# Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 19:
## Cameras, Lenses and Light Fields
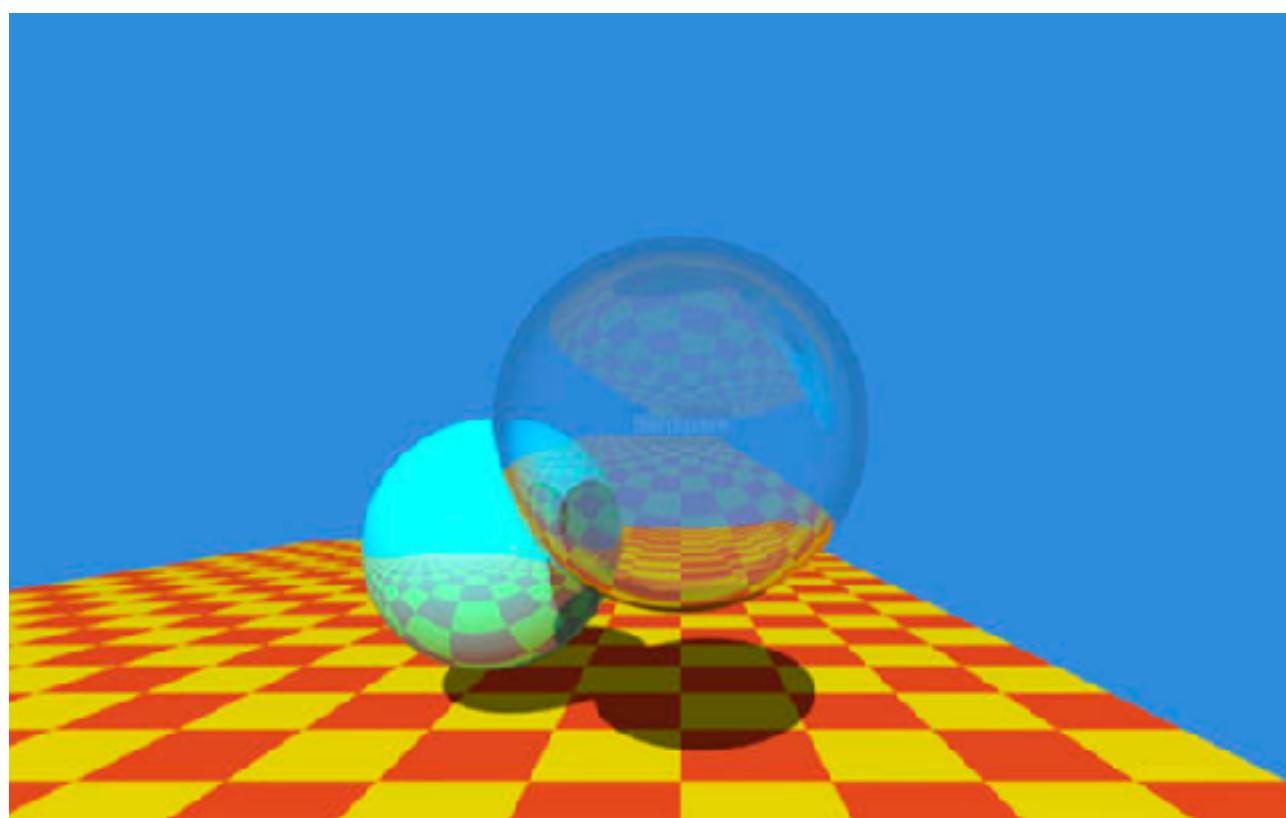
Announcements
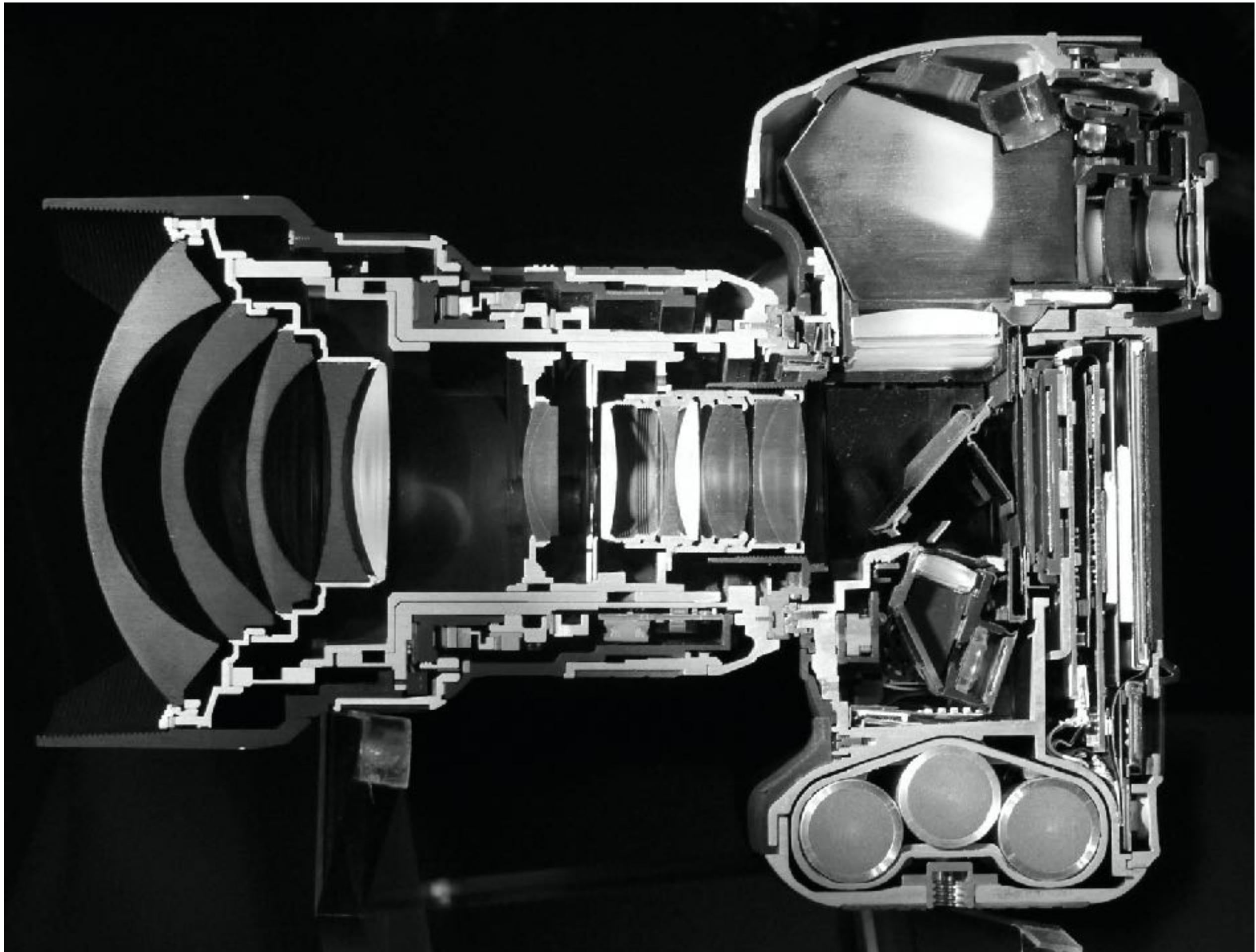
- Standalone topics this week

