Lecture 15 / 16:

Cameras & Lenses

Computer Graphics and Imaging
UC Berkeley CS184/284A

Art Competition #1 Results

Art Competition #1 – 3rd Place Winner

Riley Peterlinz & Tianchen Liu

Caption: In the Mood for Triangles

Approach: I did delaunay triangulation on the edges of the image and sampled the center colors of each triangle to get its color. Wrote some code that converts the triangles to an SVG format and plugged it into the rasterizer. Success!

Art Competition #1 – 2nd Place Winner

Annie Lin & Vivian Liu

Caption: Spot the Cow

Approach:We found out that this cow mesh was named Spot (created by Keenan Crane in 2012), so we decided to create a logo for CS 184 using Spot! We decided to go with a pixel art style to mimic the way we assume LCD pixels light up as a square of uniform color in this course. We exported the resulting artwork as an SVG file. After modifying some SVG code for compatibility, we ran it through the rasterizer.

Art Competition #1 – 1st Place Winner

Akhil Vemuri, Meiqi Sun

Caption: Low-poly, triangulated bird perched on a tree branch

Approach: For our art submission, we drew a low-poly, triangulated image of a bird sitting on a tree. While we extracted the initial pixel matrix from an image Google, we used our own script from scratch to procedurally generate it.

Rendering with Realistic Camera Model

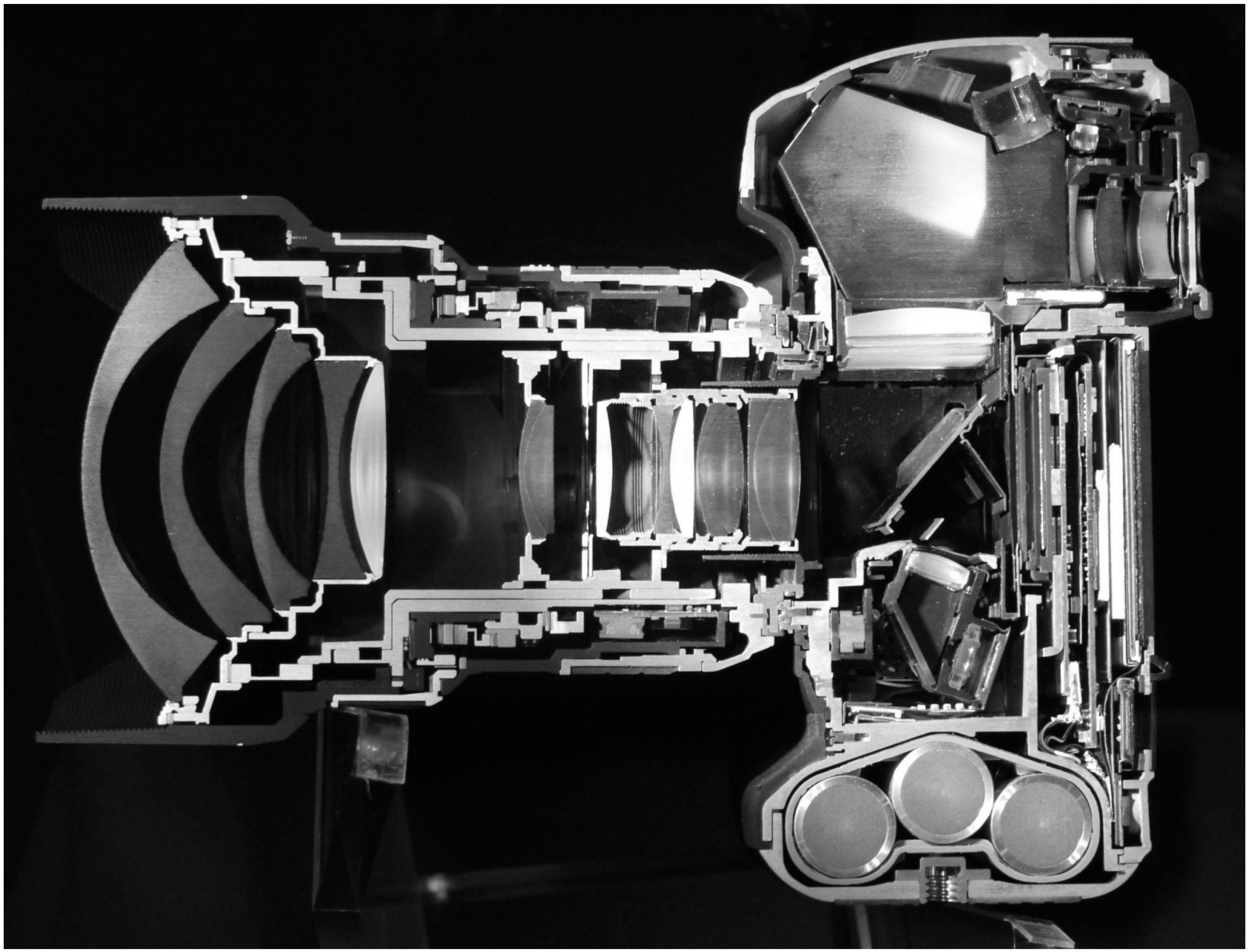
Credit: Bertrand Benoit. "Sweet Feast," 2009. [Blender /VRay]

Rendering with Realistic Camera Model

Credit: Giuseppe Albergo. "Colibri" [Blender]

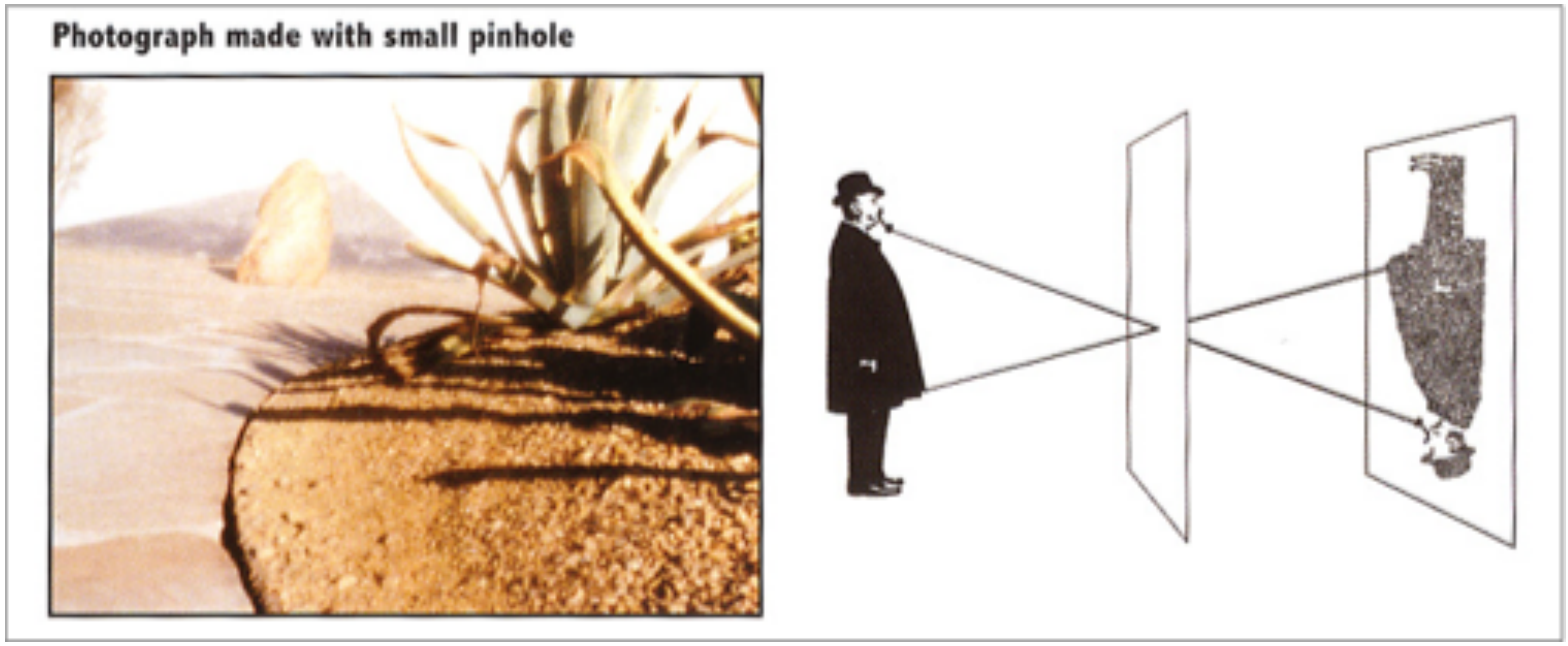
Image Capture Overview

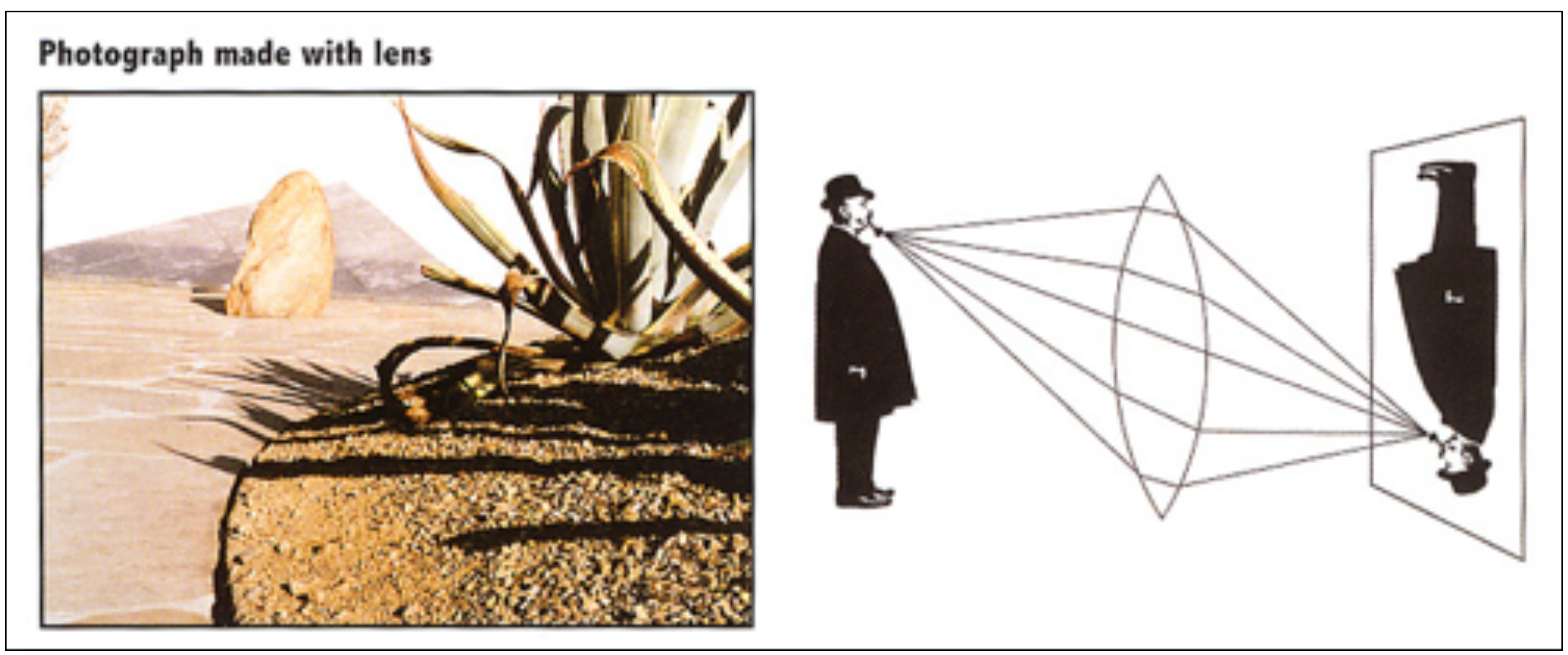
What's Happening Inside the Camera?



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

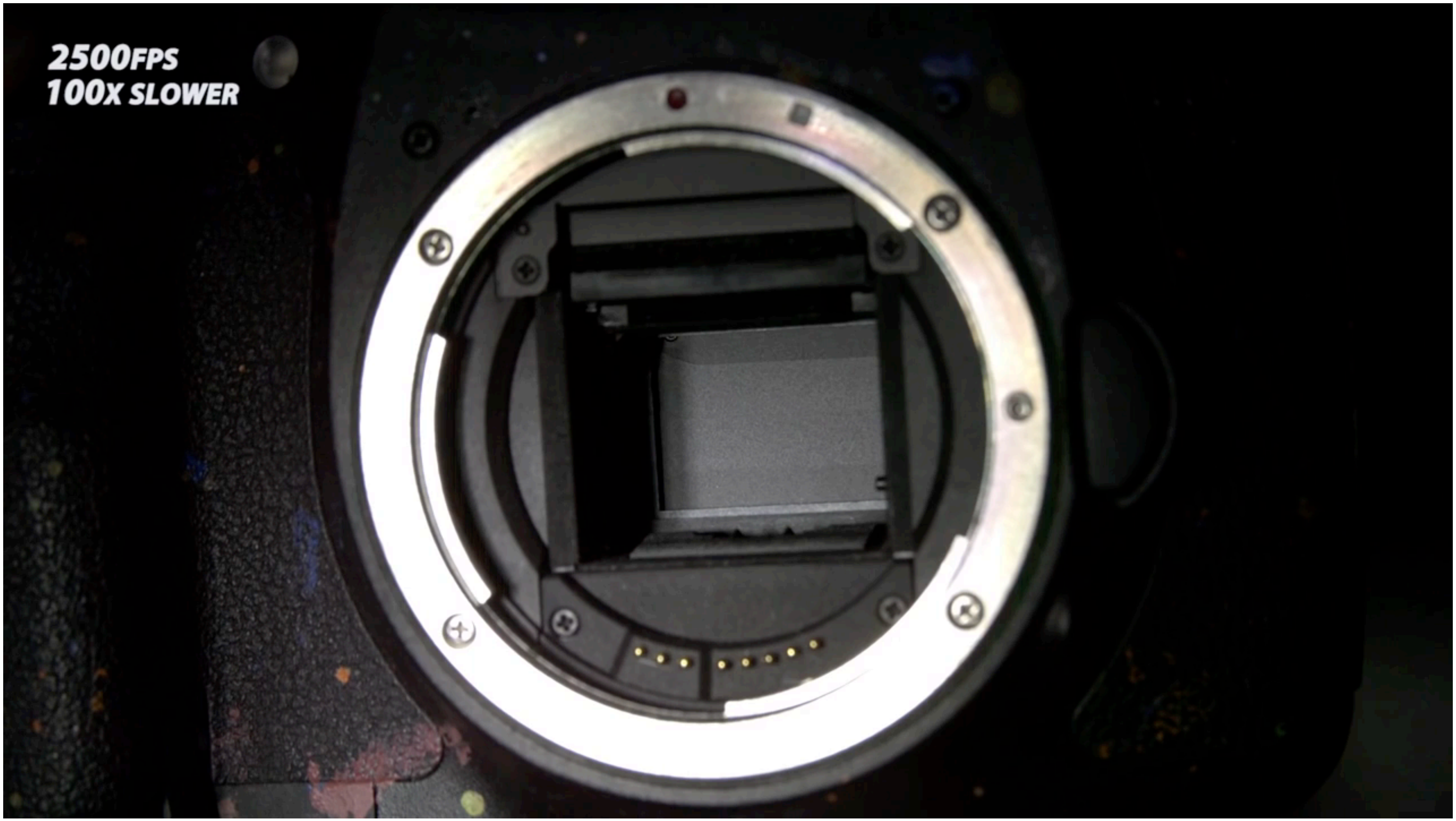
Pinholes & Lenses Form Image on Sensor





London and Upton

Shutter Exposes Sensor For Precise Duration



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

Sensor Accumulates Irradiance During Exposure

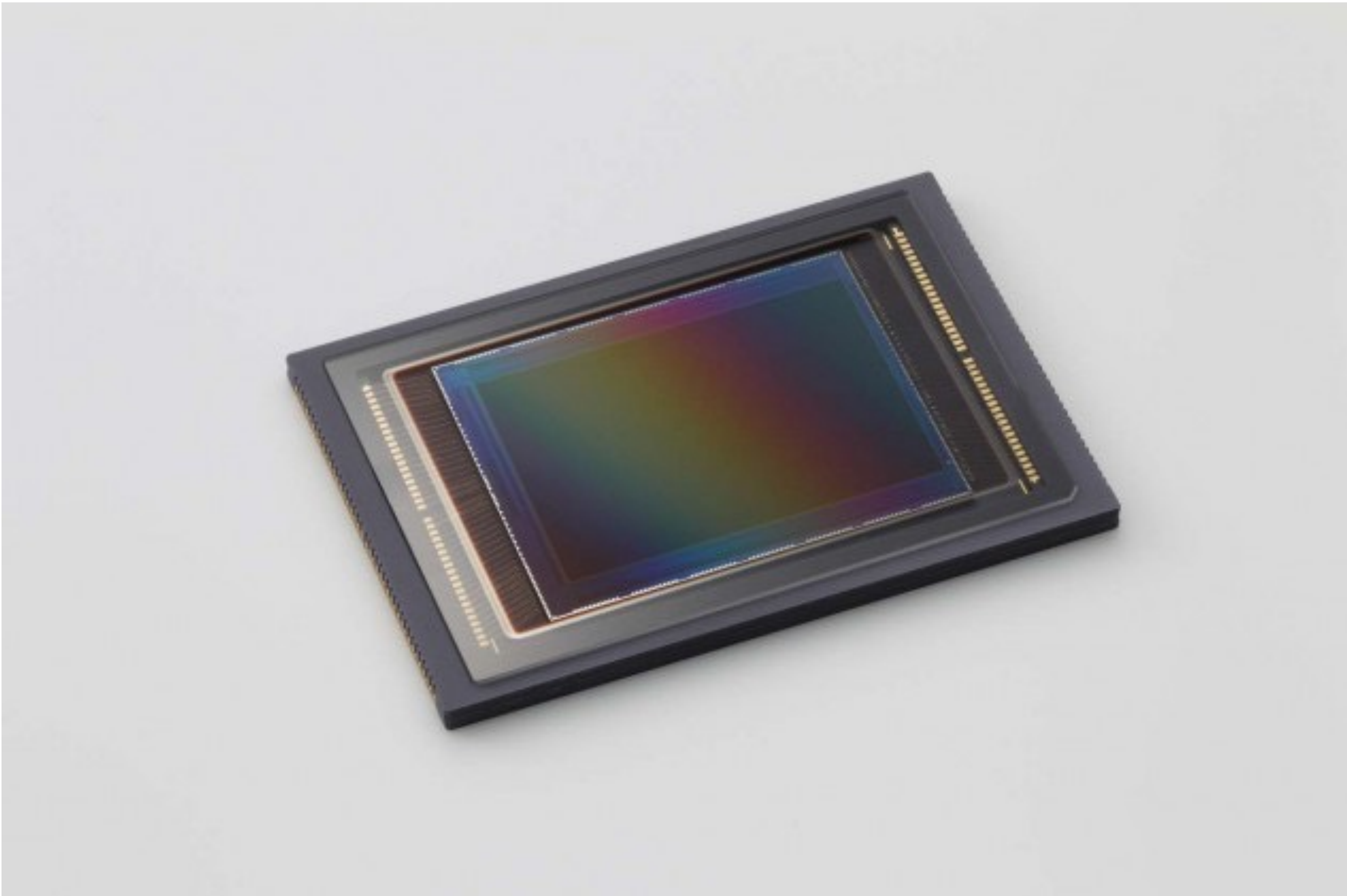
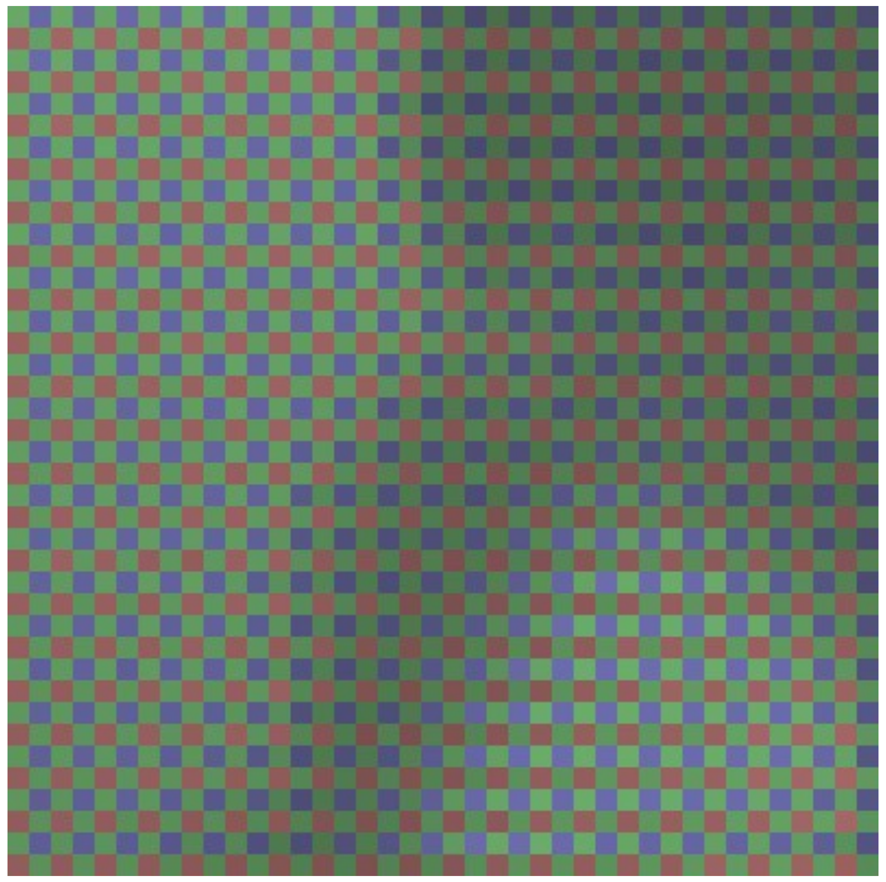
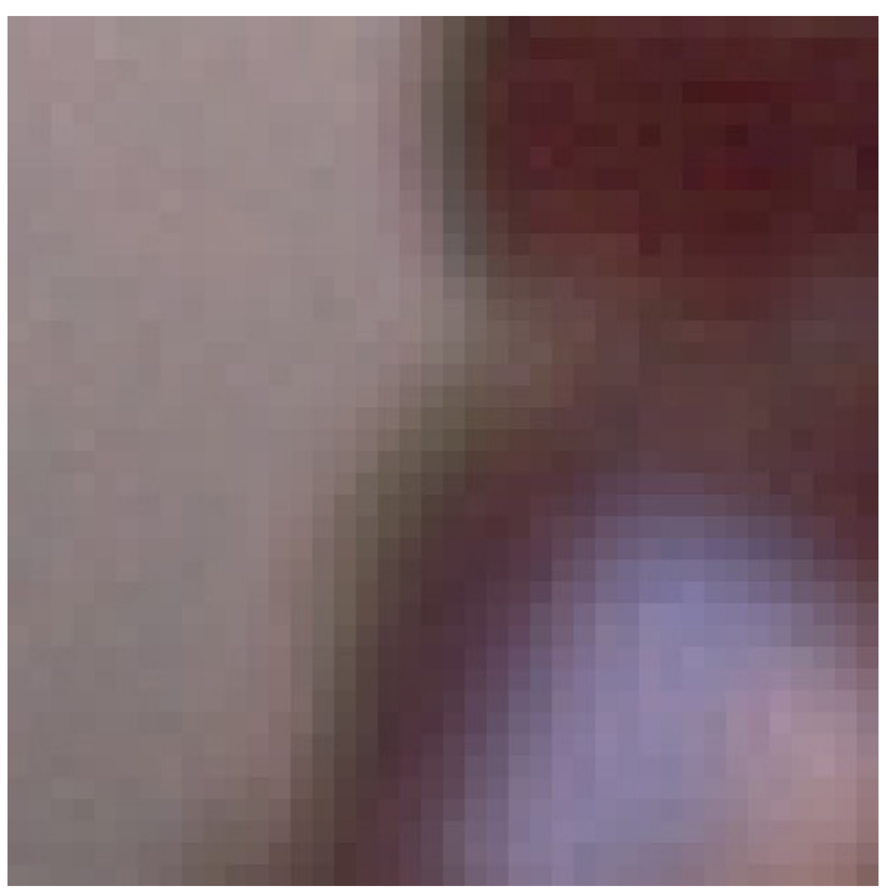


