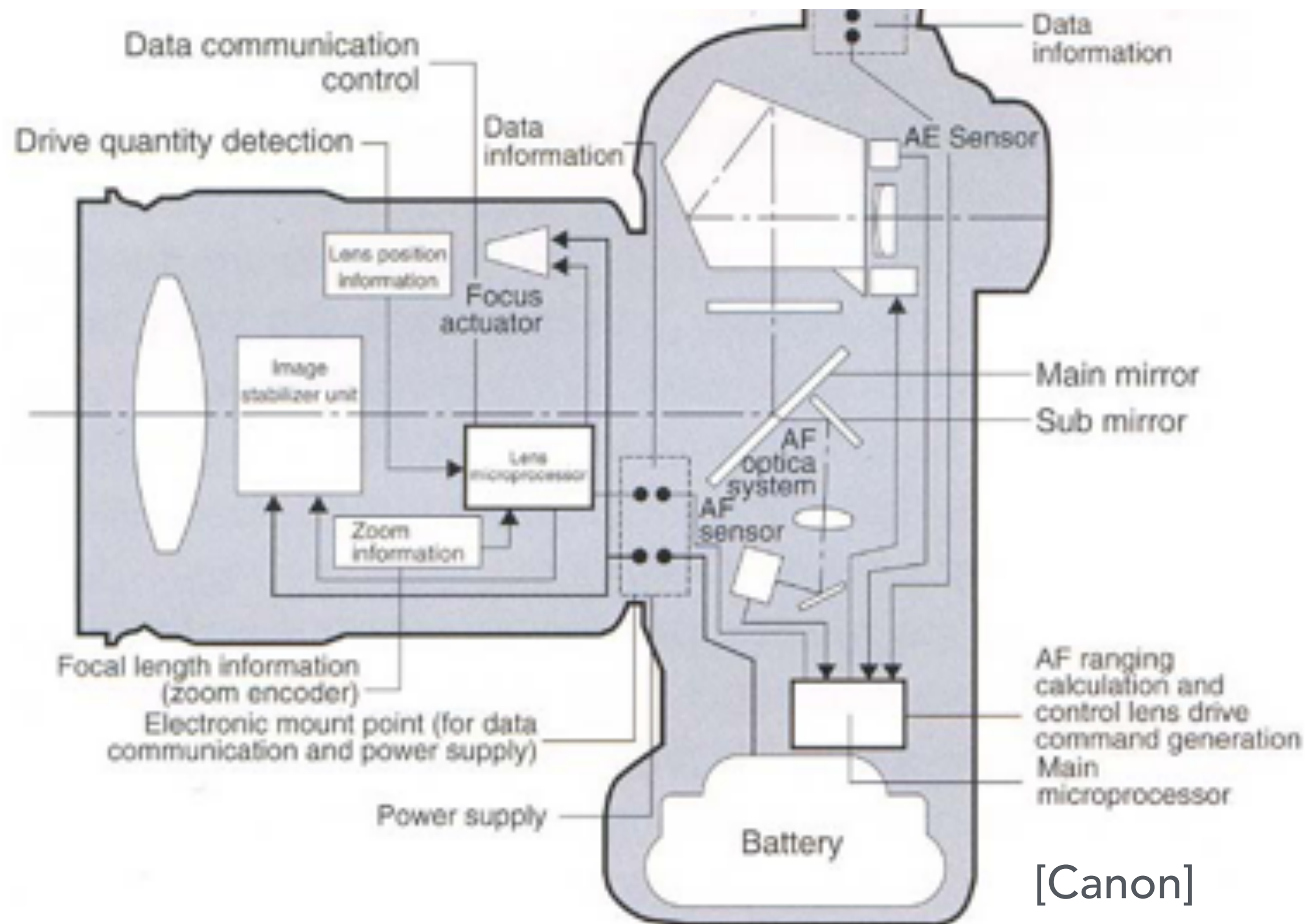


**Demo (Levoy, Willet, Adams)**

<https://graphics.stanford.edu/courses/cs178-10/applets/autofocusPD.html>



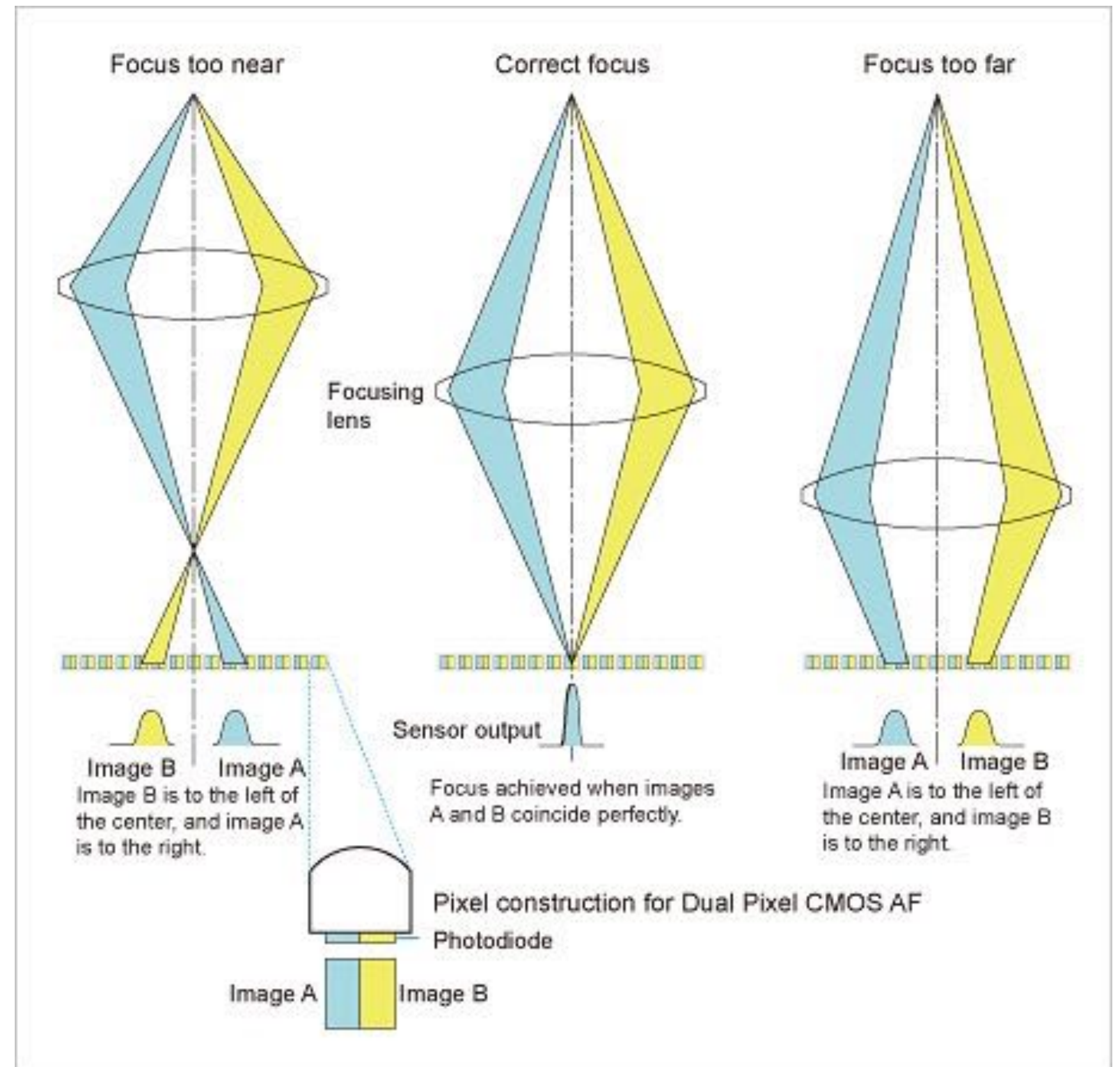