  - No related homework for lectures in this week

- Final project ideas will be released soon

  - Note: submit your (very short) proposal on/before Apr 19, if you want to do something else (encouraged)

# Imaging = Synthesis + Capture
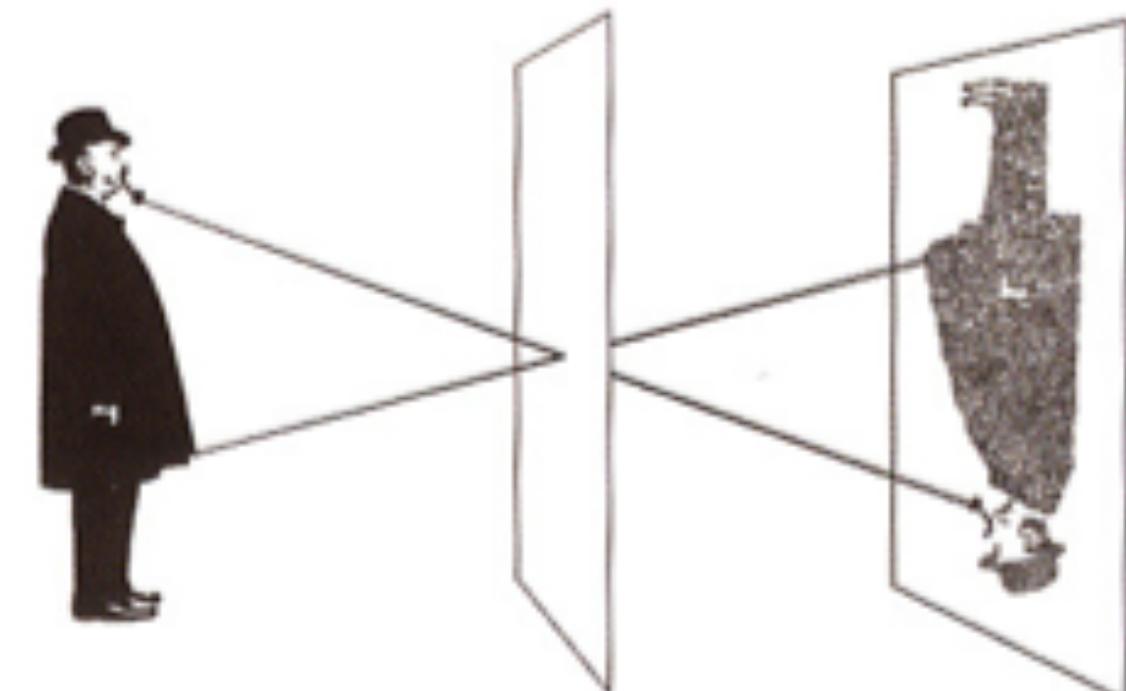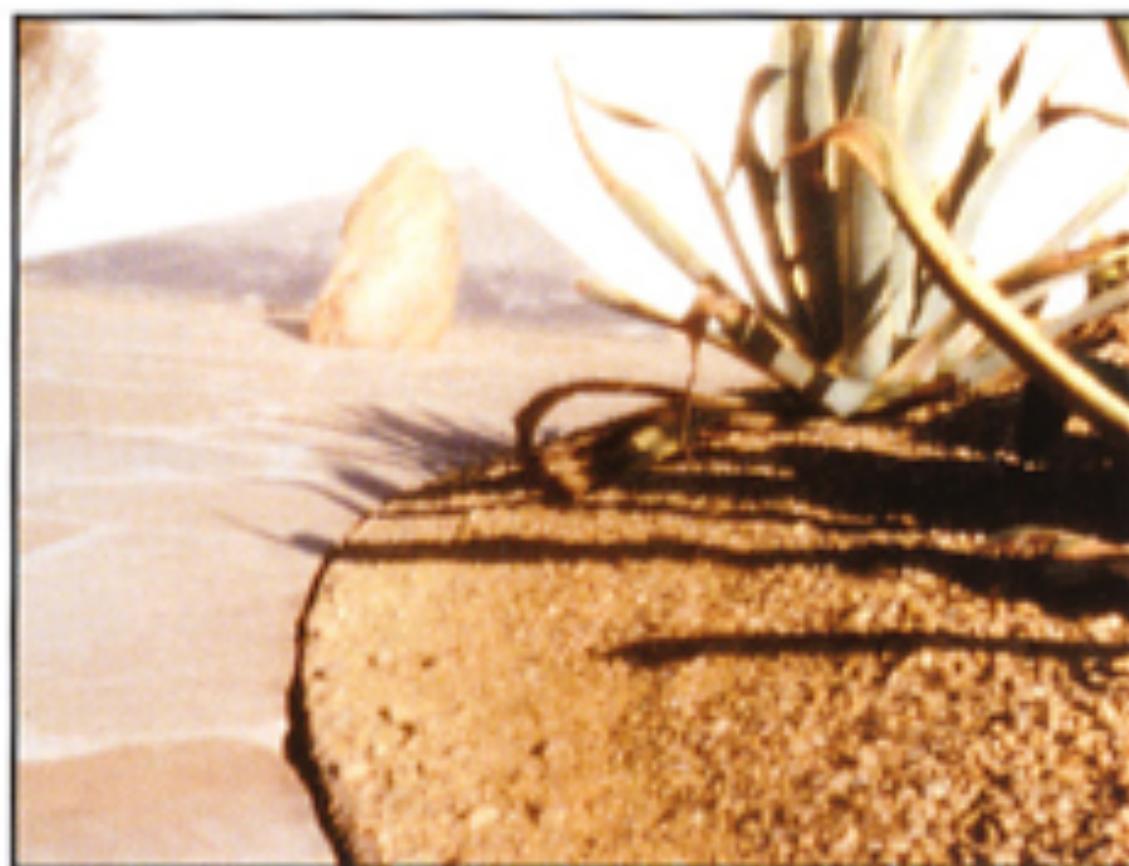
What's Happening Inside the Camera?
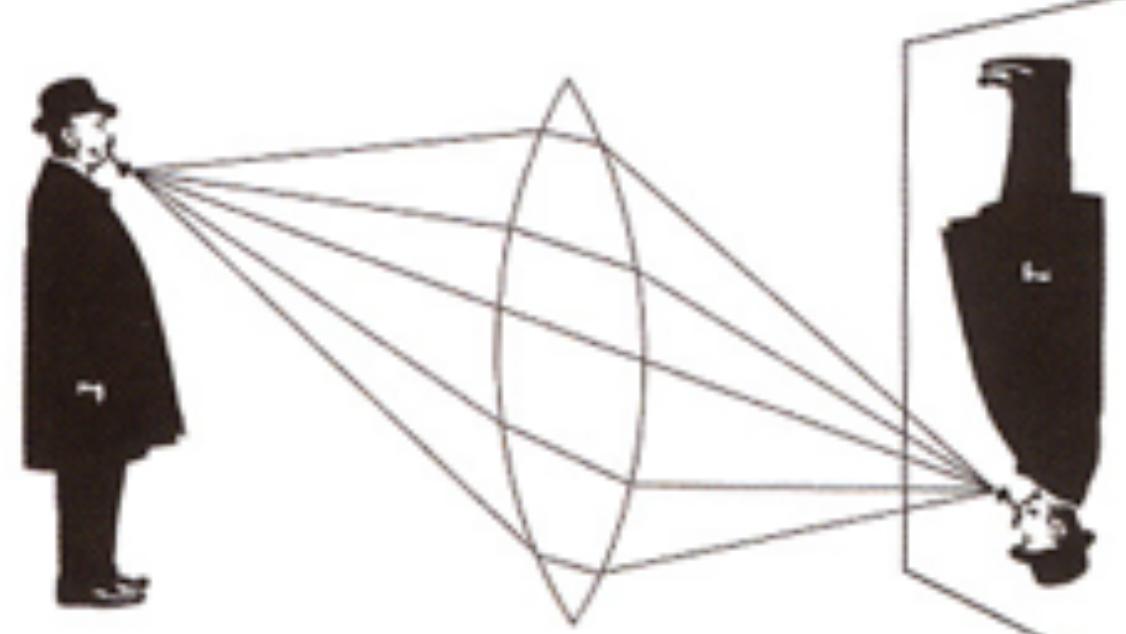
Cross-section of Nikon D3, 14-24mm F2.8 lens