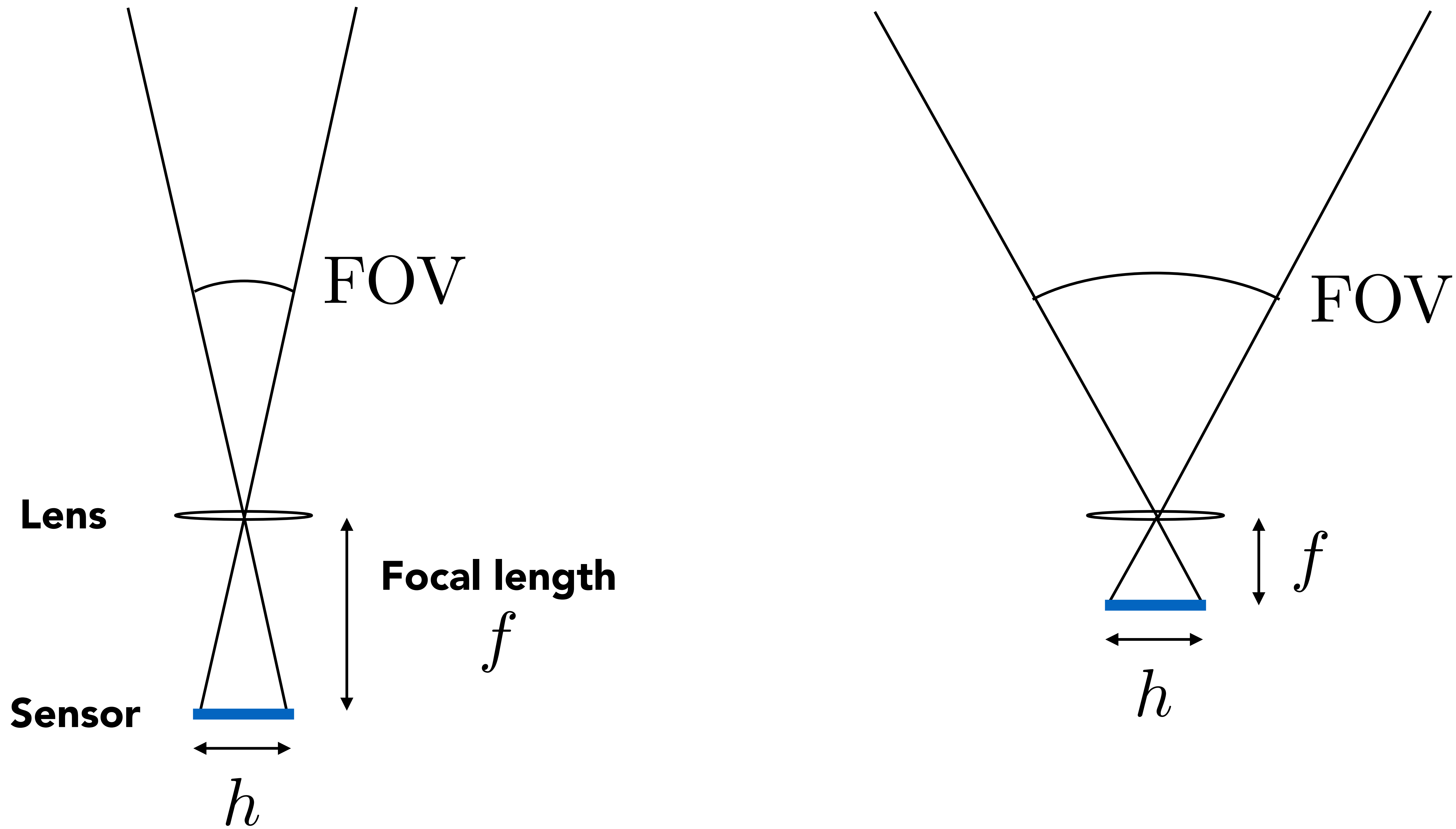
Image Processing: From Sensor Values to Image





Optics of Image Formation: Field of View

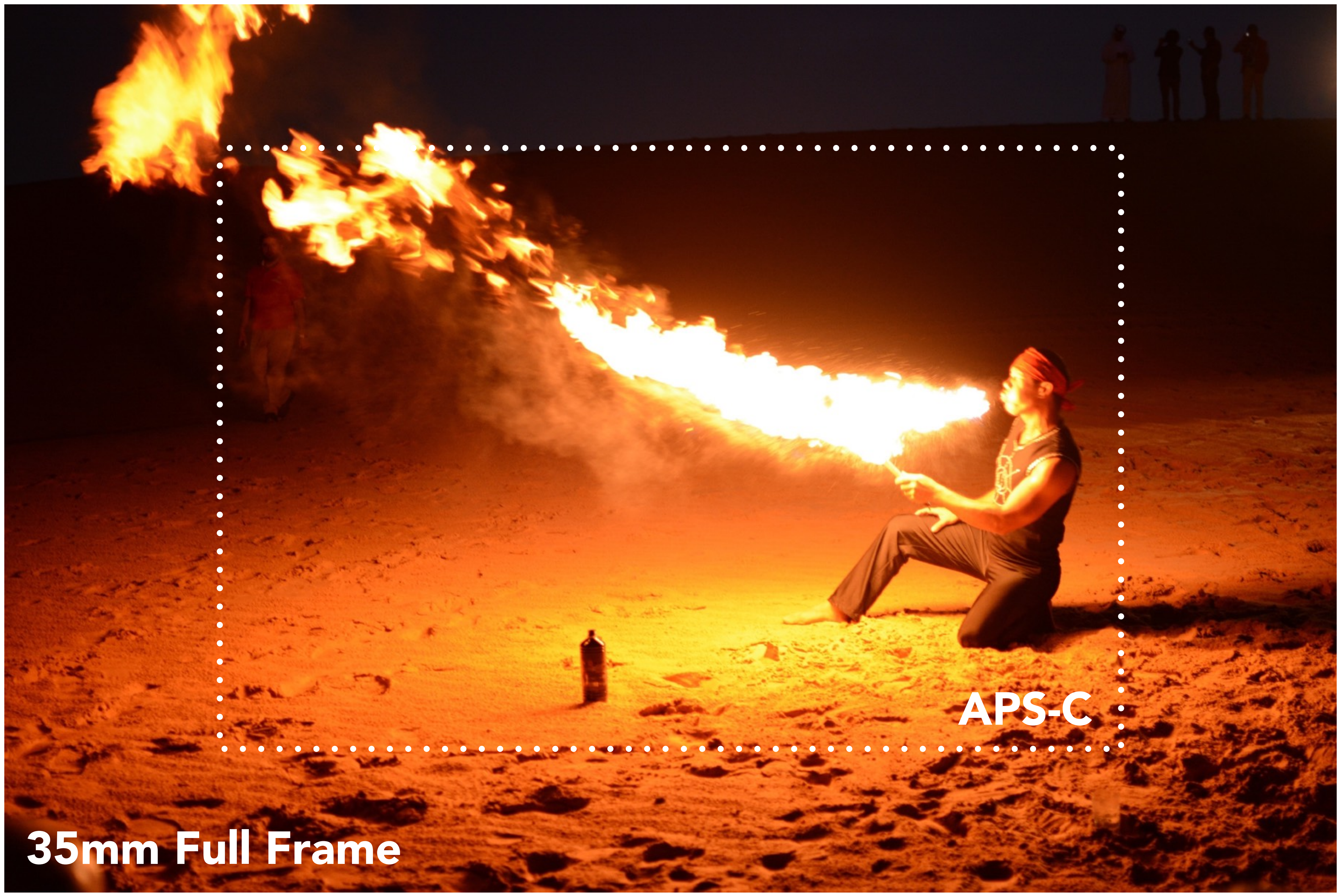
Effect of Focal Length on FOV

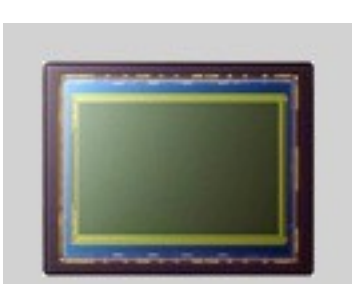


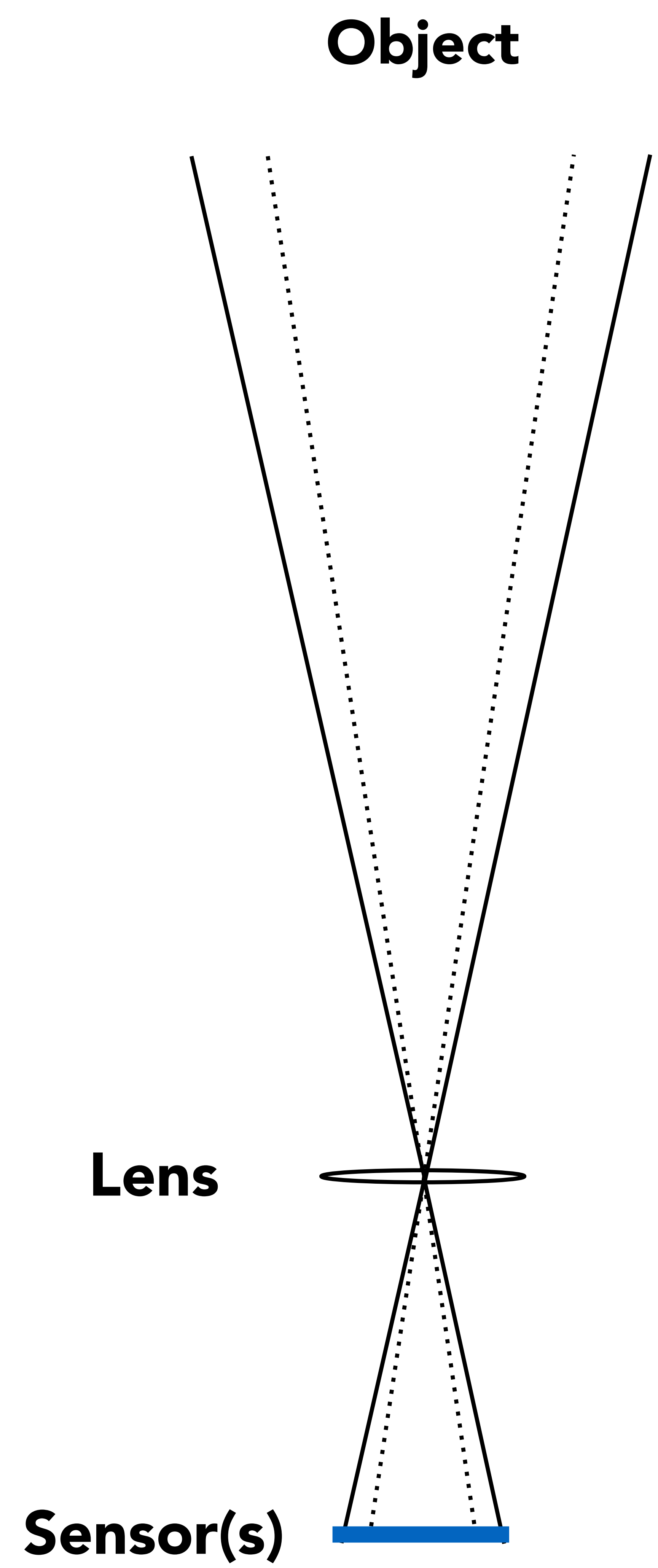
For a fixed sensor size, decreasing the focal length increases the field of view.

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

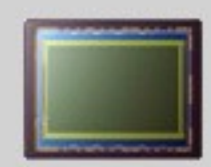
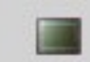
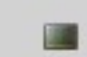
Effect of Sensor Size on FOV







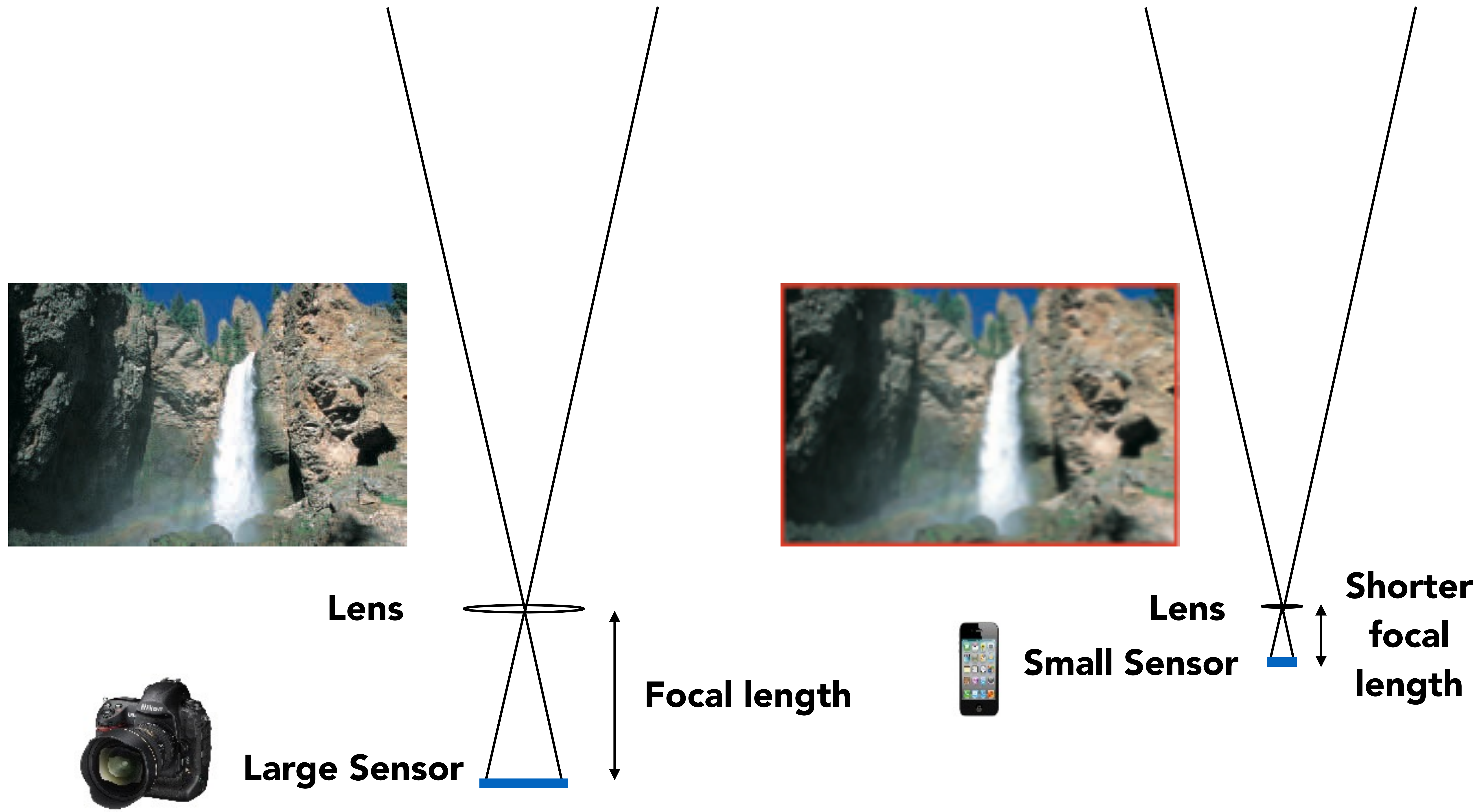
Sensor Sizes

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 cm²	8.6 cm²	5.19 cm²	3.73 cm²	2.25 cm²	1.16 cm²	0.47 cm²	0.28 cm²	0.15 cm²
Crop Factor	0.64	1.0	1.29	1.52	2.0	2.7	4.3	5.62	7.61
Image									
Example									

LensVid

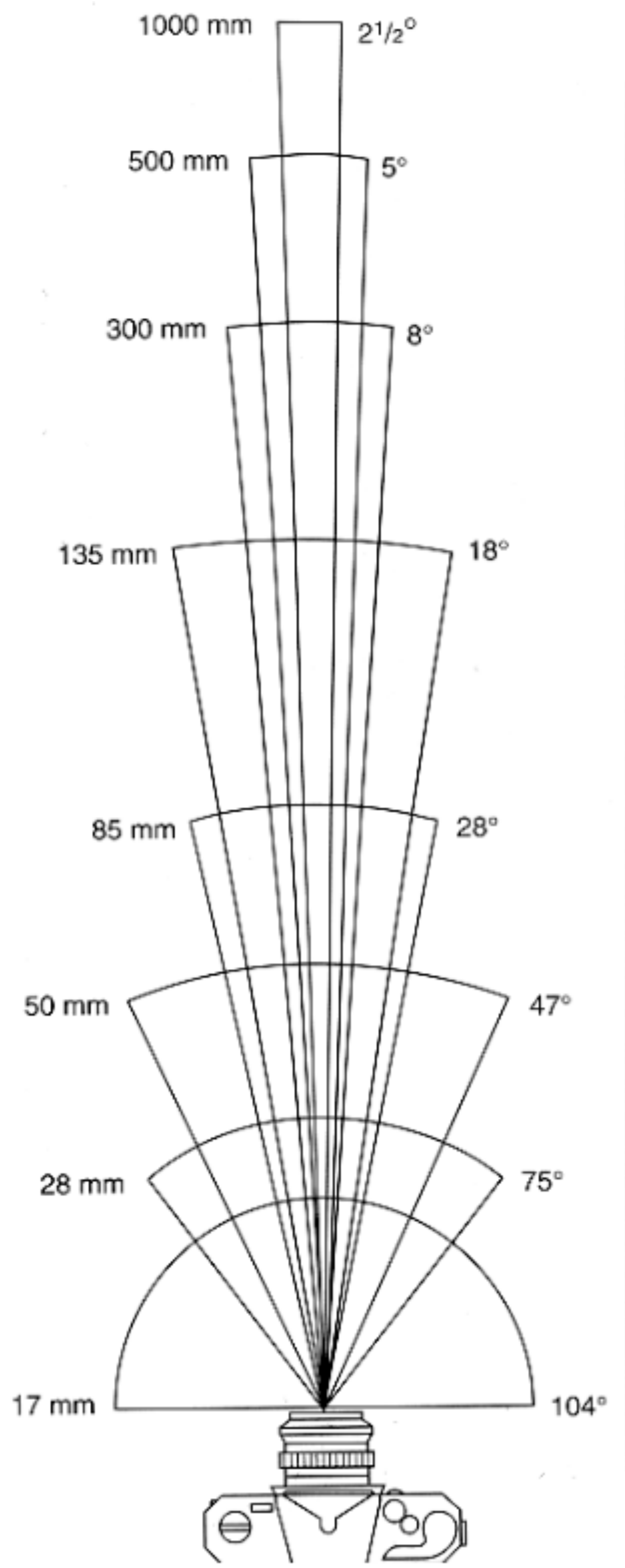
Credit: lensvid.com

Maintain FOV on Smaller Sensor?