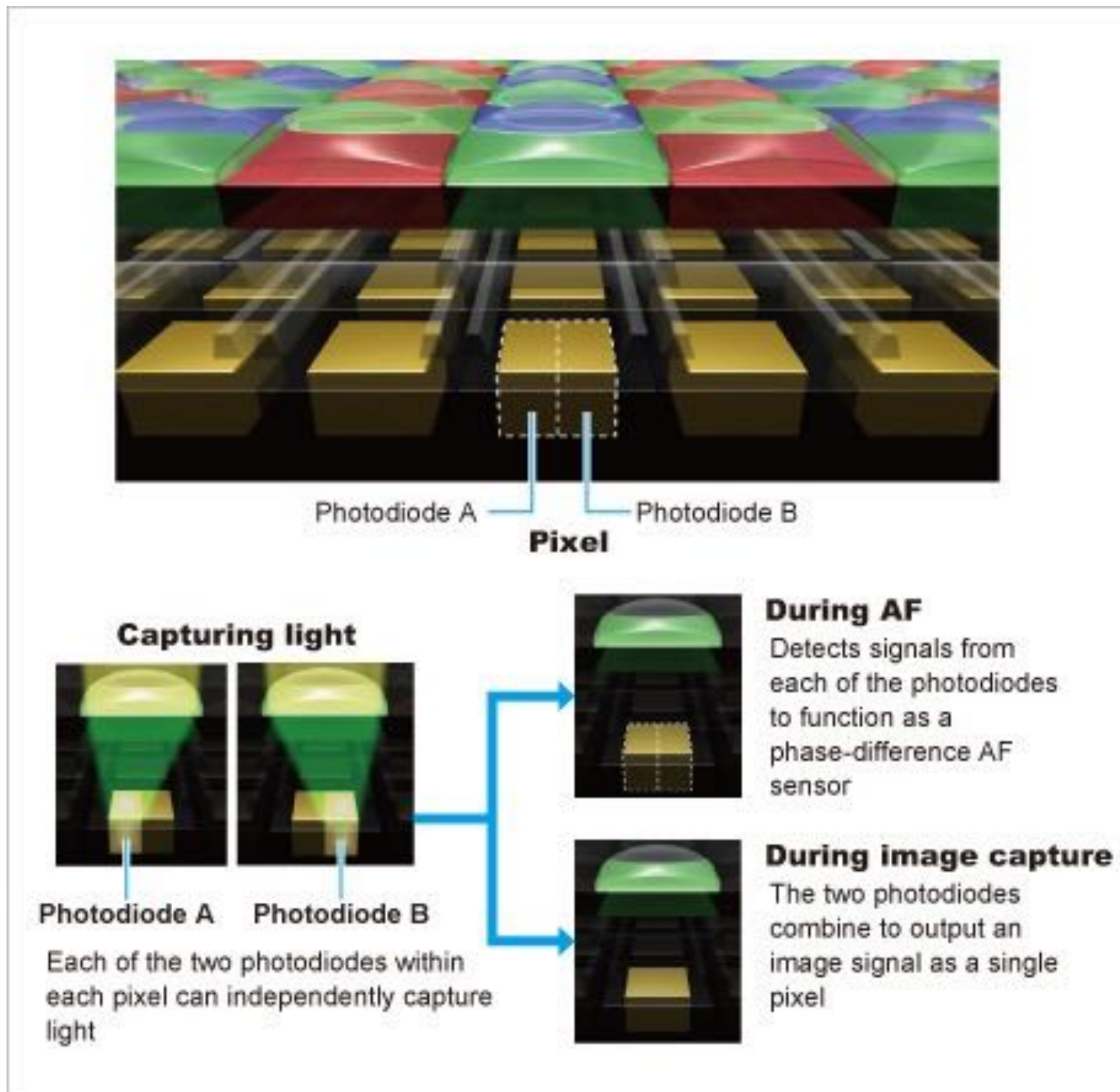
# Phase Detection AF Used in DSLRs



- Distance between phase-detect images correlates to distance in focus to target object (allows "jumping" to the right focus)
- Separate AF units cannot be used with "live view" or video recording



# Phase Detection Pixels Embedded in Sensor



Canon

- Modern image sensors have small pixels, and may embed phase detection pixels directly into sensor image arrays