Pinholes & Lenses Form Image on Sensor

(传感器)

Photograph made with small pinhole
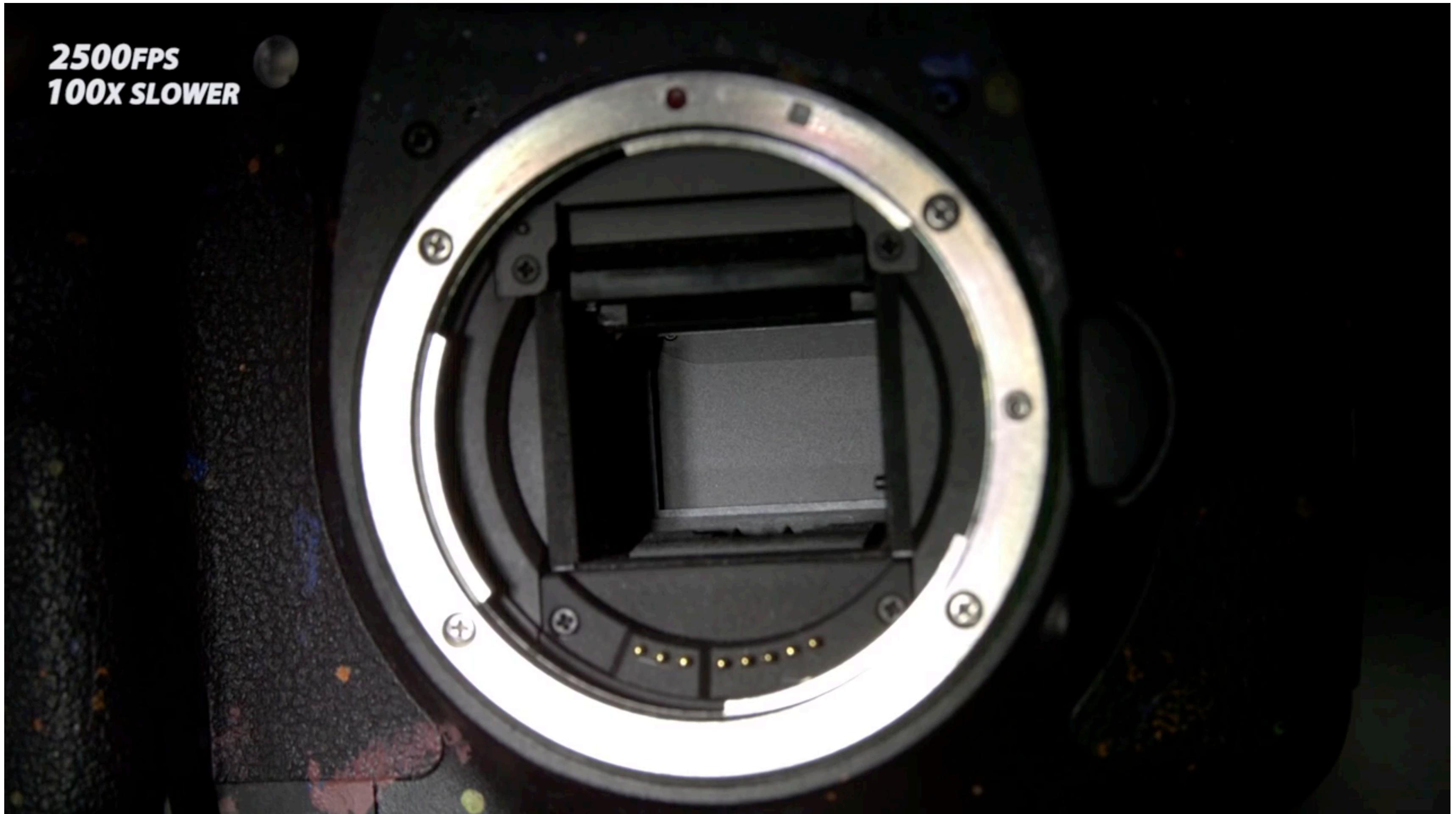
Photograph made with lens
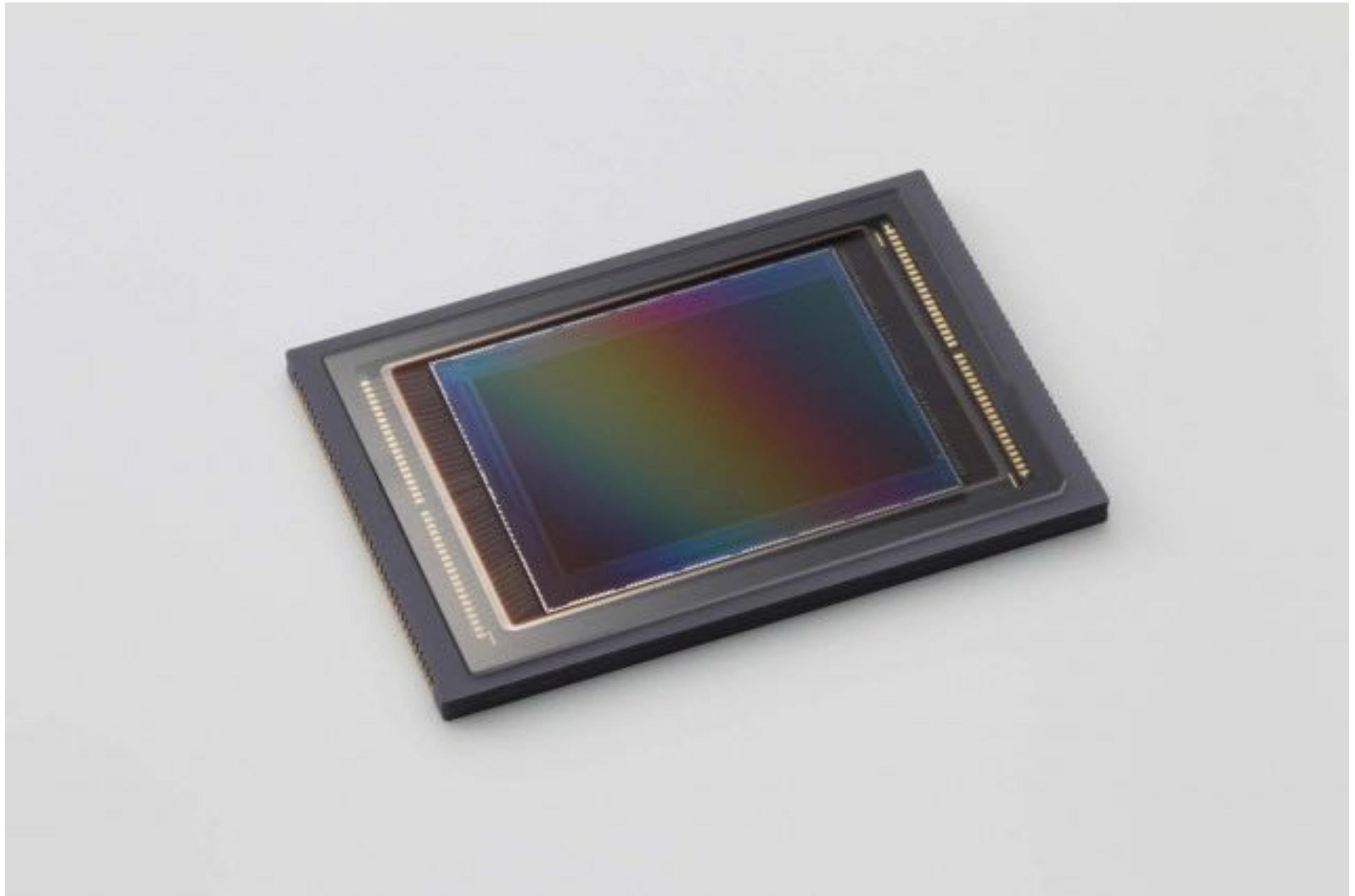
London and Upton