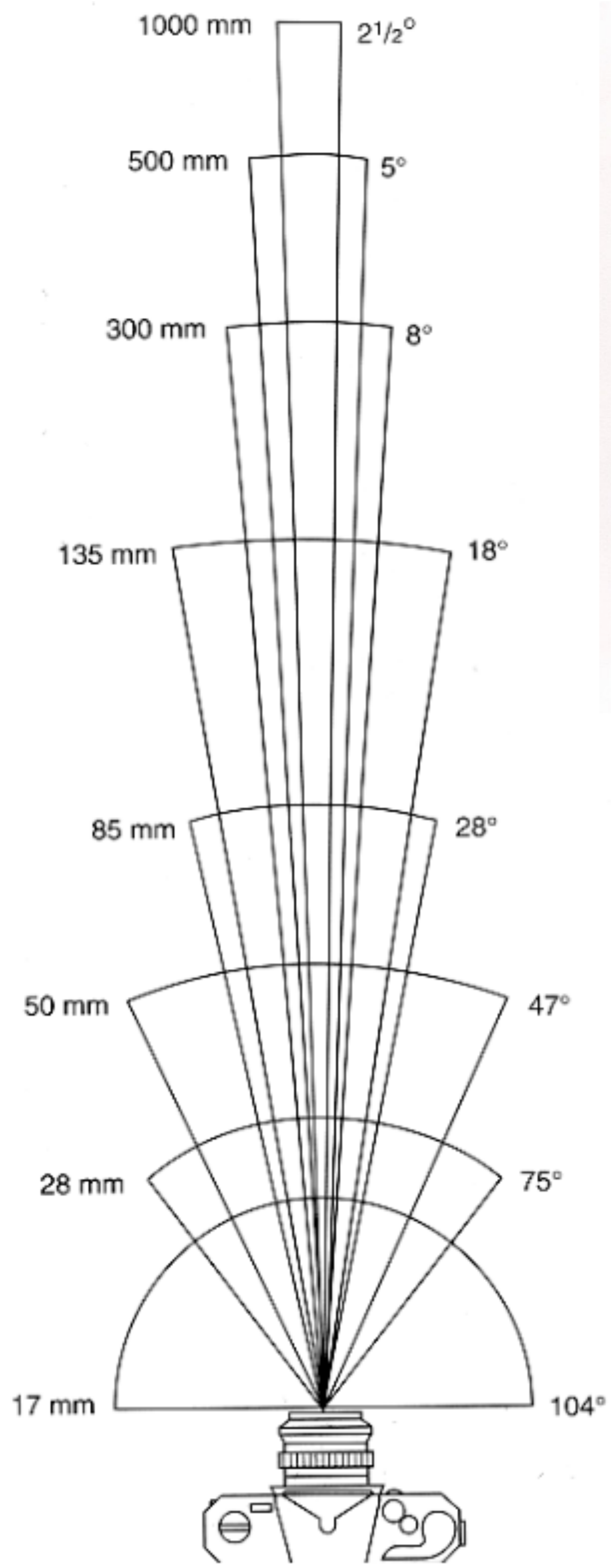
To maintain FOV, decrease focal length of lens
in proportion to width/height of sensor

Focal Length v. Field of View



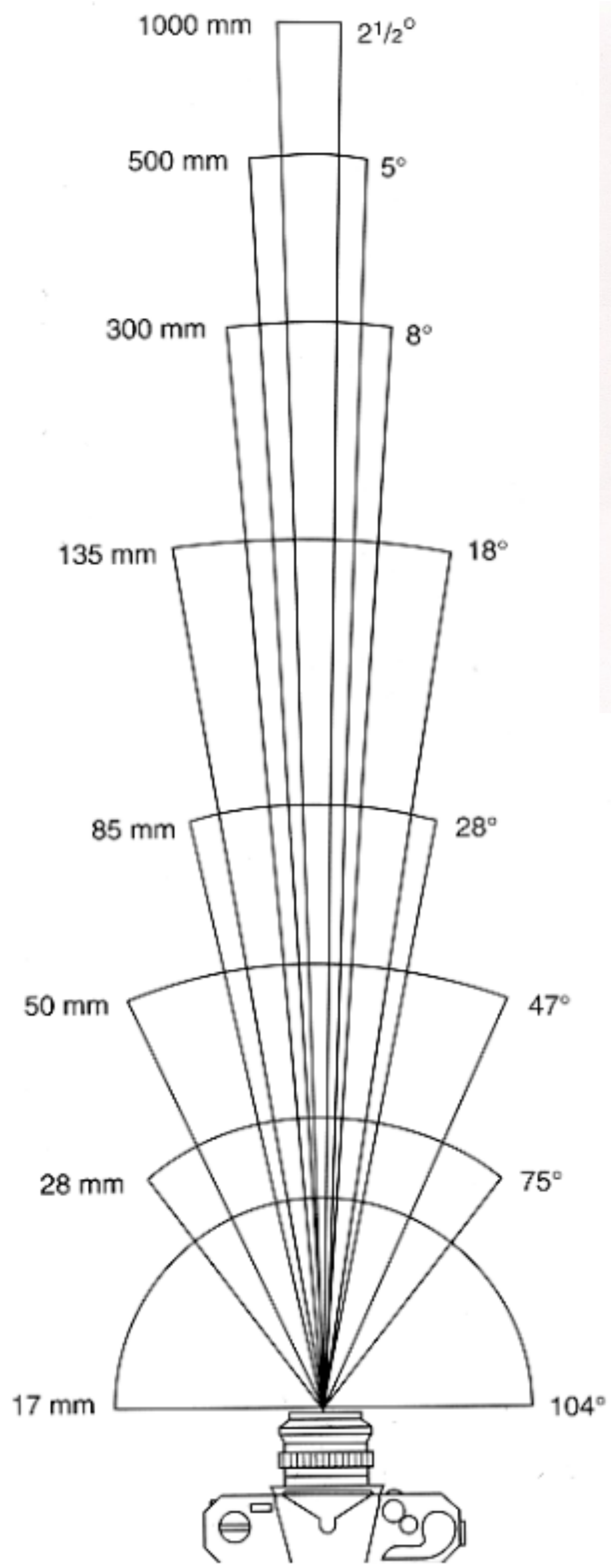
- For historical reasons, it is common to refer to angular field of view by focal length of a lens used on a 35mm-format film (36 x 24mm)
- Examples of focal lengths on 35mm format:
  - 17mm is wide angle 104°
  - 50mm is a "normal" lens 47°
  - 200mm is telephoto lens 12°
- Careful! When we say current 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



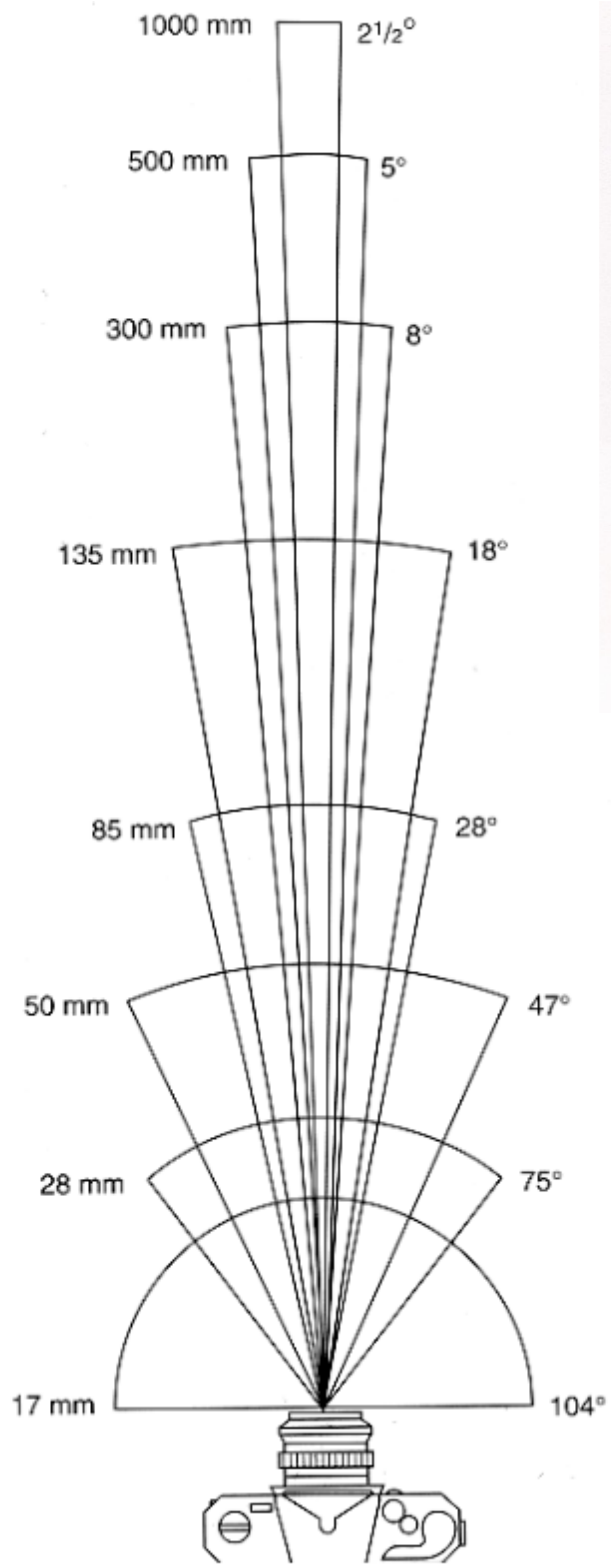
From London and Upton, and Canon EF Lens Work III

Focal Length v. Field of View



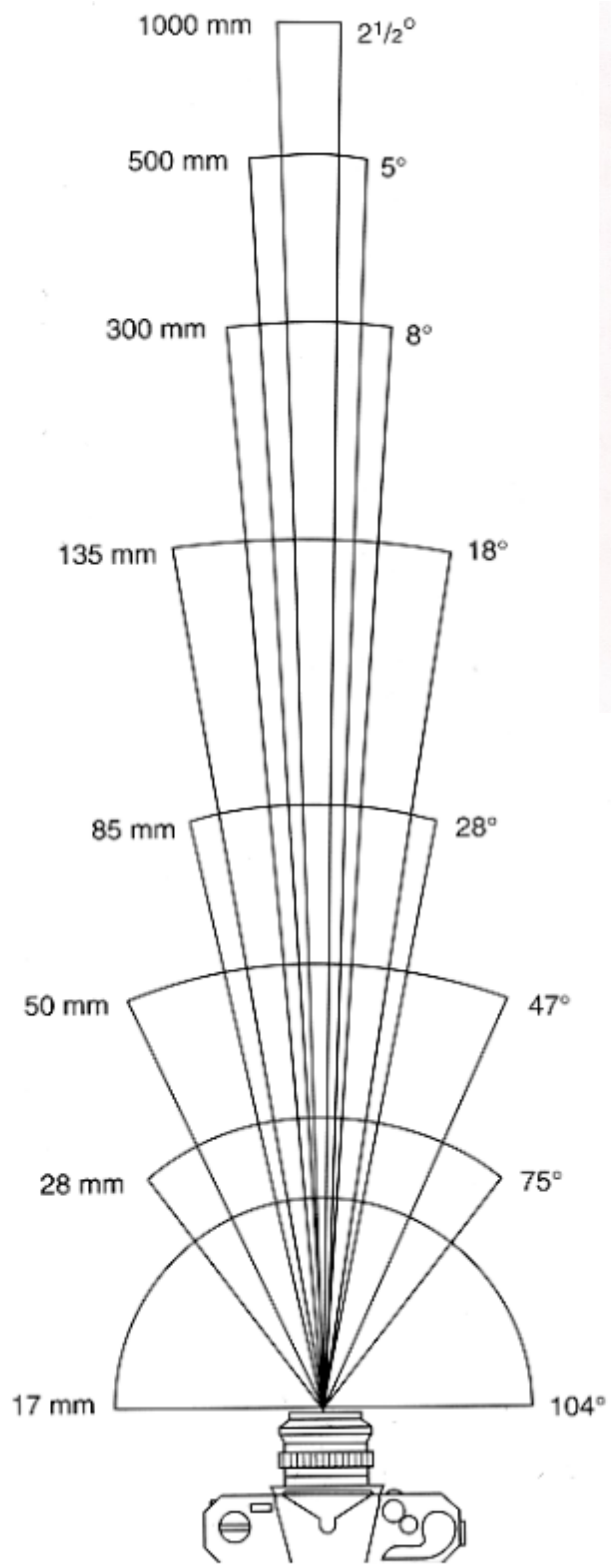
From London and Upton, and Canon EF Lens Work III

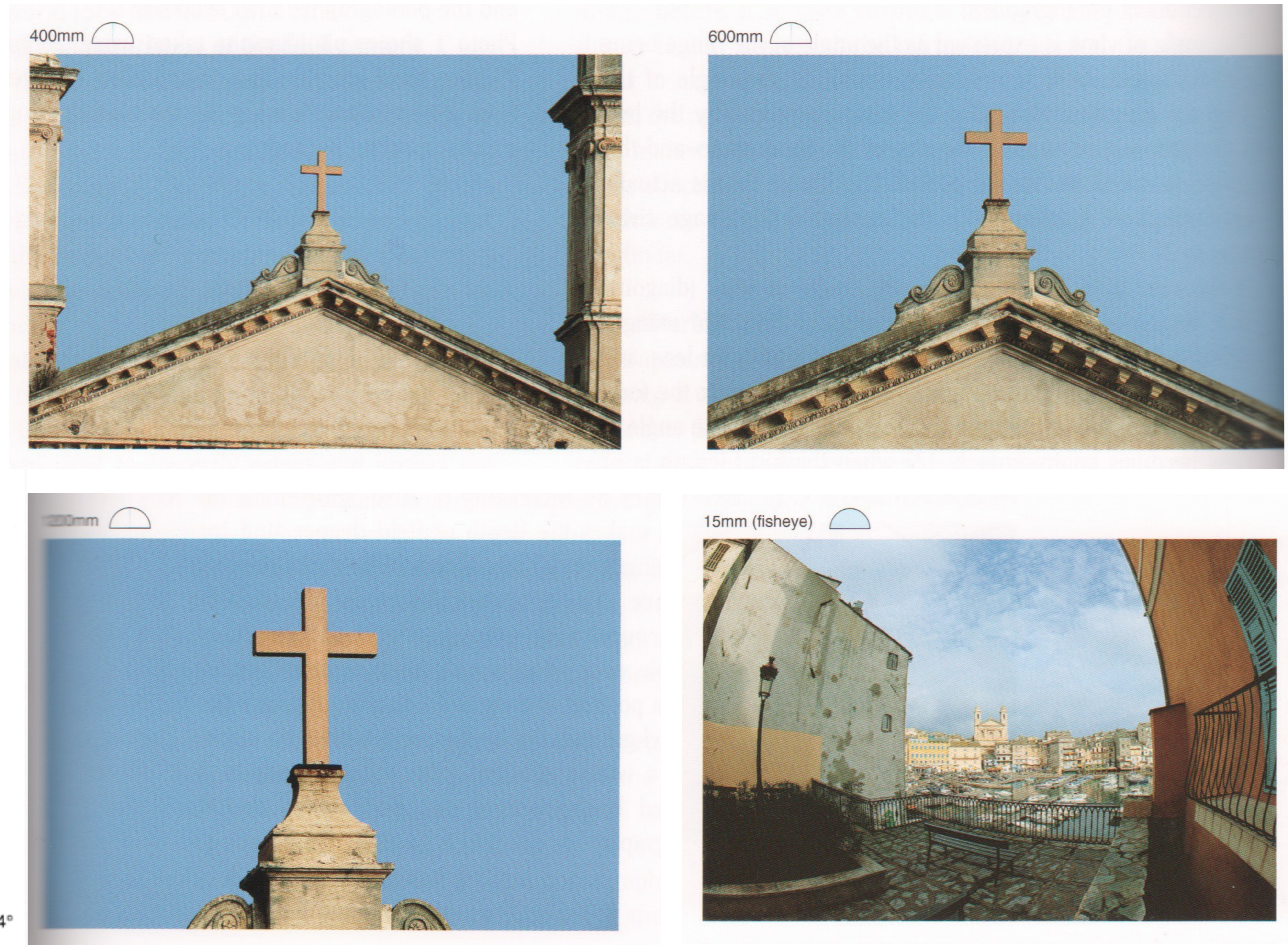
Focal Length v. Field of View



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

Perspective Composition (Photographer's Mindset)

Perspective Composition – Camera Position / Focal Length

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.

From Canon EF Lens Work III

Perspective Composition – Camera Position / Focal Length

24 mm

From Canon EF Lens Work III

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

Notice the dramatic change in background perspective.

Perspective Composition – Camera Position / Focal Length

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

Perspective Composition – Camera Position / Focal Length

135 mm

From Canon EF Lens Work III

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

Notice the dramatic change in background perspective.

Perspective Composition – Camera Position / Focal Length

200 mm

From Canon EF Lens Work III

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

Notice the dramatic change in background perspective.

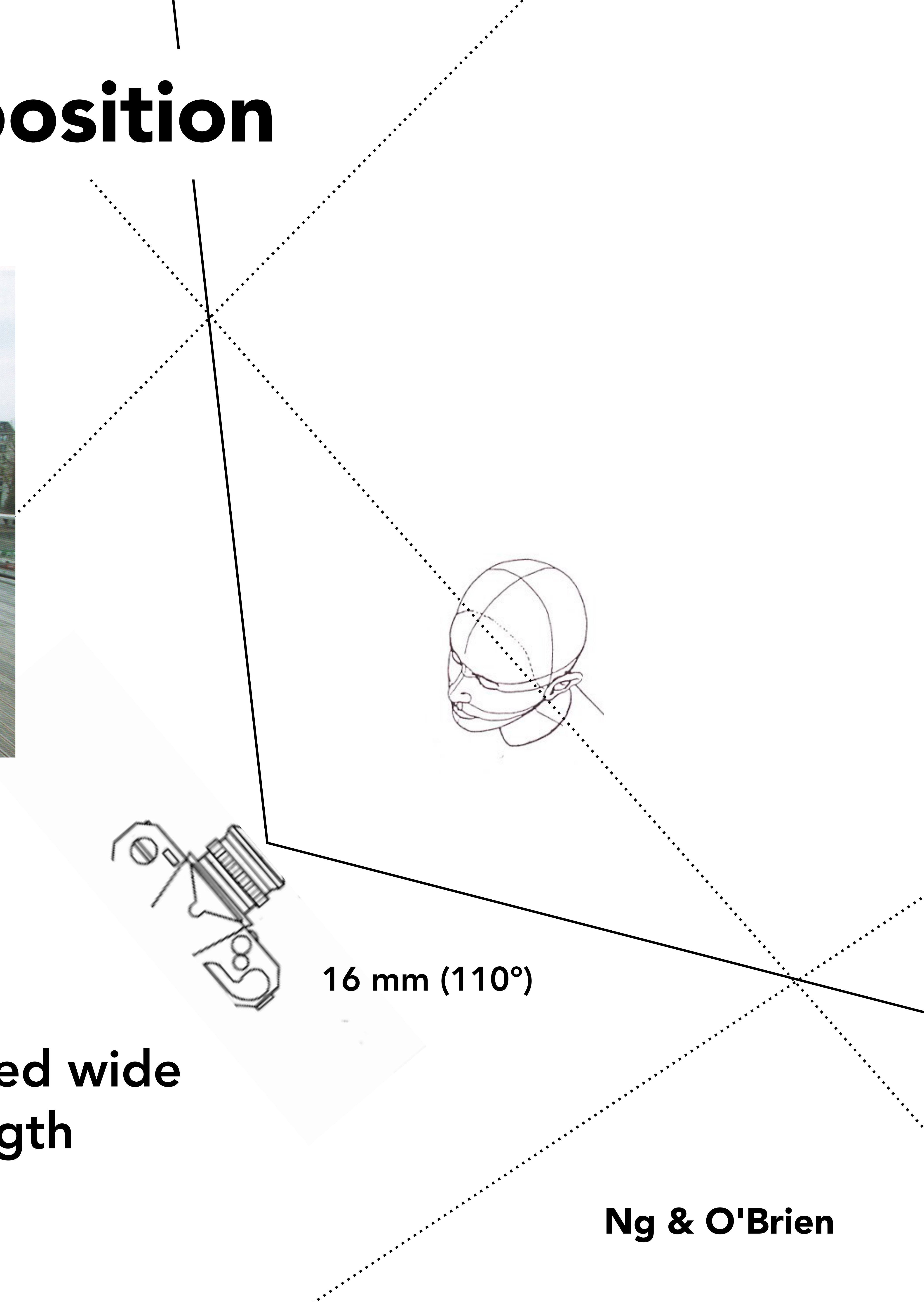
Perspective Composition – Camera Position / Focal Length

From Canon EF Lens Work III

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

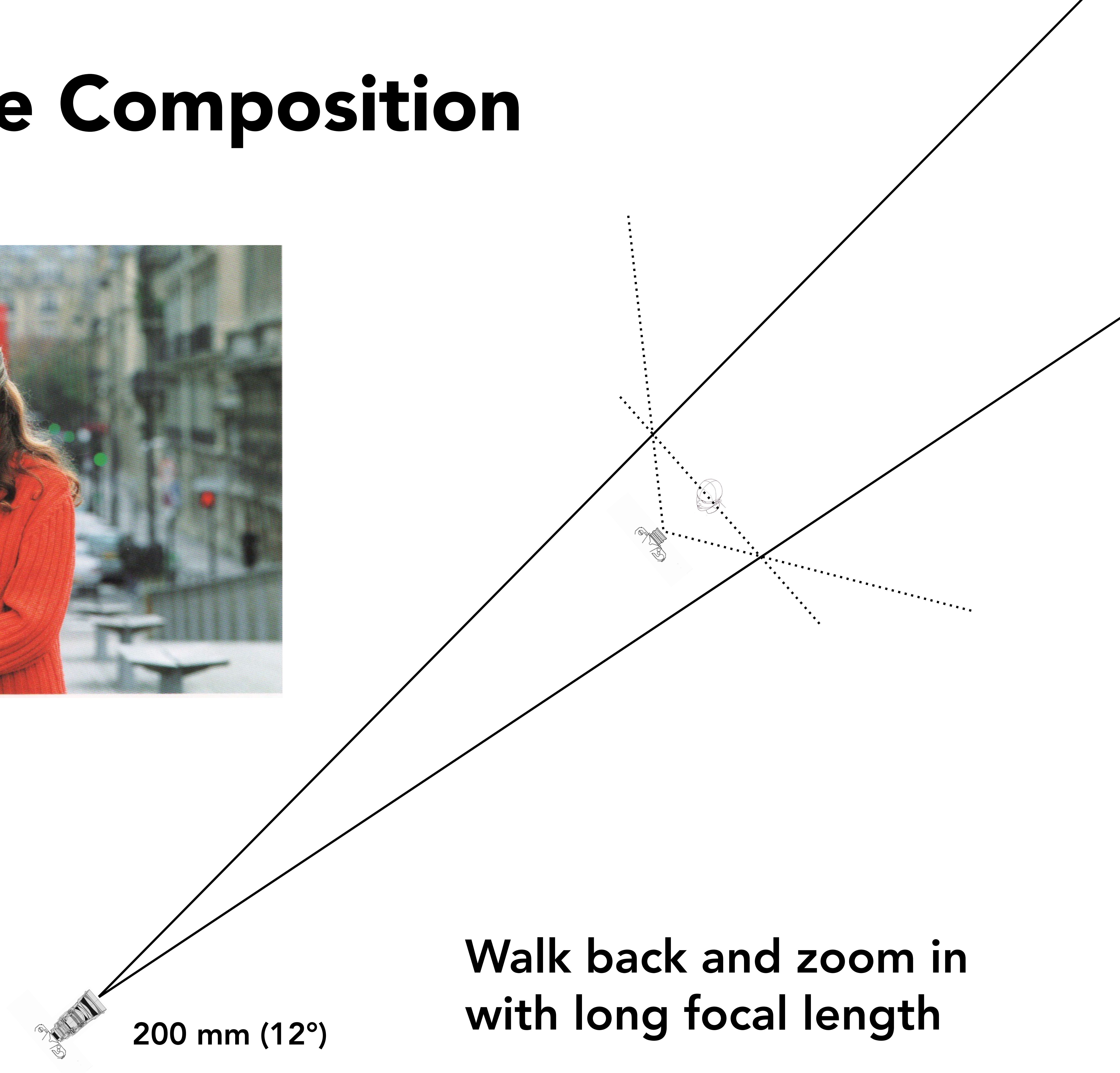
Notice the dramatic change in background perspective.

Perspective Composition



Up close and zoomed wide
with short focal length

Perspective Composition

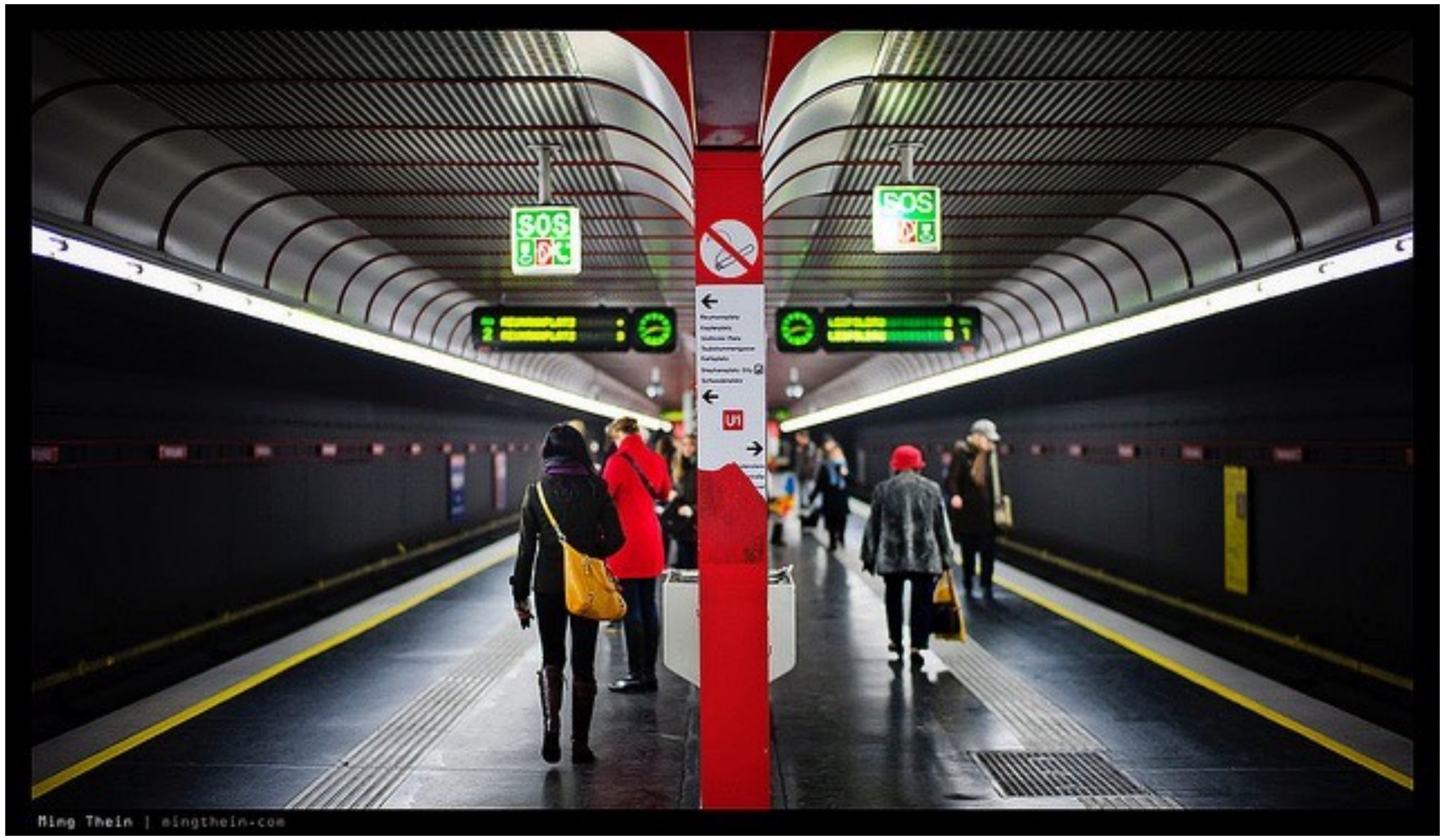


Walk back and zoom in with long focal length

Dolly-Zoom Cinema Technique – a.k.a. "Vertigo Effect"

By Steven Spielberg in "Jaws" 1975

A Photographer's Mindset



"Choose your perspective before you choose your lens."

— Ming Thein, 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!

Exposure

Exposure Levels - “Stops” are Logarithmic

- Here, different exposure levels with +/– 1 “stop” of exposure
- In photography, a “stop” = a doubling of exposure
- The natural, perceptual scale of exposure is logarithmic

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

Exposure

- Exposure = irradiance x time x gain
- Irradiance
    - Power of light falling on image sensor pixel
    - Affected by scene brightness, pixel size, lens aperture…
- Exposure time
    - Duration that the image sensor exposed to light
    - Affected by shutter opening / closing
- Gain
    - Amplification of sensor pixel values
    - Affected by pixel-value amplifiers in image sensor

Exposure Controls: Aperture, Shutter, Gain (ISO)

Aperture

- Change the lens f-stop by opening / closing its physical aperture (if lens has iris control)

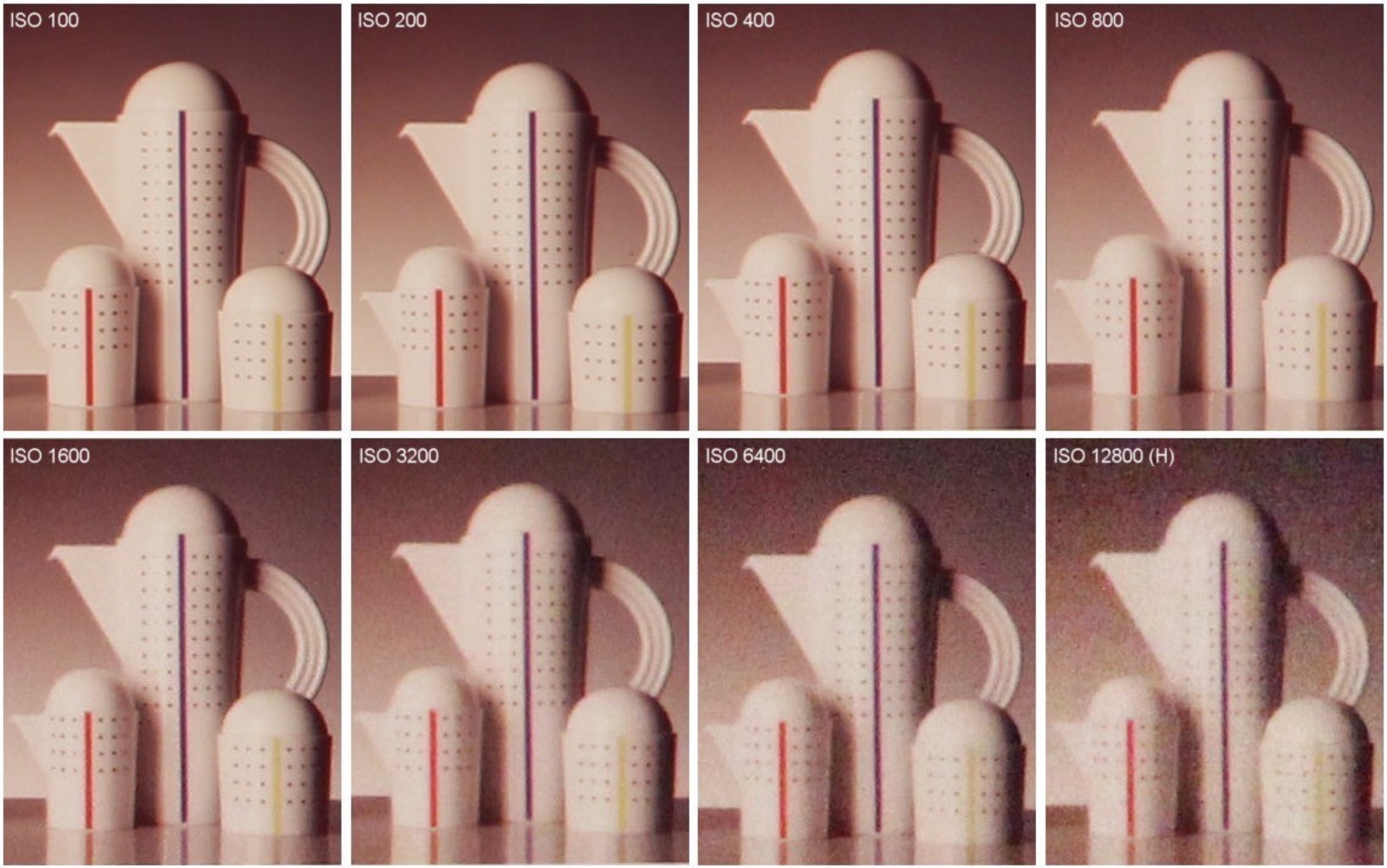
Shutter speed

- Change the duration that the sensor pixels are integrating light (physical or electronic shutter)

ISO gain

- Change the system amplification between sensor values and digital image values

Gain (ISO) — Noise Increases



Credit: bobatkins.com

 Note: trend is same in current sensors, but much less noise!

ISO (Gain)

Image sensor: trade sensitivity for noise

- Multiply signal before analog-to-digital conversion
- Linear effect (ISO 200 needs half the light as ISO 100)
- Typically, set gain to lowest value that works for the scene light level, to minimize noise

Many Ways to Achieve the Same Exposure

Have multiple ways to adjust aperture, shutter, gain to achieve a desired exposure

Example: all the following pairs of aperture and shutter give equivalent exposure (not same image, though!)

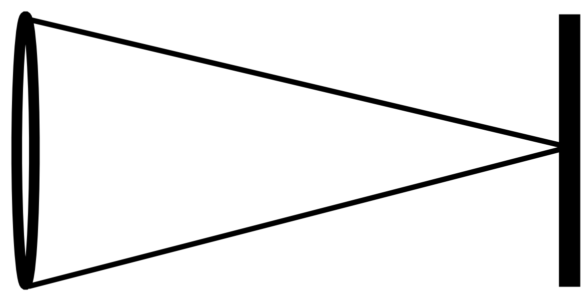
F-Stop	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0	22.0	32.0
Shutter	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1