Shutter Exposes Sensor For Precise Duration
(快门)

The Slow Mo Guys, https://youtu.be/CmjeCchGRQo
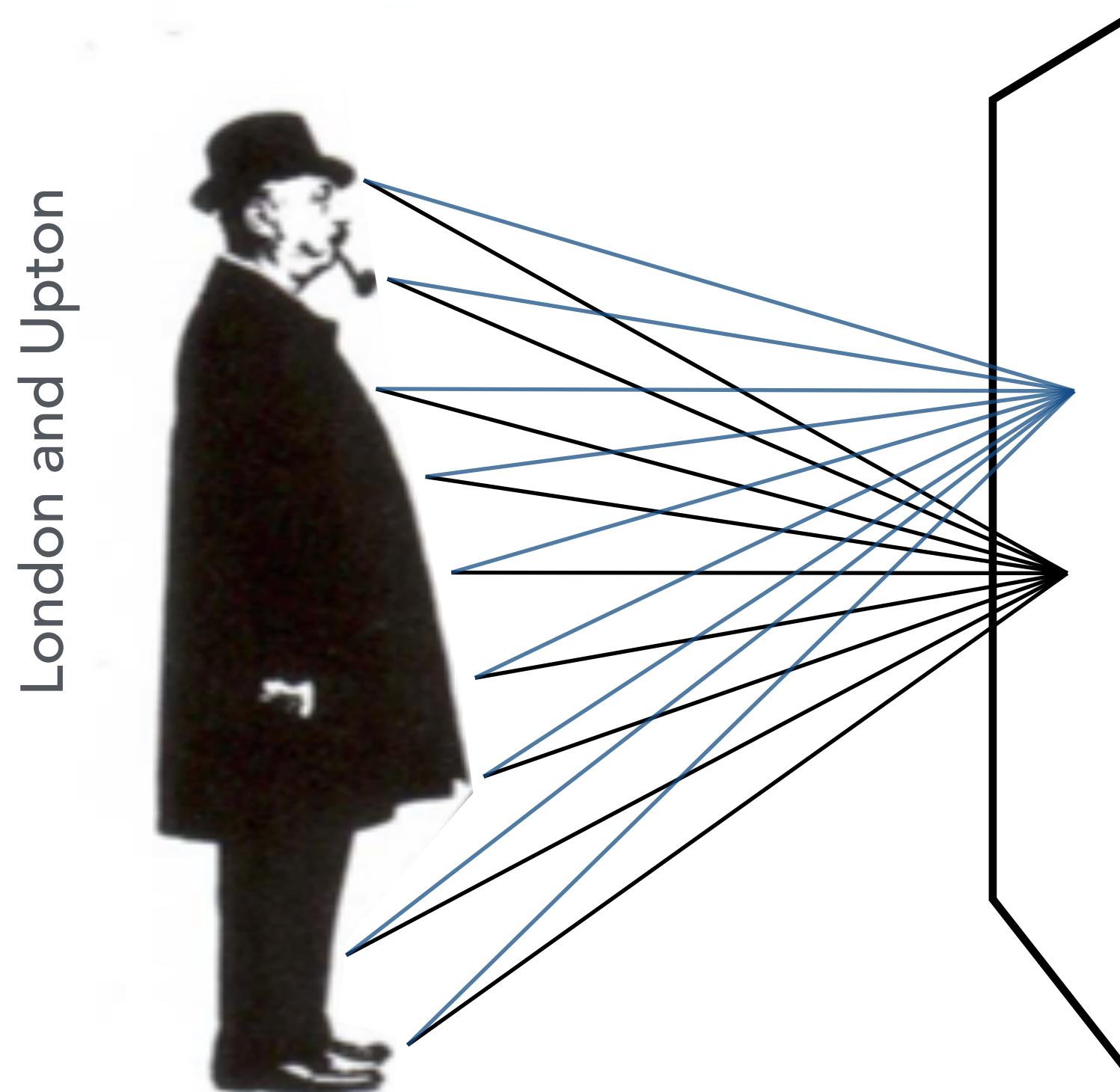
Sensor Accumulates Irradiance During Exposure

Why Not Sensors Without Lenses?
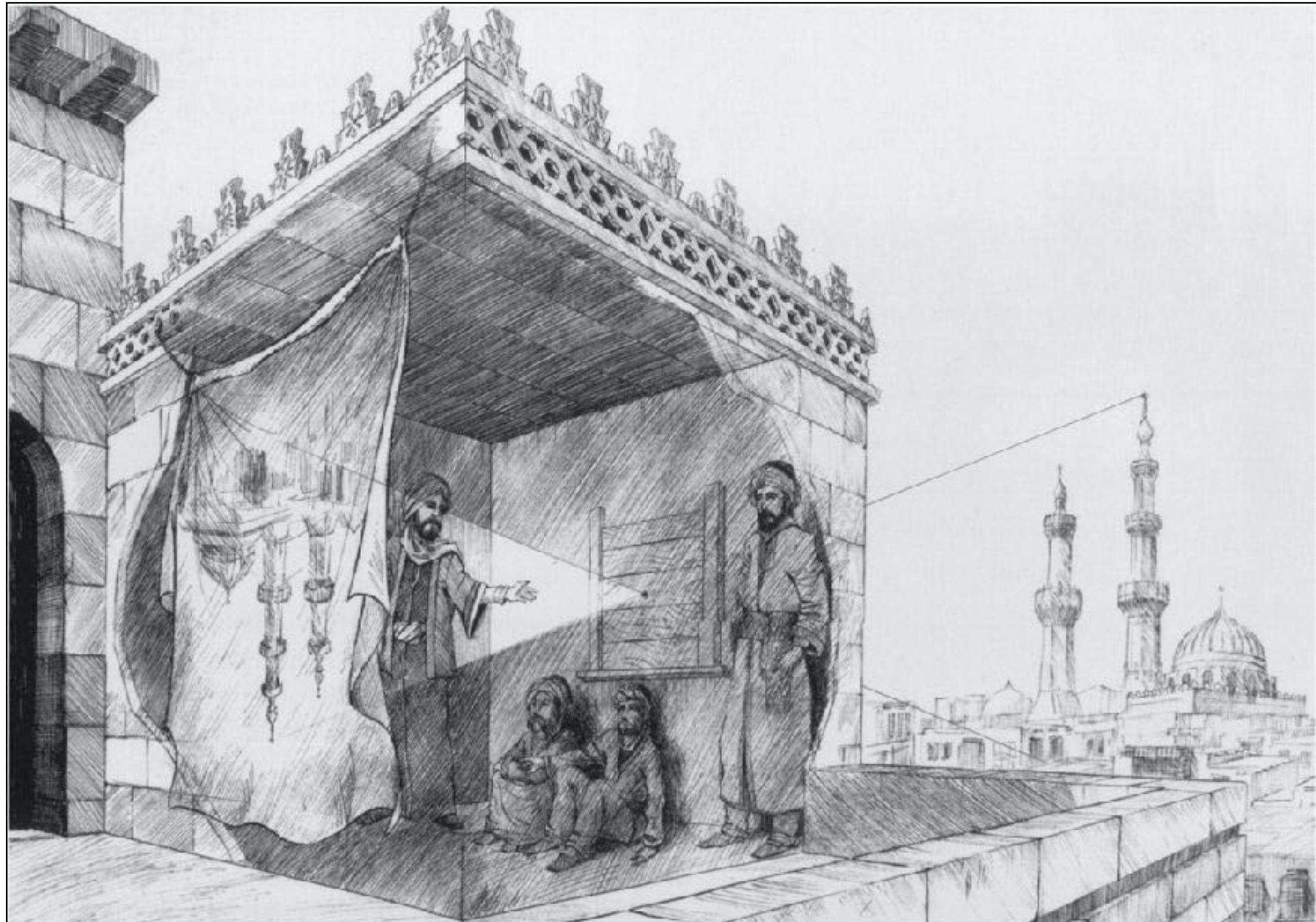
Each sensor point would integrate light from all points on the object, so all pixel values would be similar
i.e. the sensor records **irradiance**

London and Upton

but there is computational imaging research…

Pinhole Image Formation

Pinhole Camera

Mo Tzu (c. 470–c. 390 BC)

Aristotle (384–322 BC)

Ibn al-Haytham (965–1040)
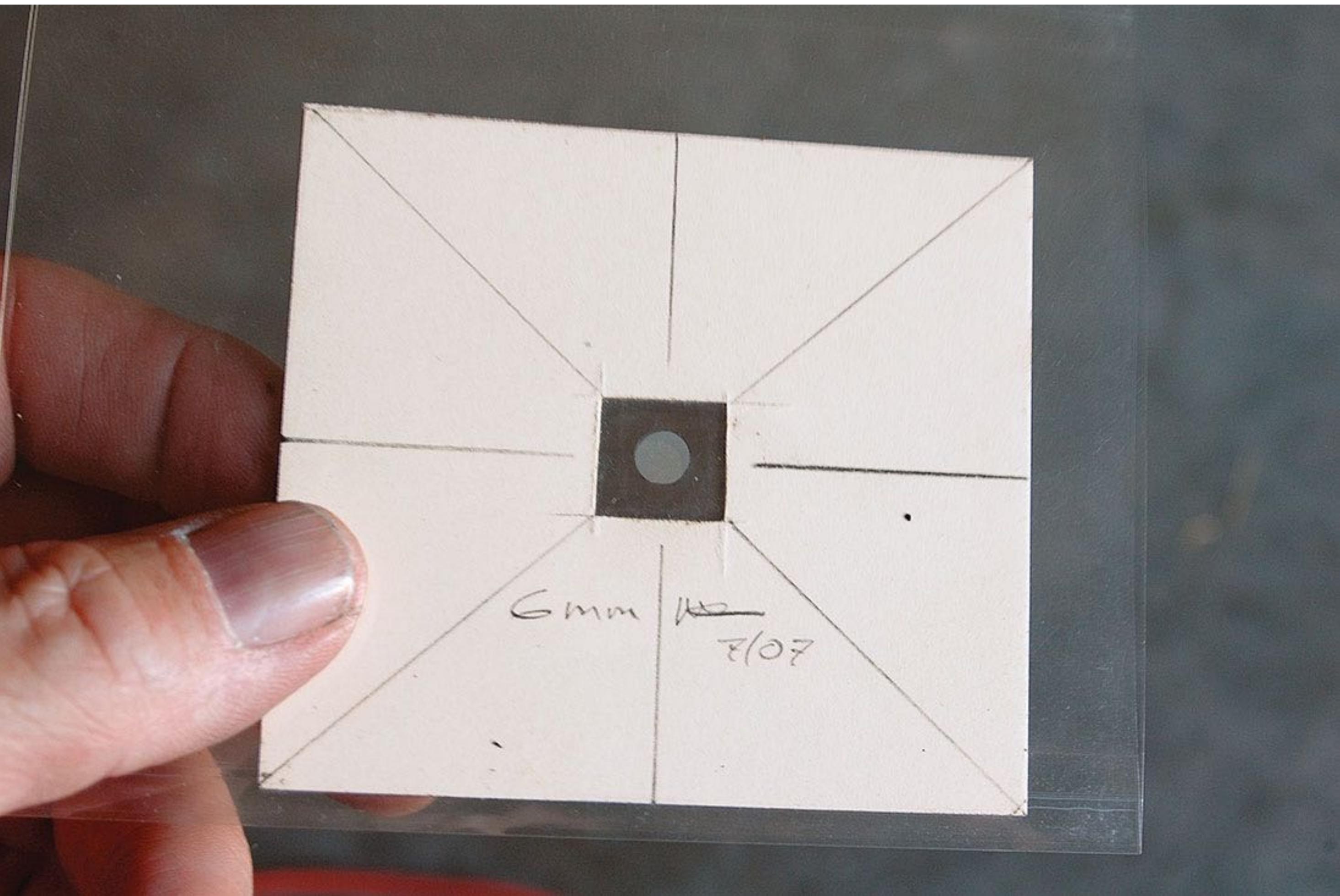
Shen Kuo (1031–1095)