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

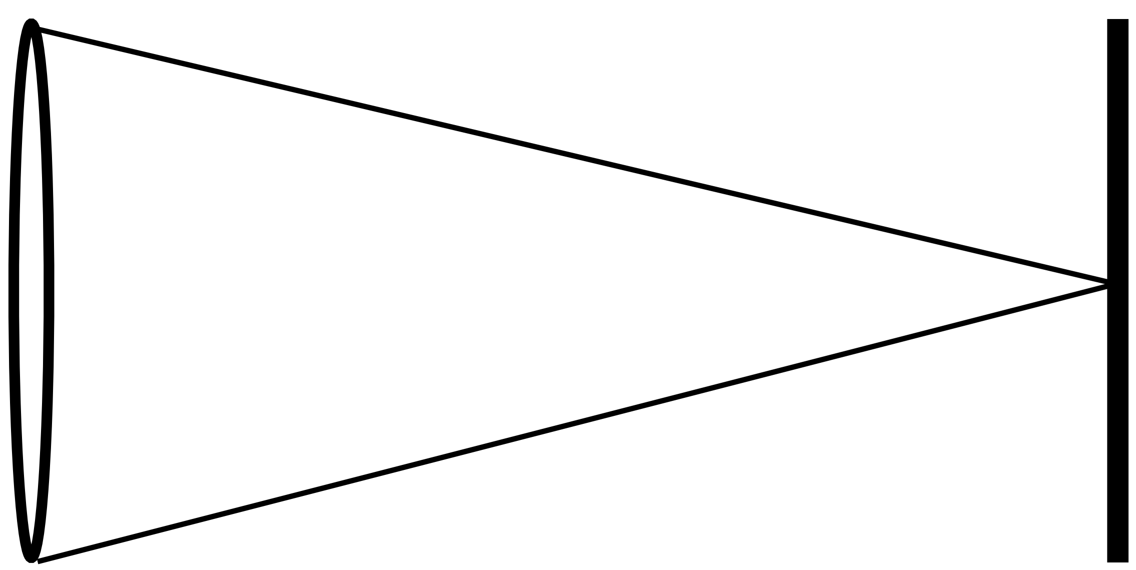
Definition: F-Number of a Lens

- 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 or F2

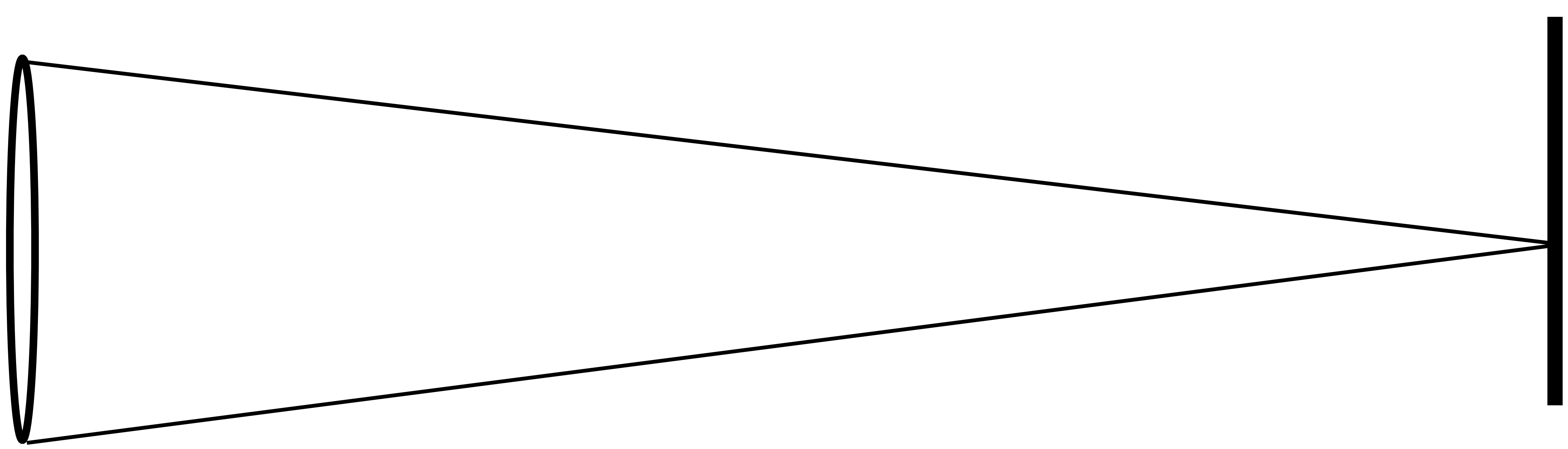
Example F-Number Calculations



$$D = 50\,\mathrm{mm}$$
$$f = 100\,\mathrm{mm}$$
$$N = f/D = 2$$



$$D = 100\,\mathrm{mm}$$
$$f = 200\,\mathrm{mm}$$
$$N = f/D = 2$$



$$D = 100\,\mathrm{mm}$$
$$f = 400\,\mathrm{mm}$$
$$N = f/D = 4$$

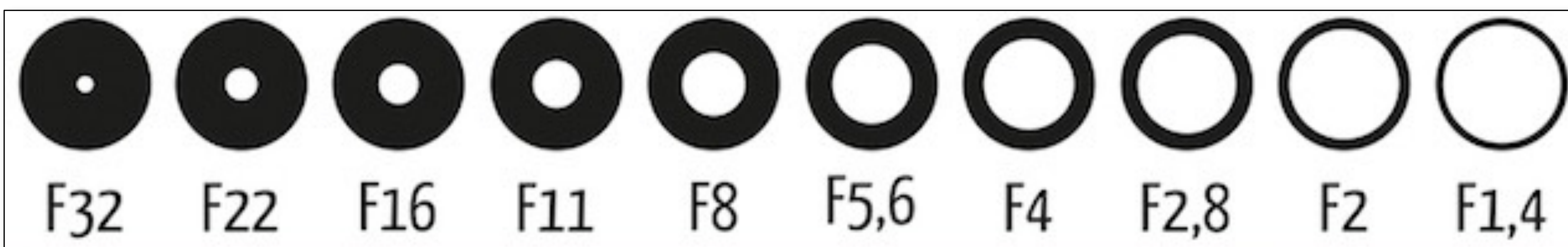
Lens's F-Number vs F-Number for Photo

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

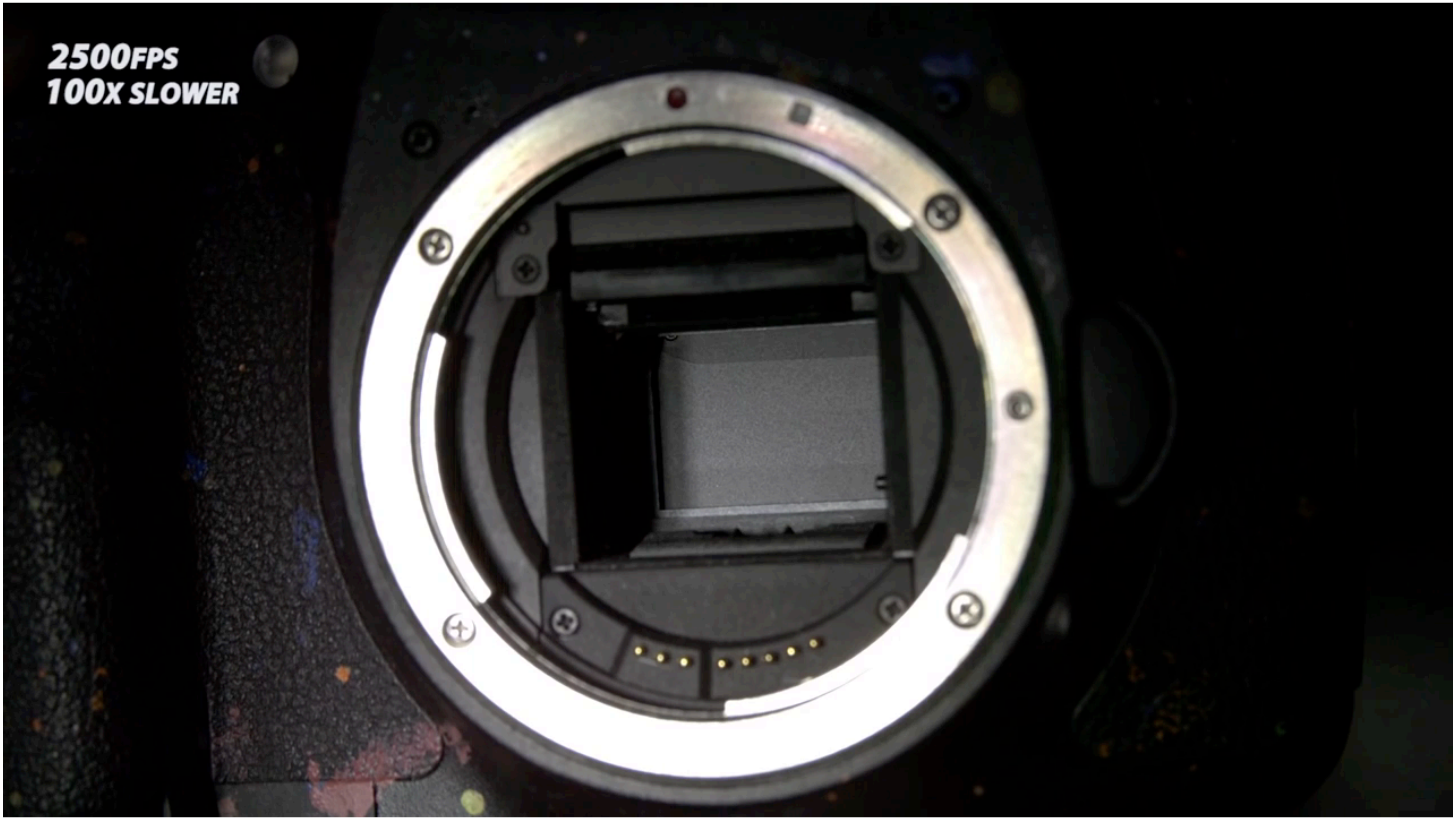
- E.g. 50 mm F/1.4 is a high-quality telephoto lens
  - Maximum aperture is 50/1.4 = 36 mm diameter

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



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

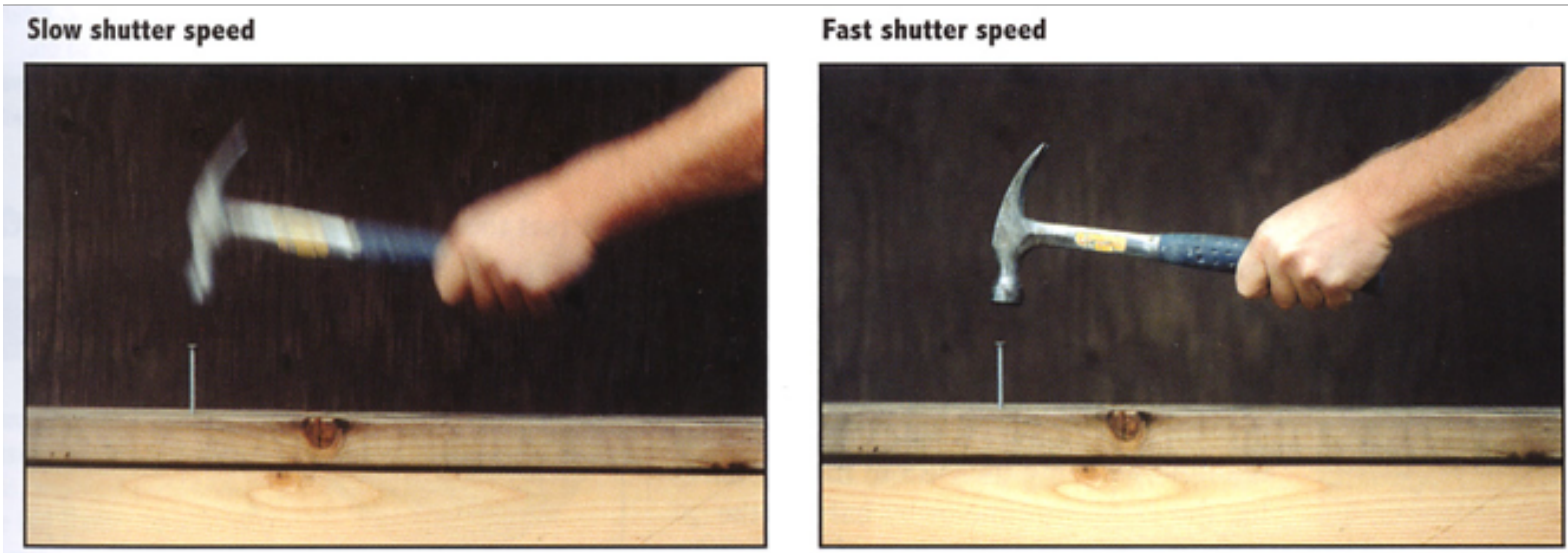
http://www.gavtrain.com/?p=3960

Gavin Hoey

Main Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur



London

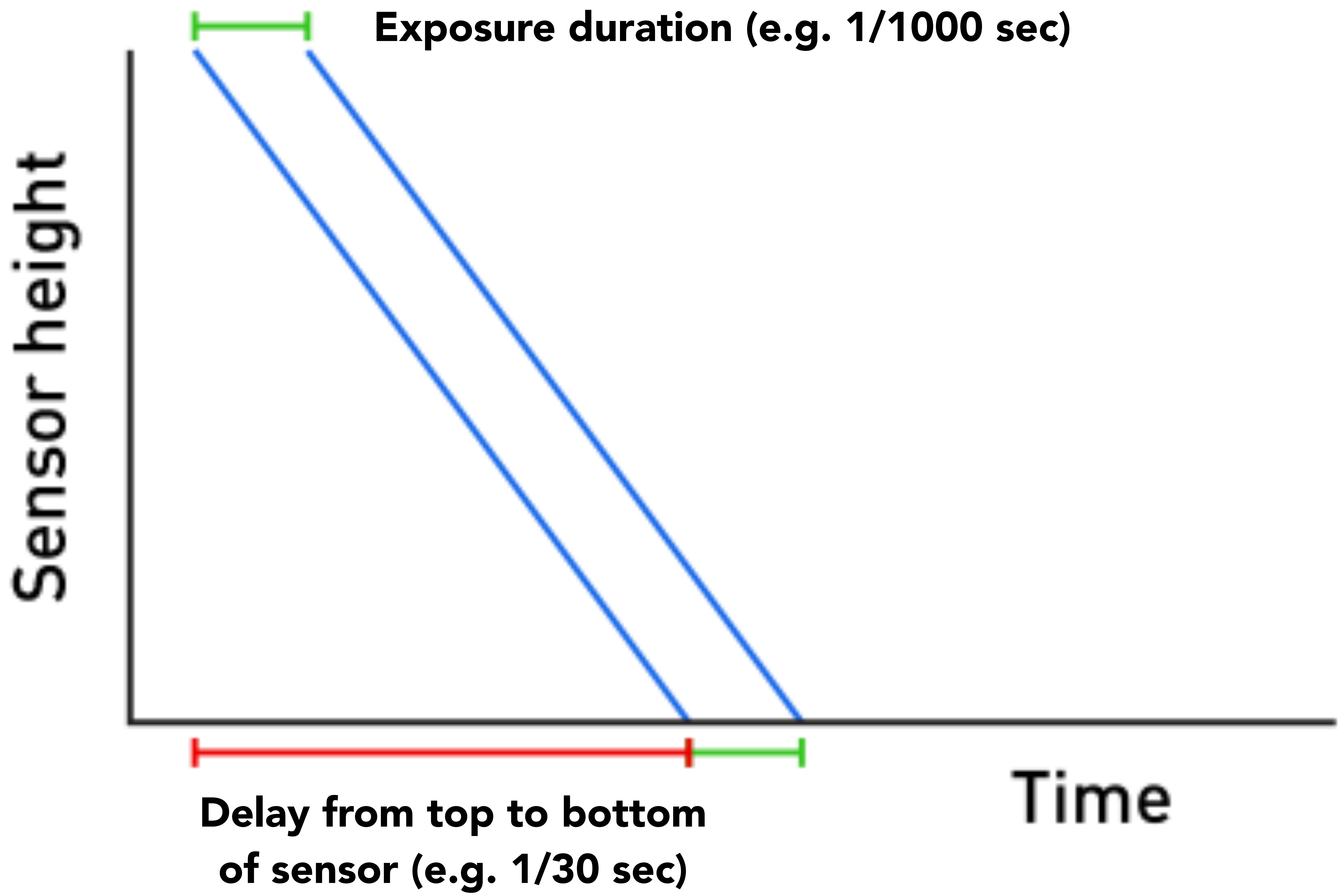
Electronic Shutter

- 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

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

Electronic Rolling Shutter



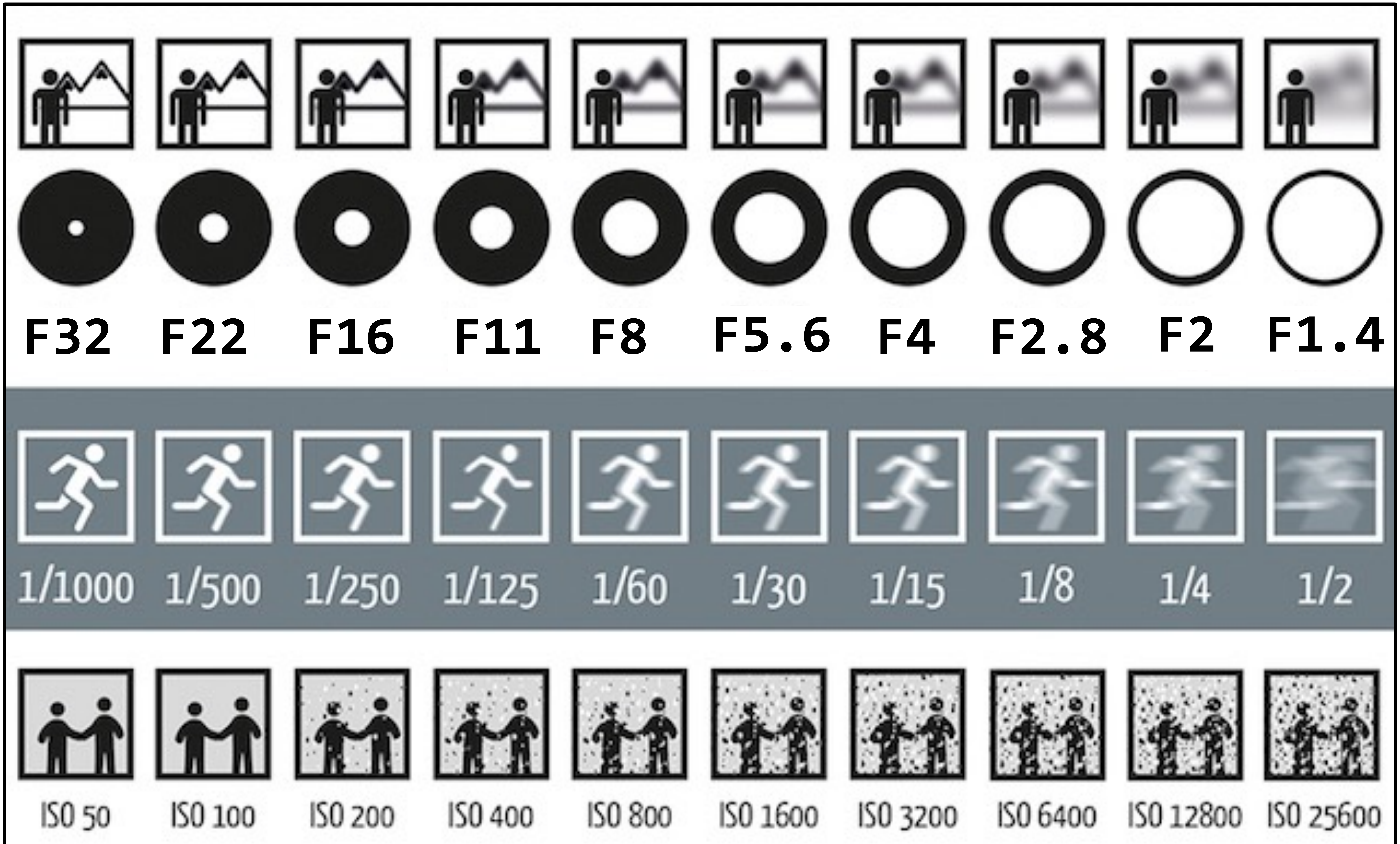
dpreview.com

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

Exposure Controls: Aperture, Shutter, Gain (ISO)



Photoblog Hamburg

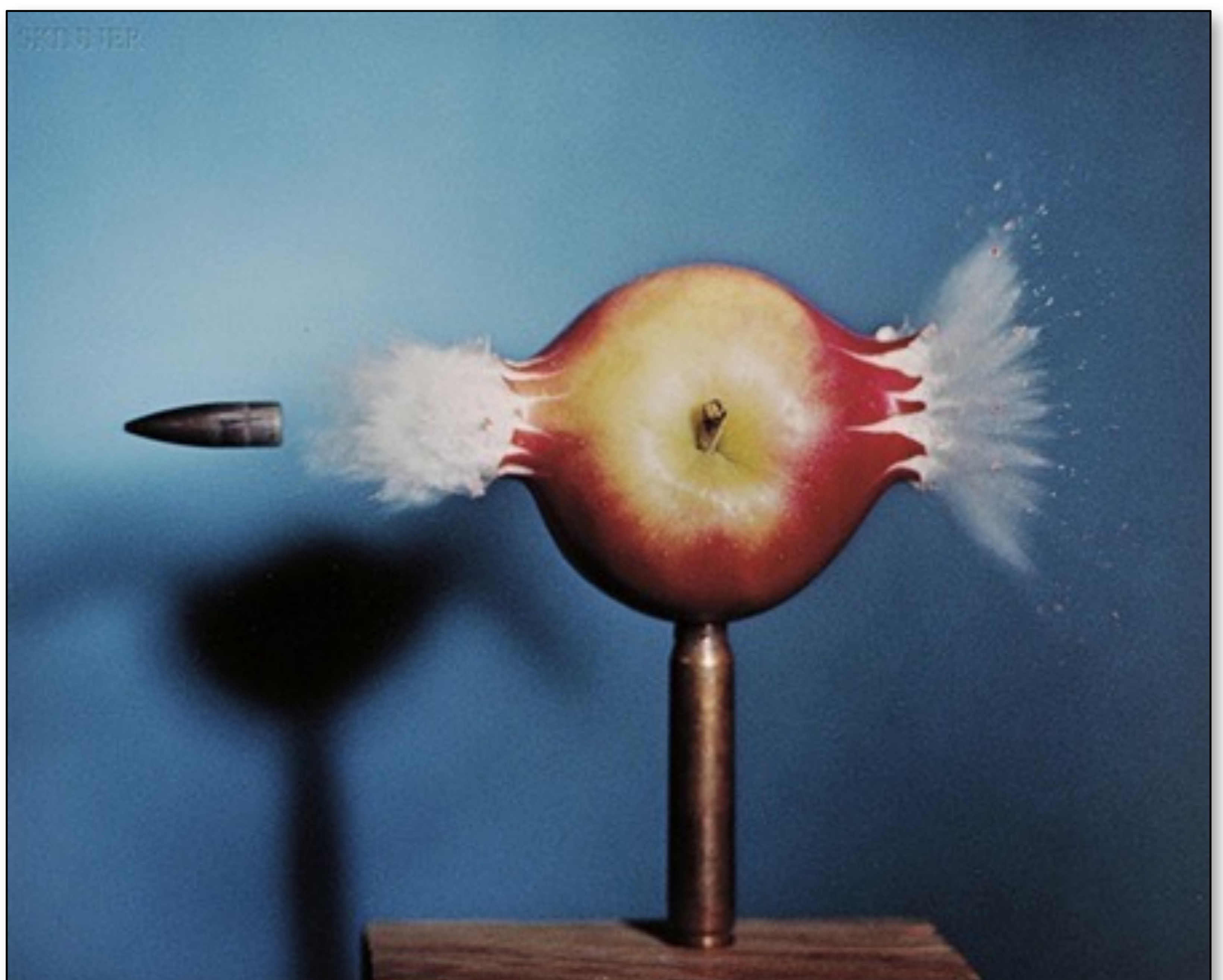
Exposure Duration:
Fast and Slow Photography