Roger Bacon (c. 1214–1294)

Johannes Kepler (1571–1630)

A. H. Zewail, *Phil. Trans. R. Soc.* A 2010;368:1191-1204

Largest Pinhole Photograph

Largest Pinhole Photograph

legacyphotoproject.com

Field of View (FOV)

(视场)
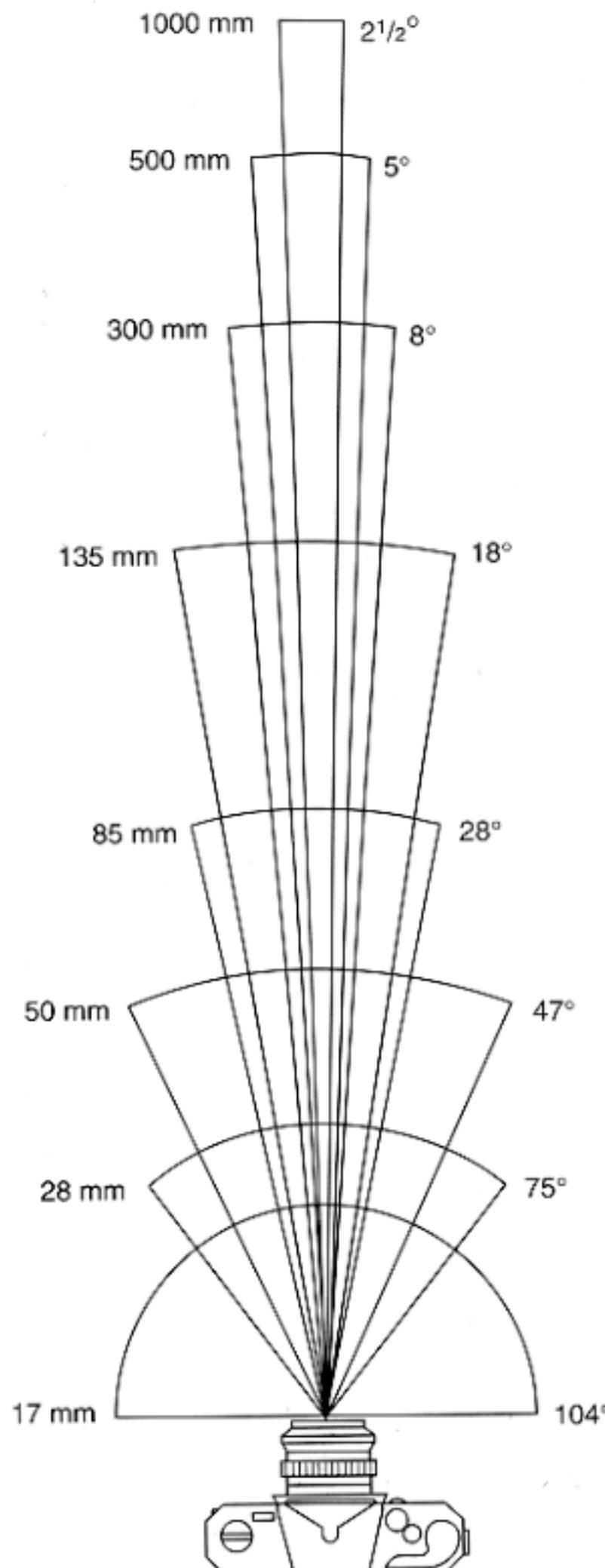
Effect of Focal Length on FOV

(焦距)