High-Speed Photography (Short Shutter)

long exposure

bright strobe illumination

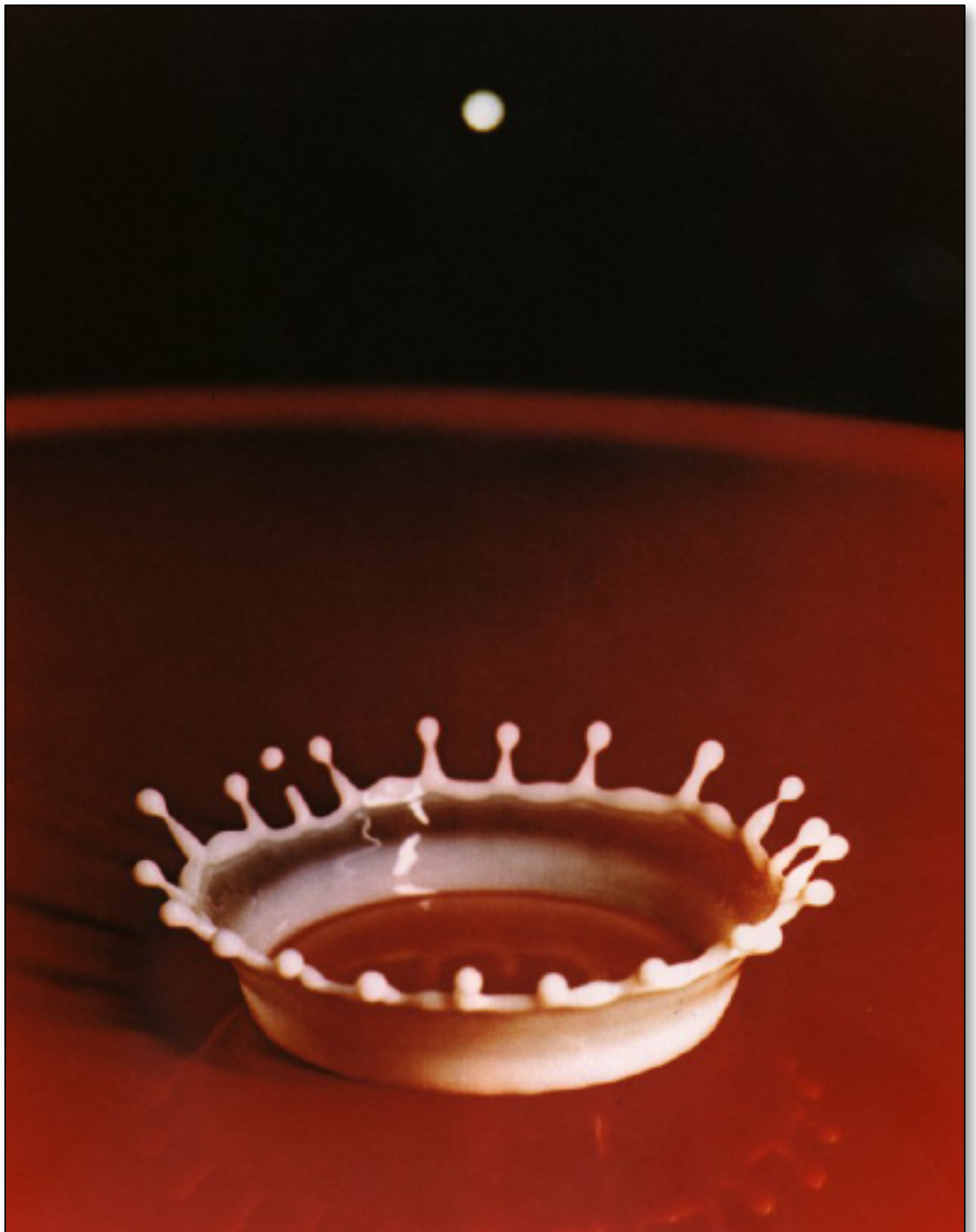
gun synced to camera

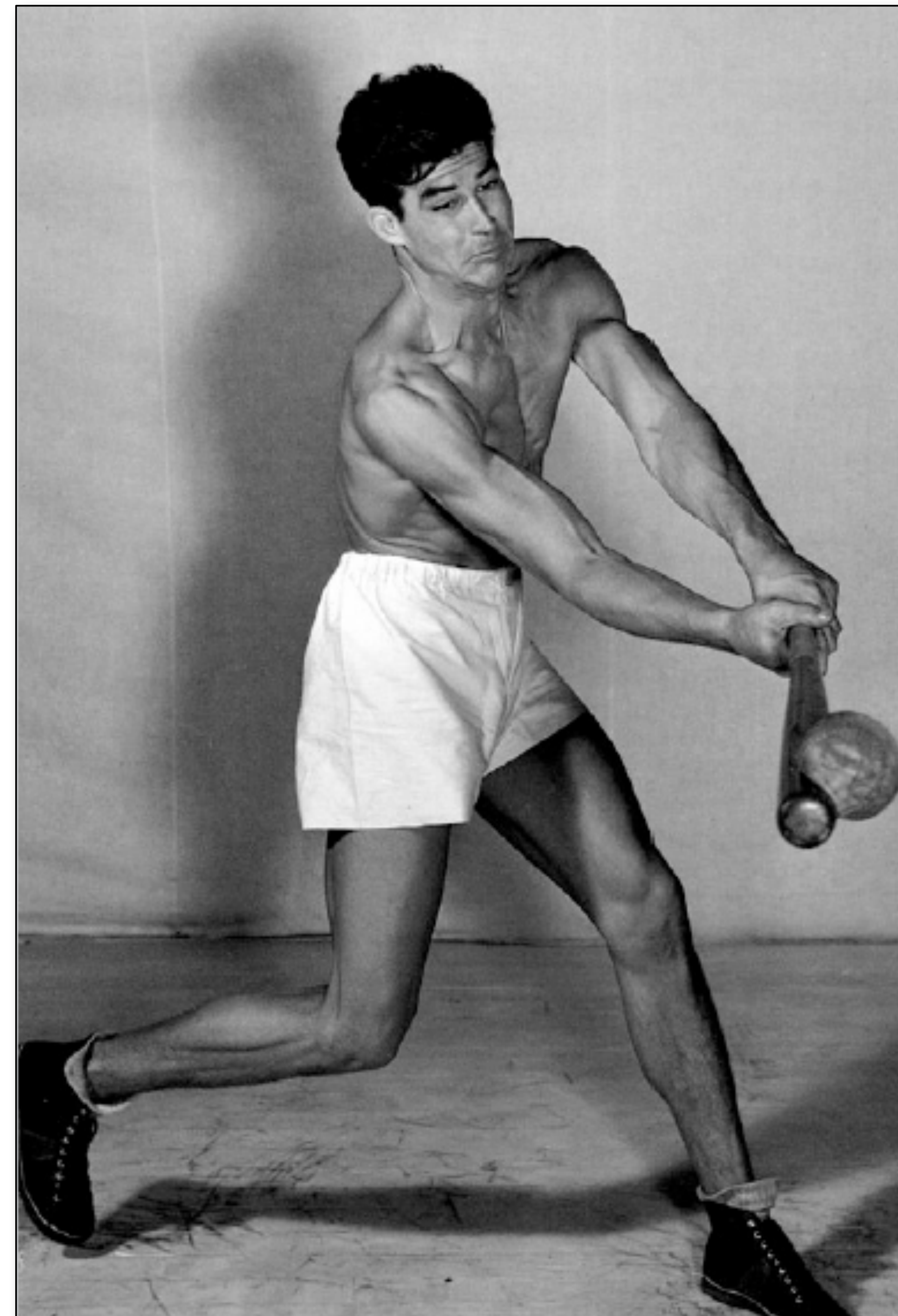


Mark Watson

Harold Edgerton

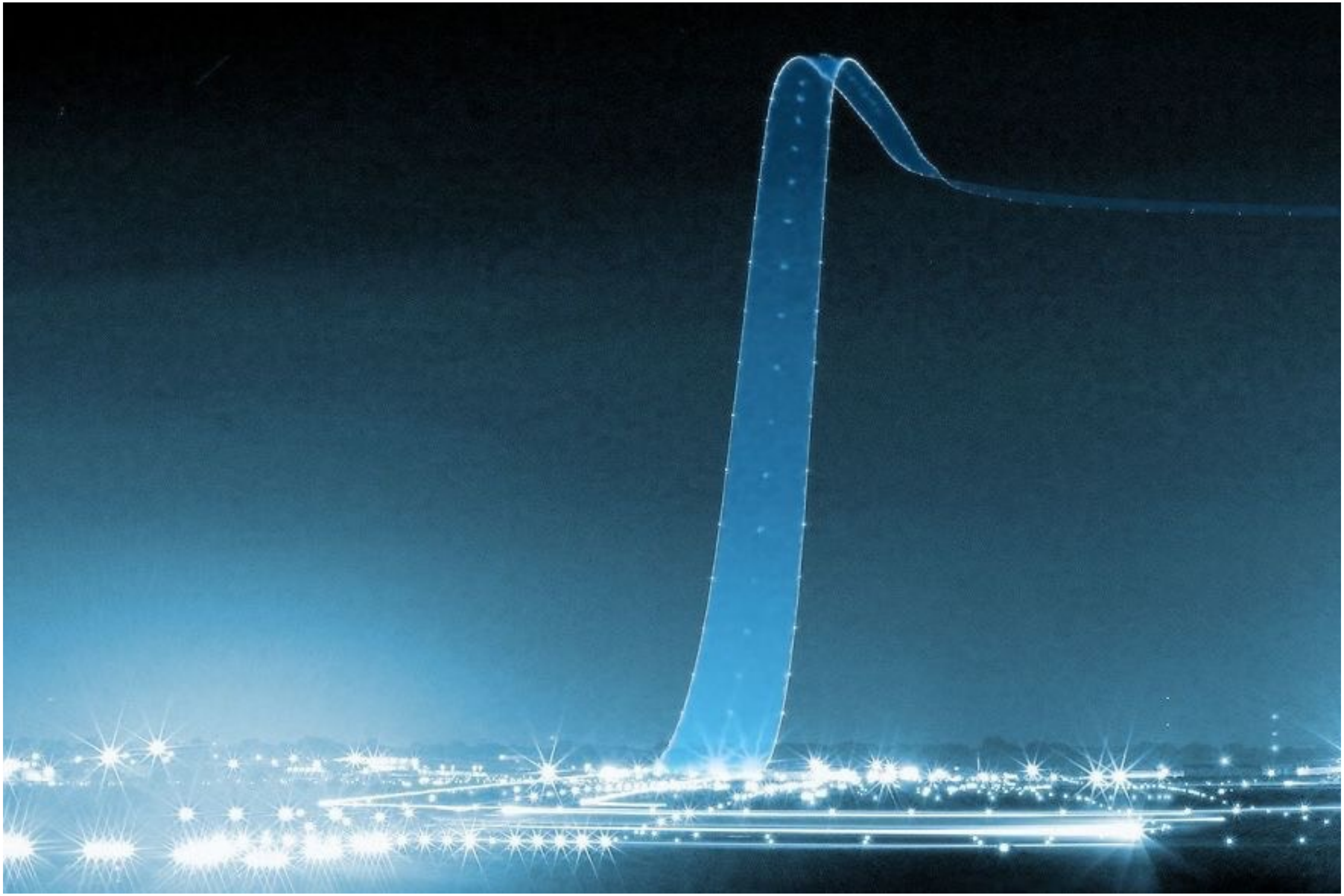
High-Speed Photography (Short Shutter)





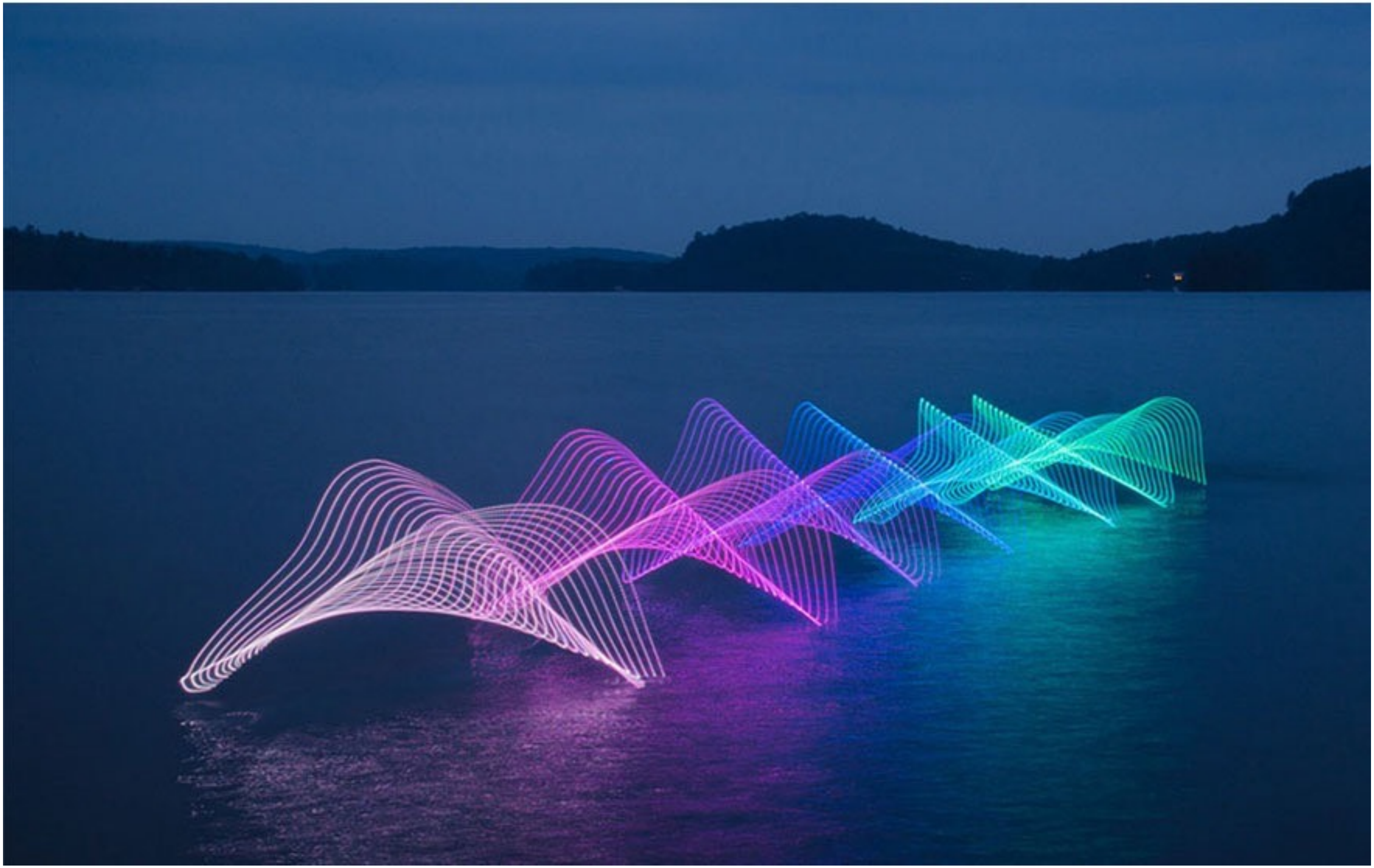
Harold Edgerton

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

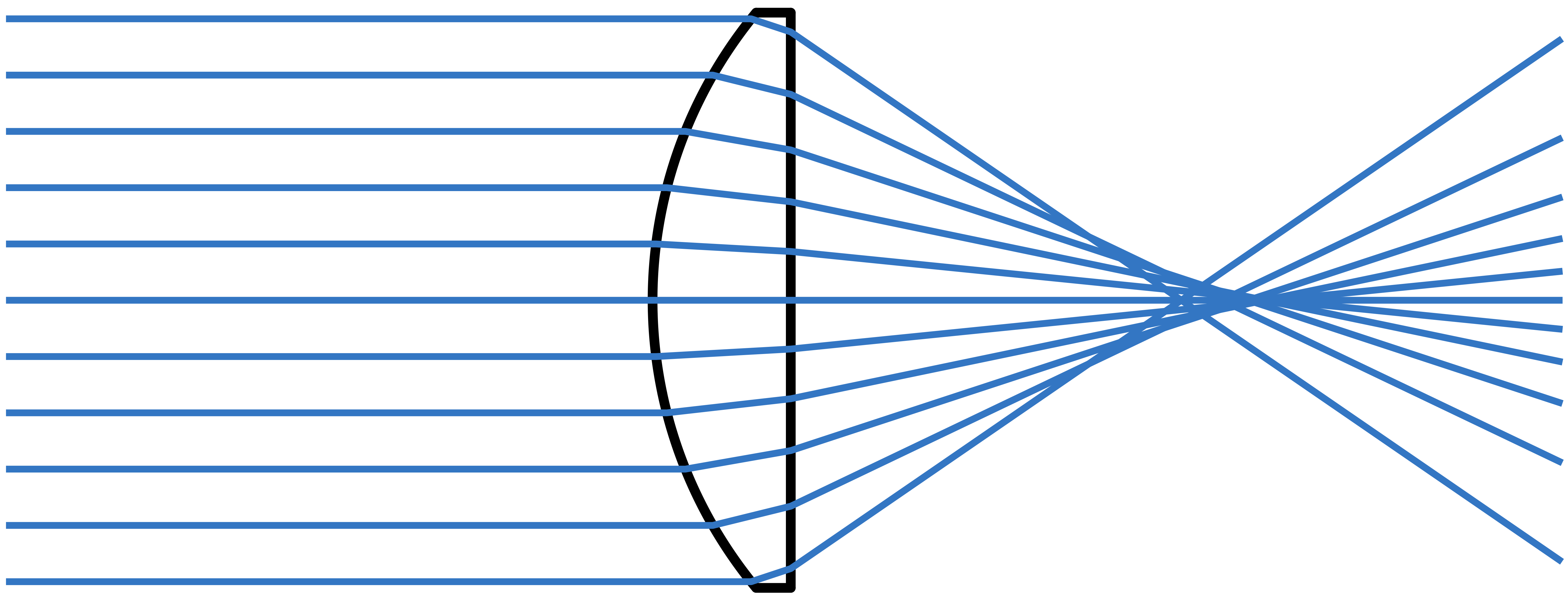
https://www.demilked.com/best-long-exposure-photos/

Optics of Lenses

Real Lens Designs Are Highly Complex

[Apple]

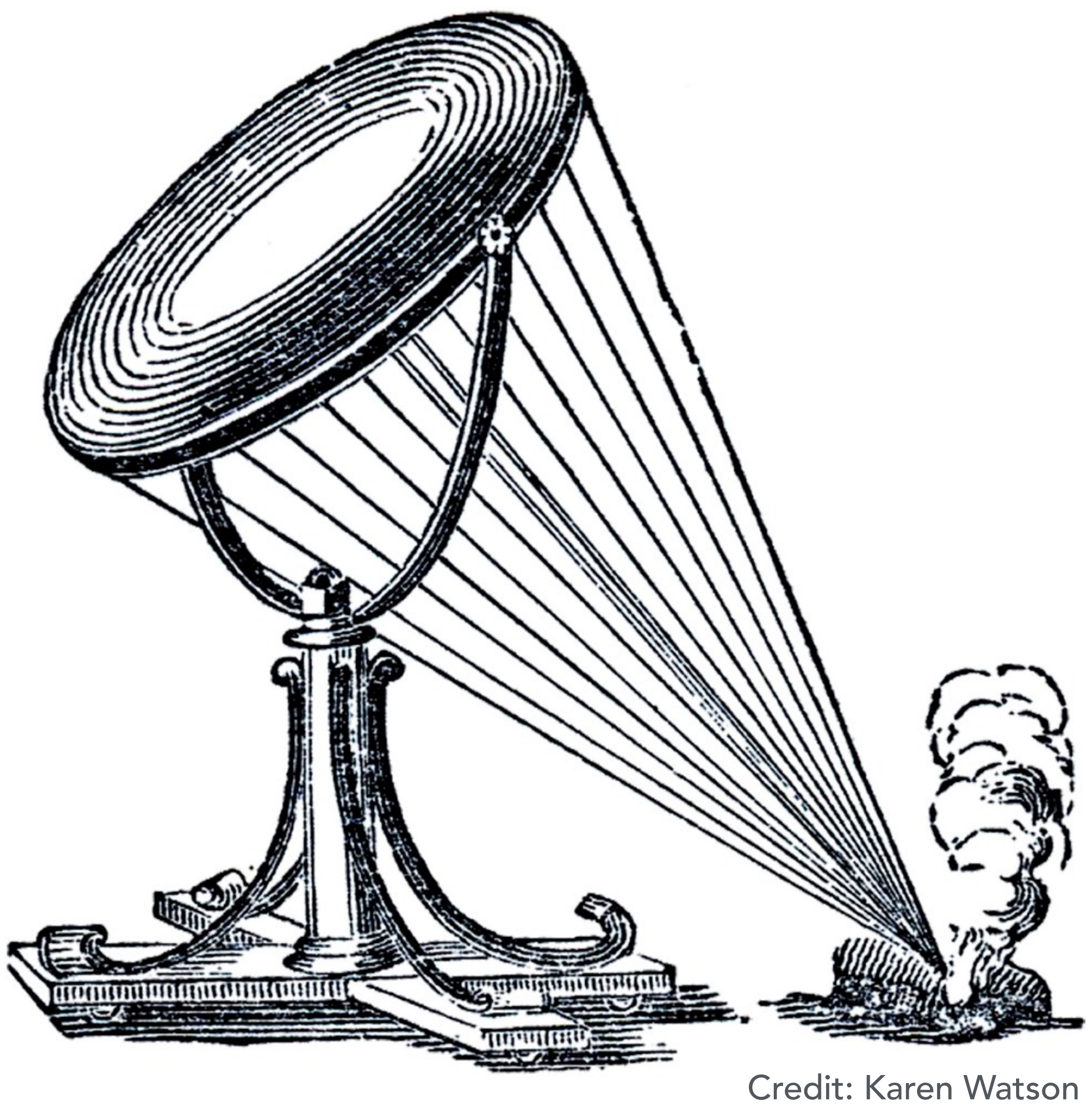
Real Lens Elements Are Not Ideal – Aberrations

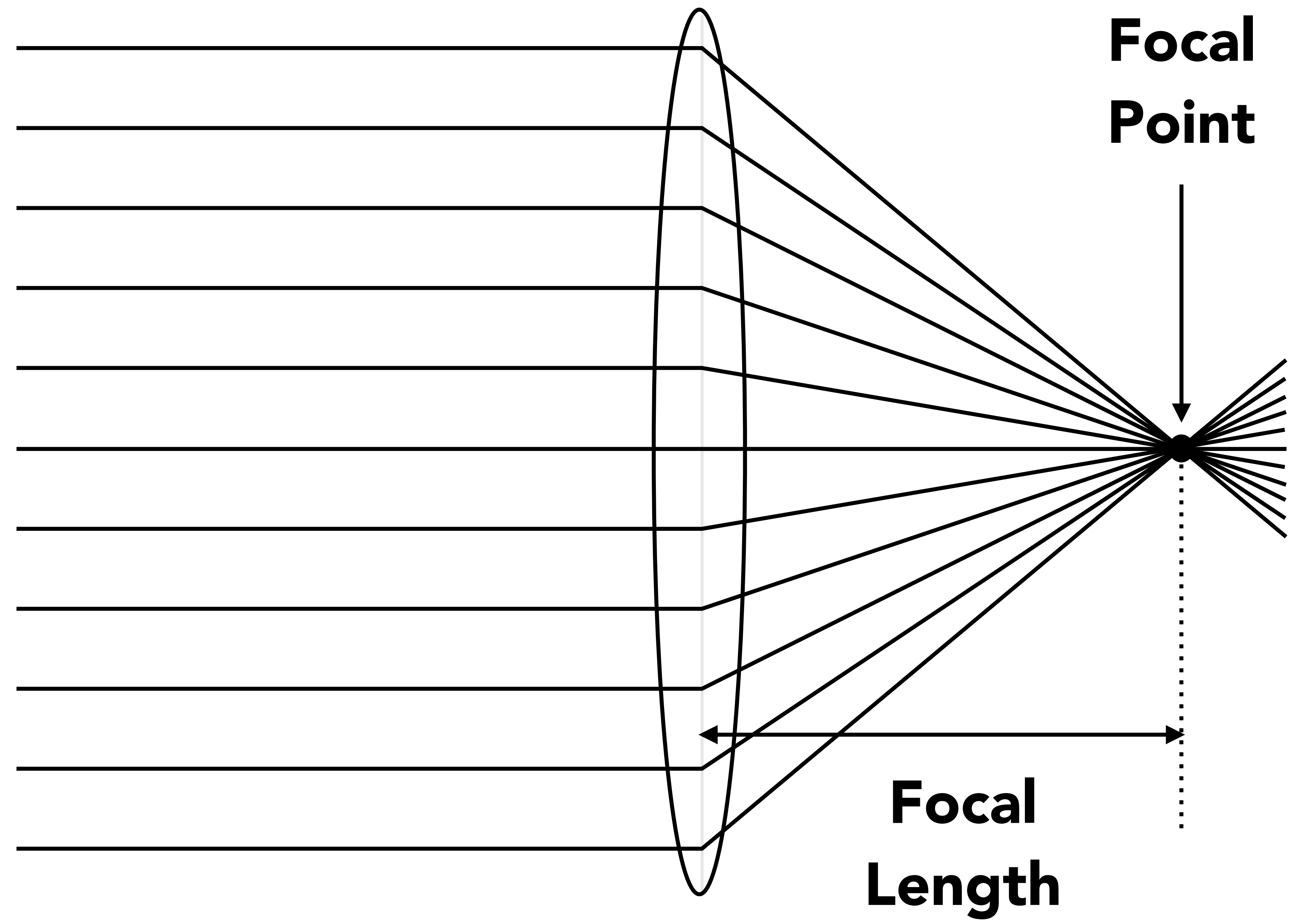


Real plano-convex lens (spherical surface shape).
Lens does not converge rays to a point anywhere.

First: Thin Lens Approximation

Ideal Thin Lens – Focal Point

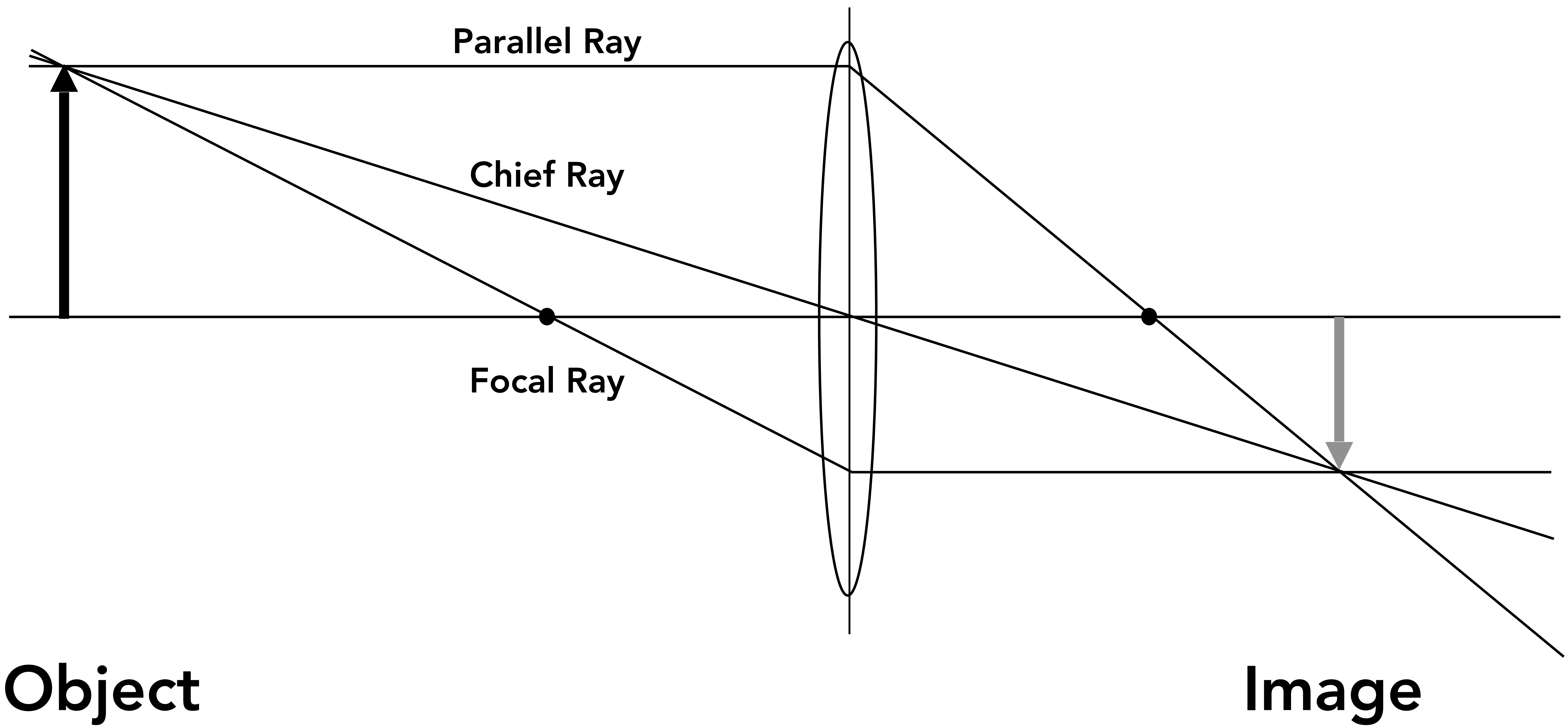




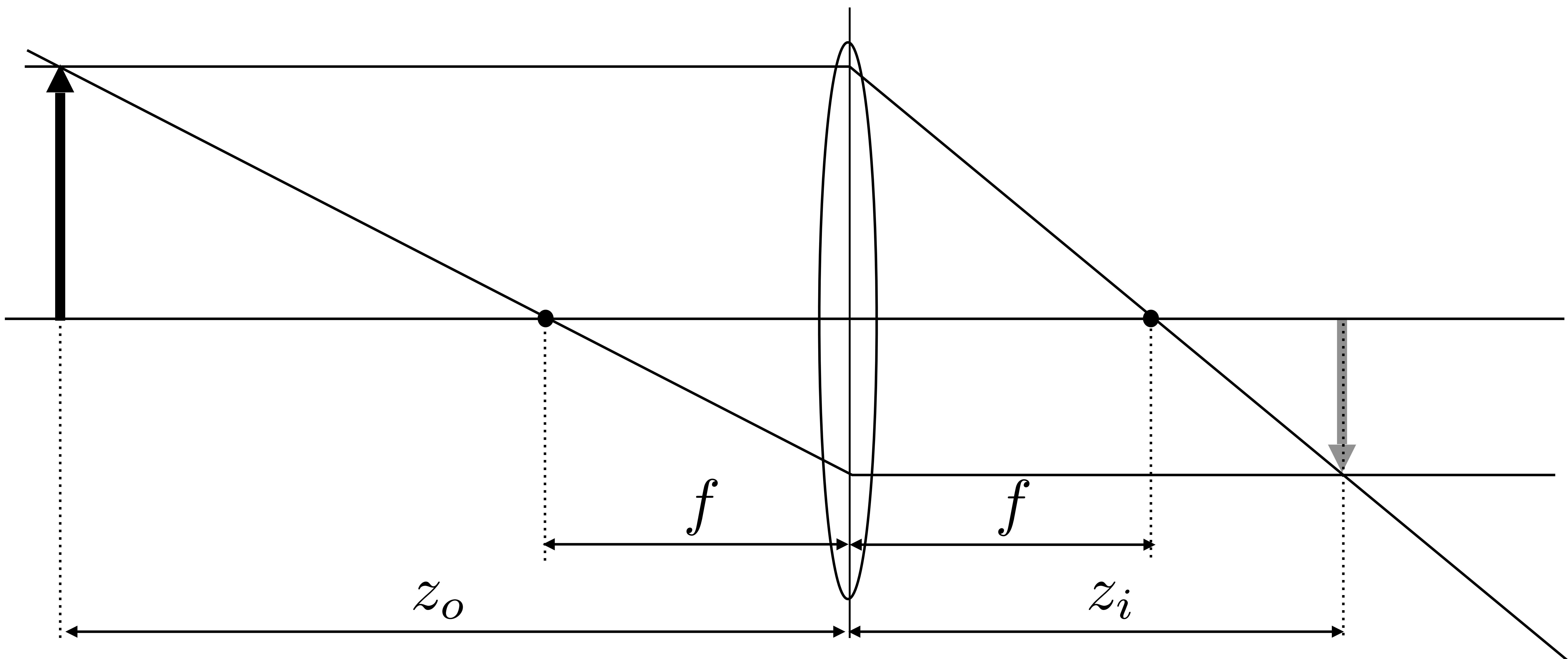
Assume all parallel rays entering a lens pass through its focal point.

Gauss’ Ray Diagrams

Gauss' Ray Tracing Construction

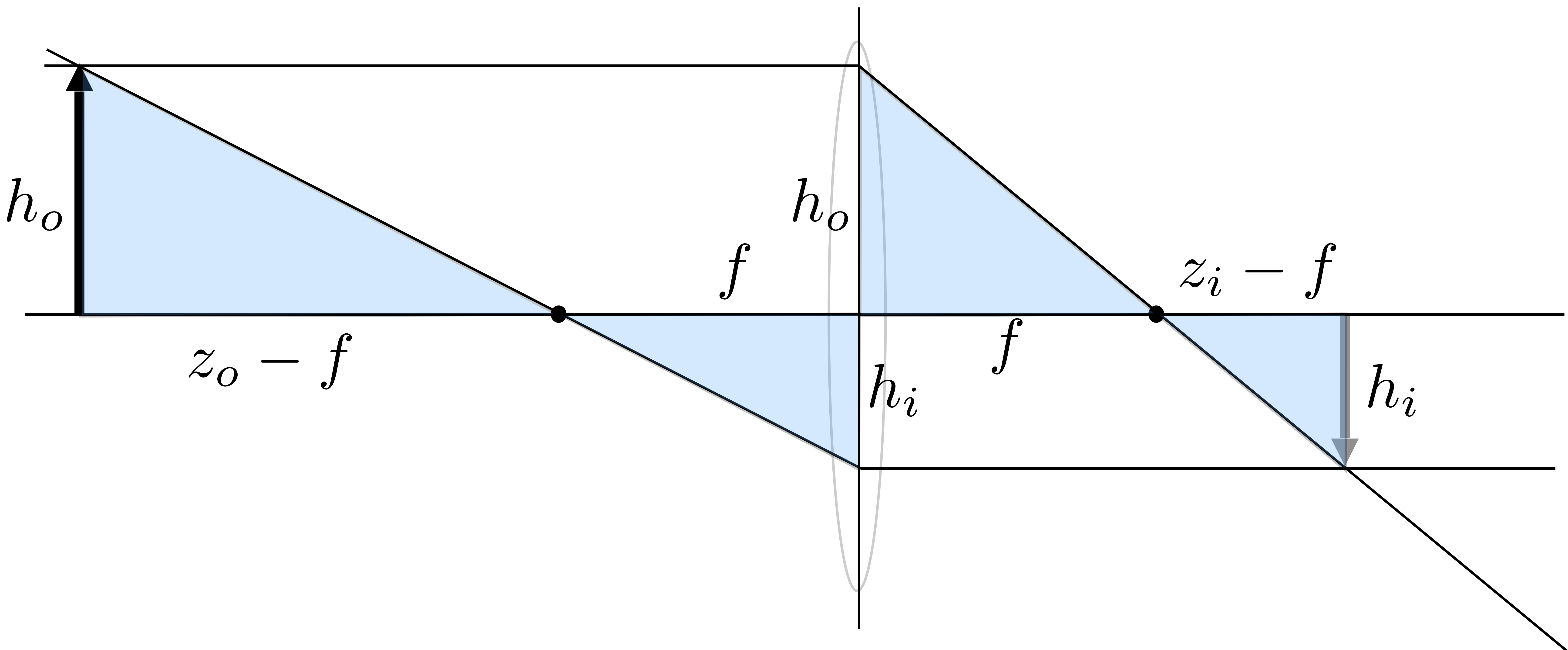


Gauss' Ray Tracing Construction



What is the relationship between conjugate depths z_o, z_i?

Gauss' Ray Tracing Construction



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

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

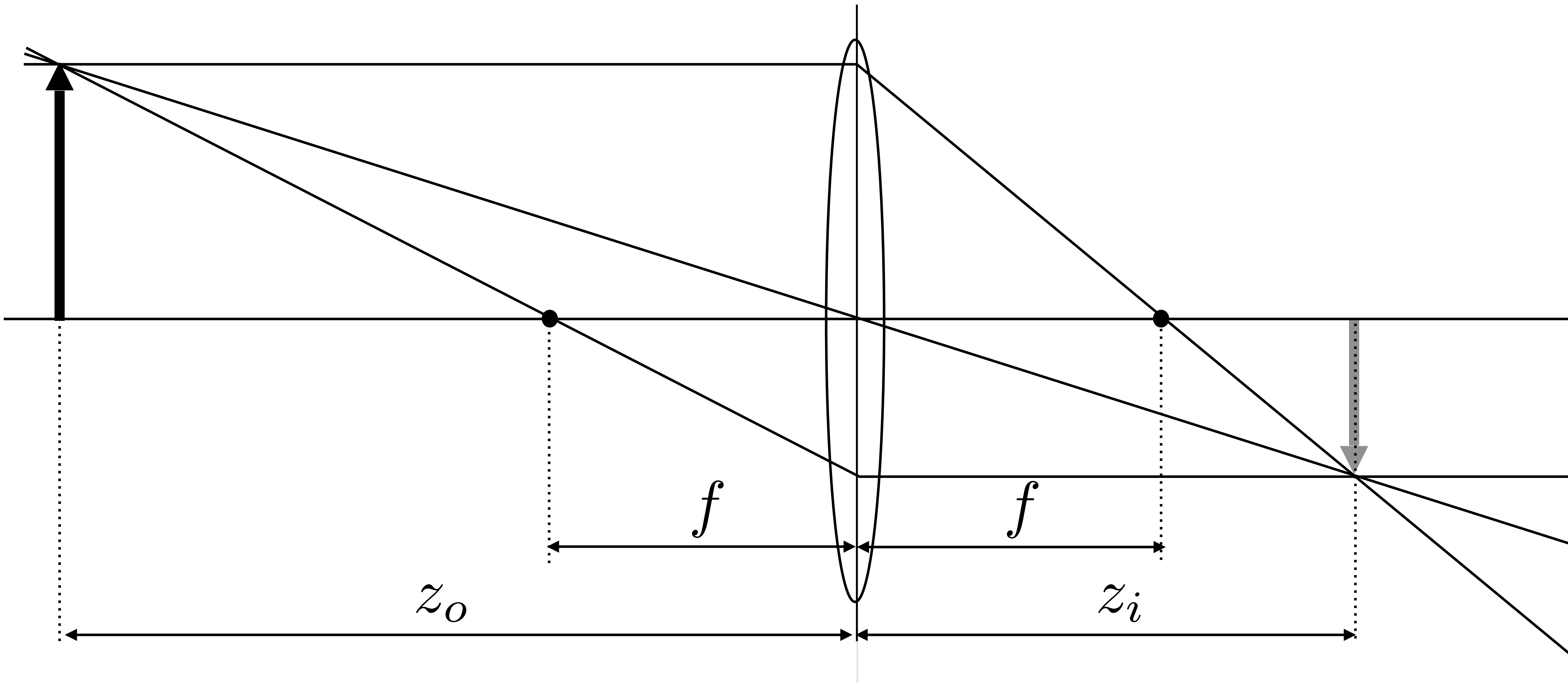
$$z_o z_i - (z_o + z_i) f + f^2 = f^2$$

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

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

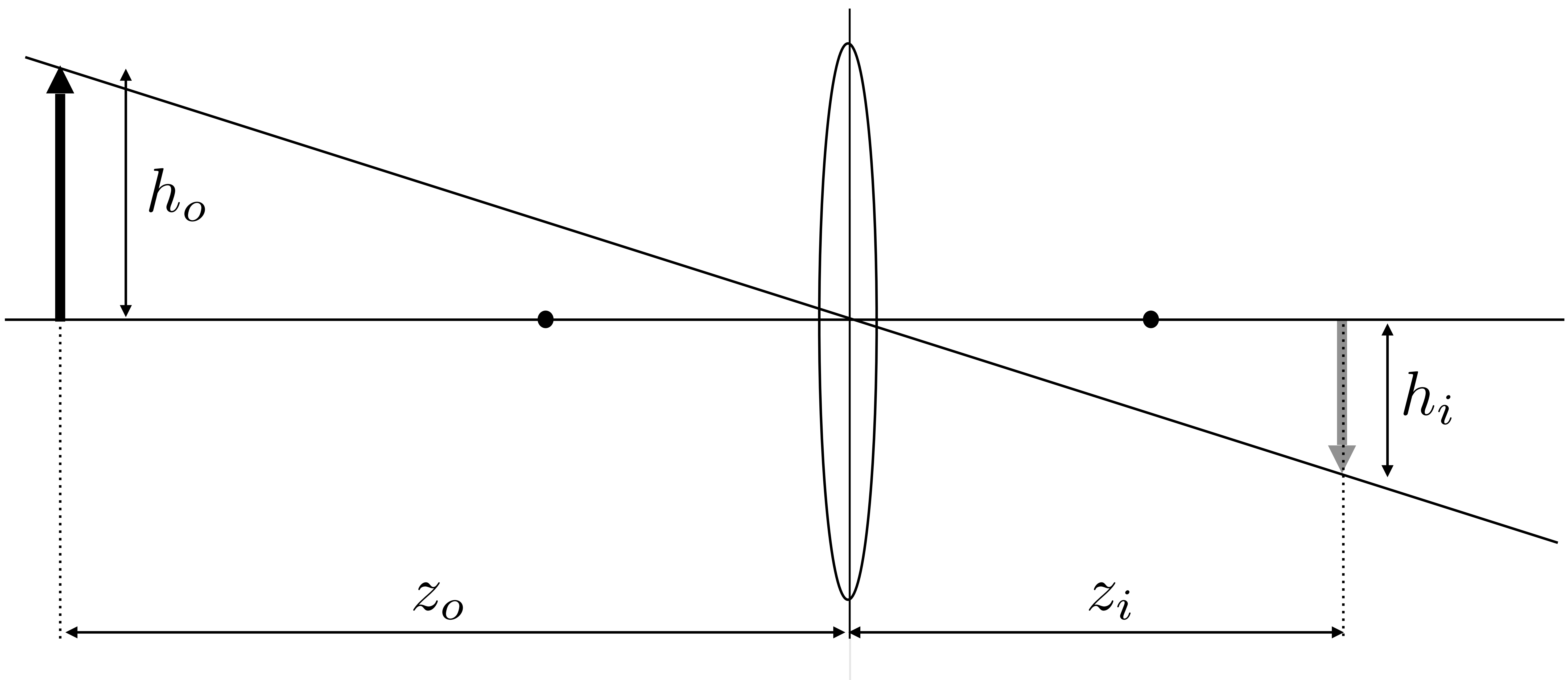
Gaussian Thin Lens Equation

The Thin Lens Equation



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

Magnification



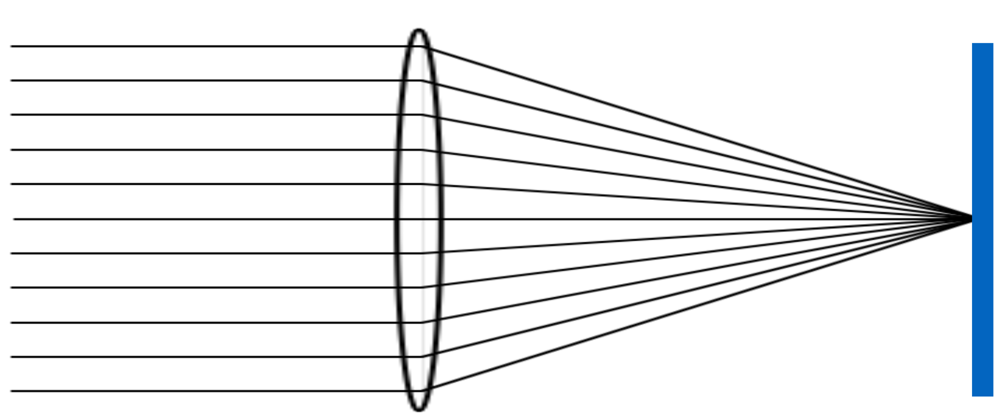
$$m = \frac{h_i}{h_o} = \frac{z_i}{z_o}$$

Magnification Example – Focus at Infinity

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

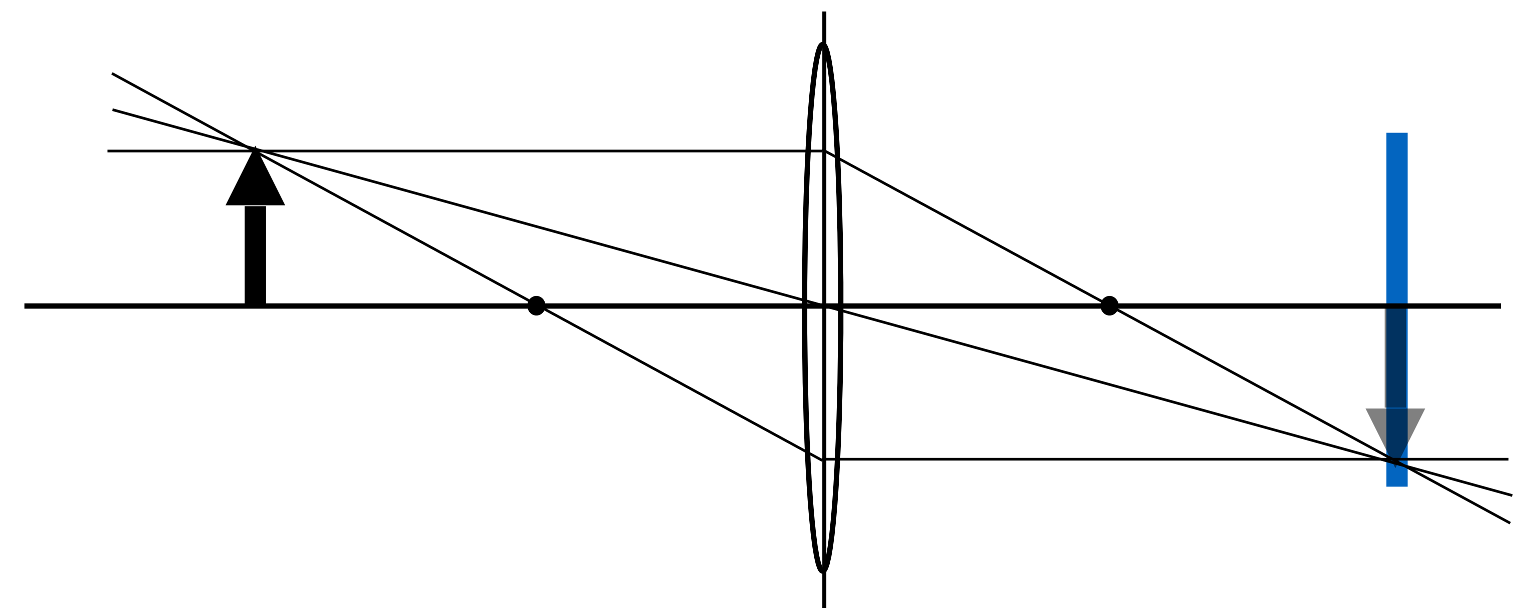
If focused on a distant mountain

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



Magnification Example – Focus at 1:1 Macro

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



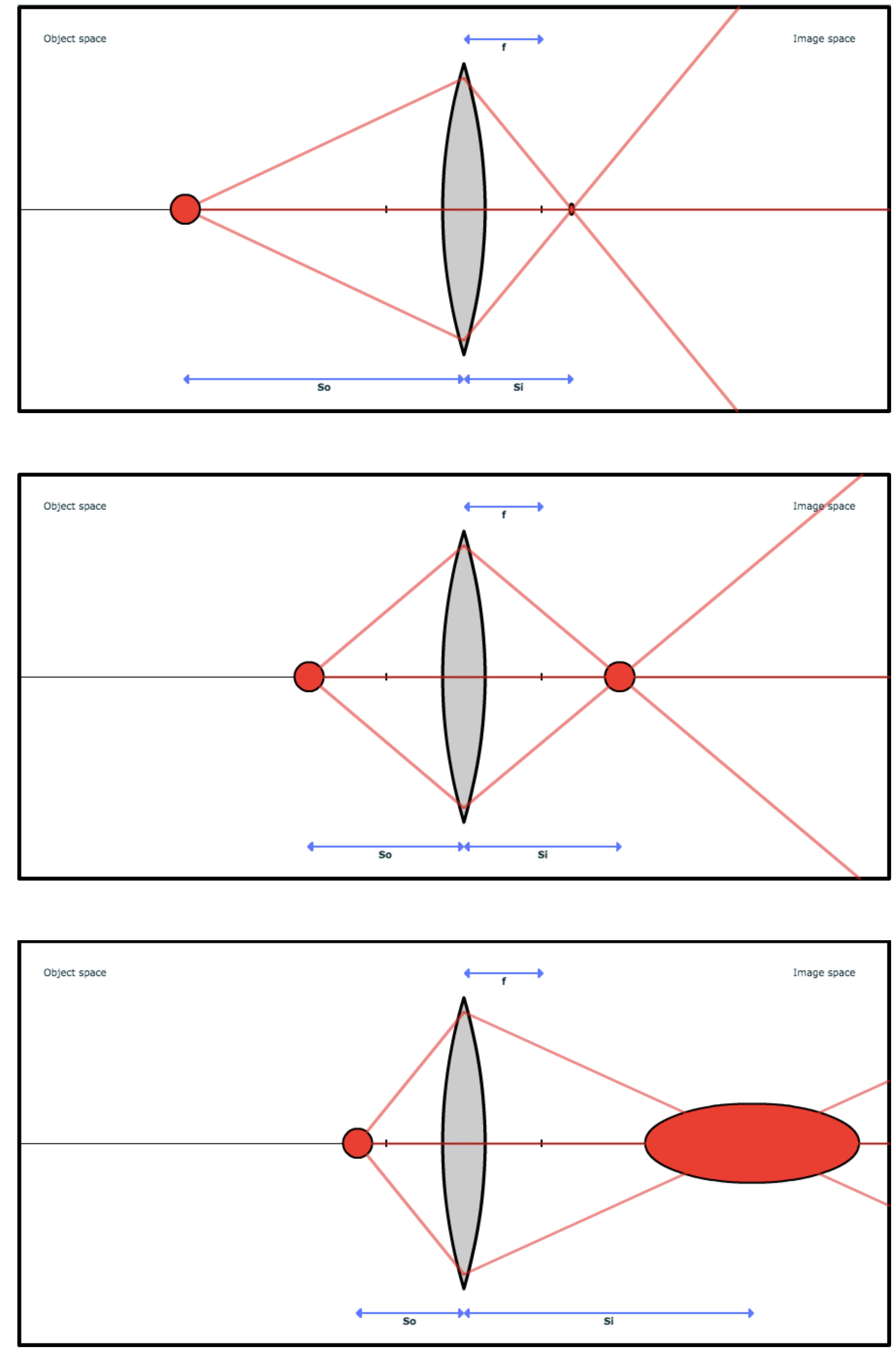
What configuration do we need to achieve a magnification of 1 (i.e. image and object the same size, a.k.a. 1:1 macro)?

- 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 Effects — Observations in 3D

3D image of object is:

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



Credit: Stanford CS 178

Defocus Blur

Circle of Confusion

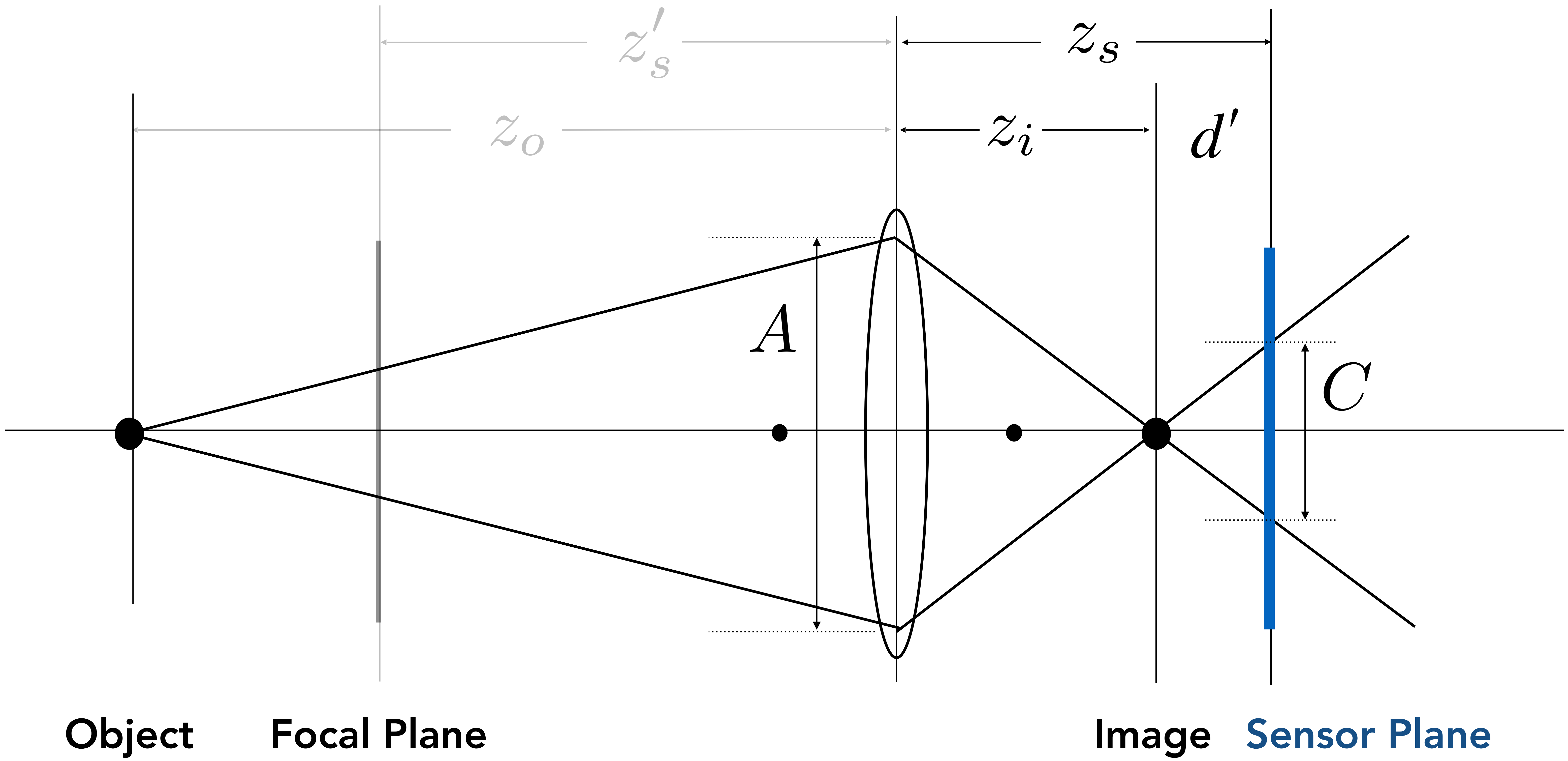
Circle of Confusion

Circle of Confusion

Size of blur kernel depends on depth from focal plane.
Only see the blur kernel itself if you have a point light. Why?

Circle of Confusion

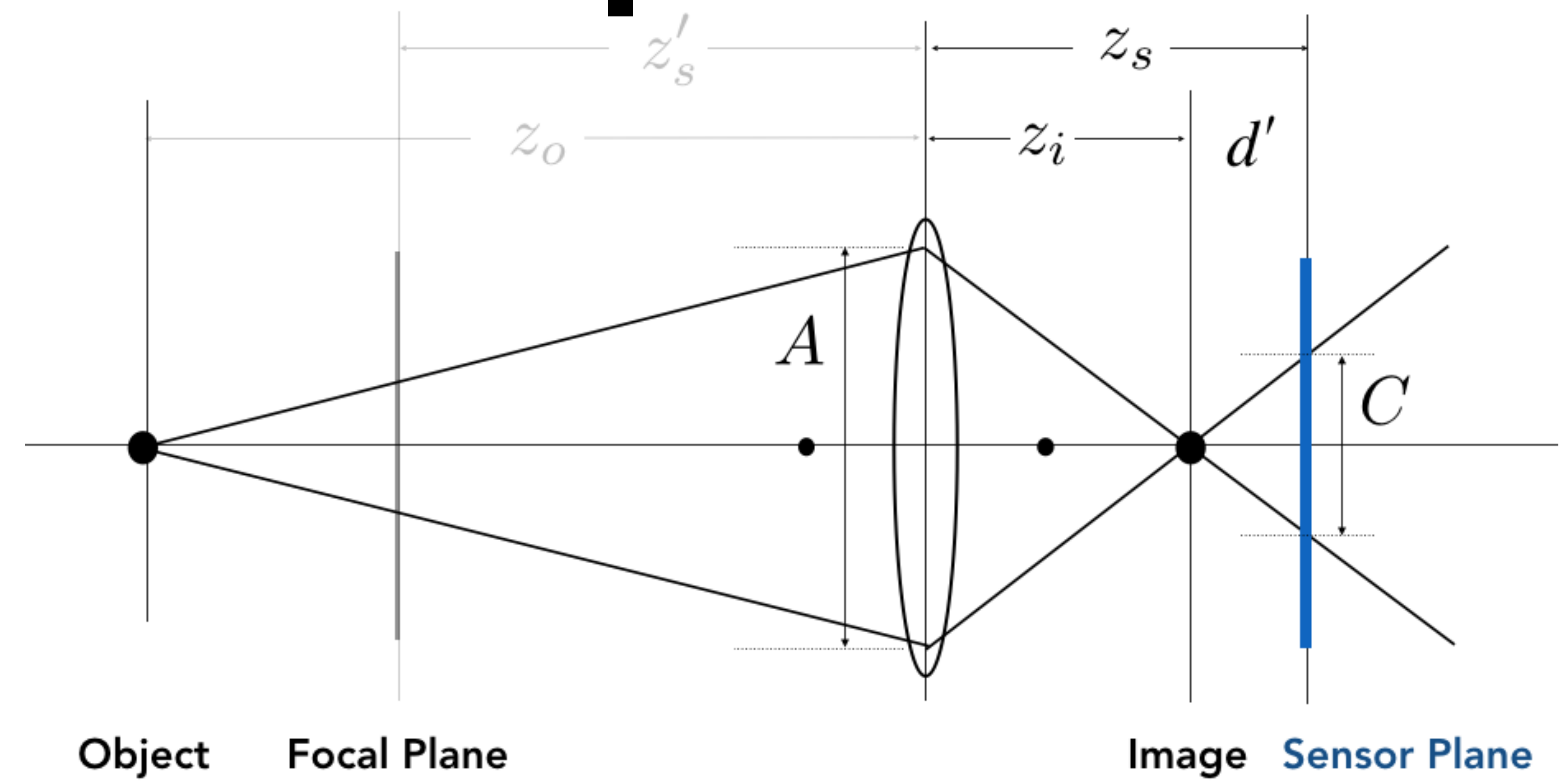
Computing Circle of Confusion Diameter (C)



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

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

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

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

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

$$C = A|z_s - z_i|/z_i = 1.18\text{mm}$$

~130 pixels on 4K TV

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

$$C = A|z_s - z_i|/z_i = 3.07\text{mm}$$

~338 pixels on 4K TV

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

R. Berdan, 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

Same 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

To Be Continued