FOV

Lens

Focal length
f

Sensor

h

FOV

f

h

For a fixed sensor size, decreasing the focal length increases the field of view.
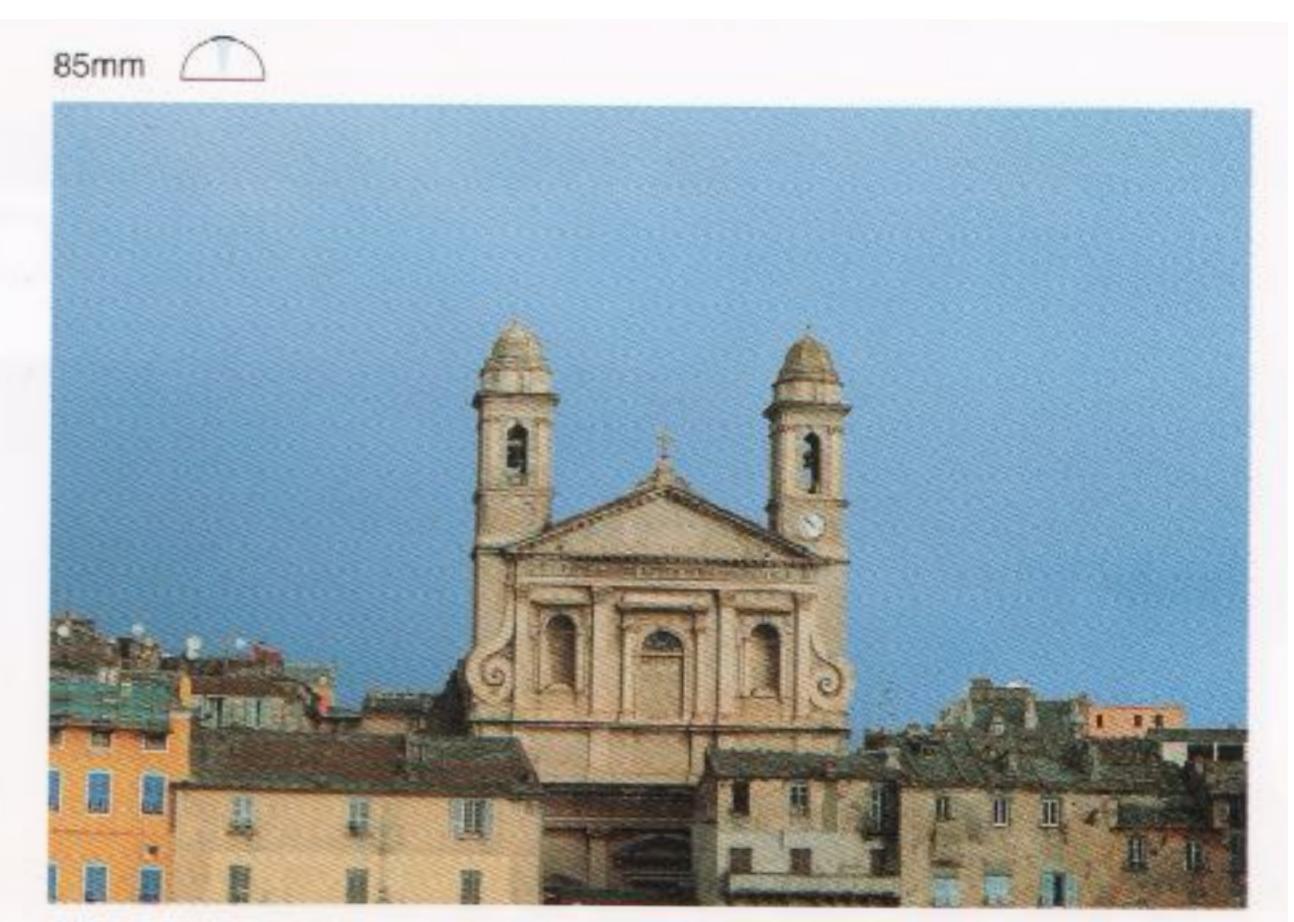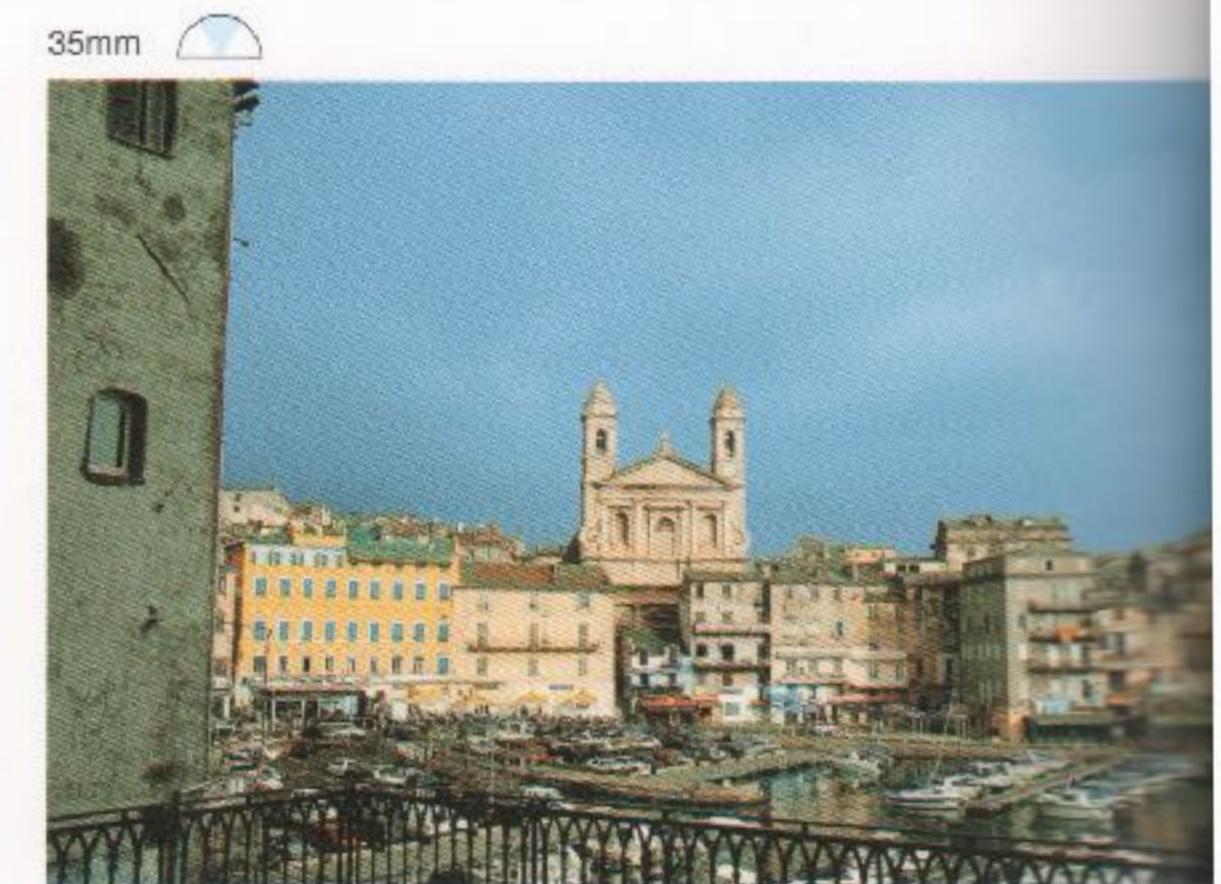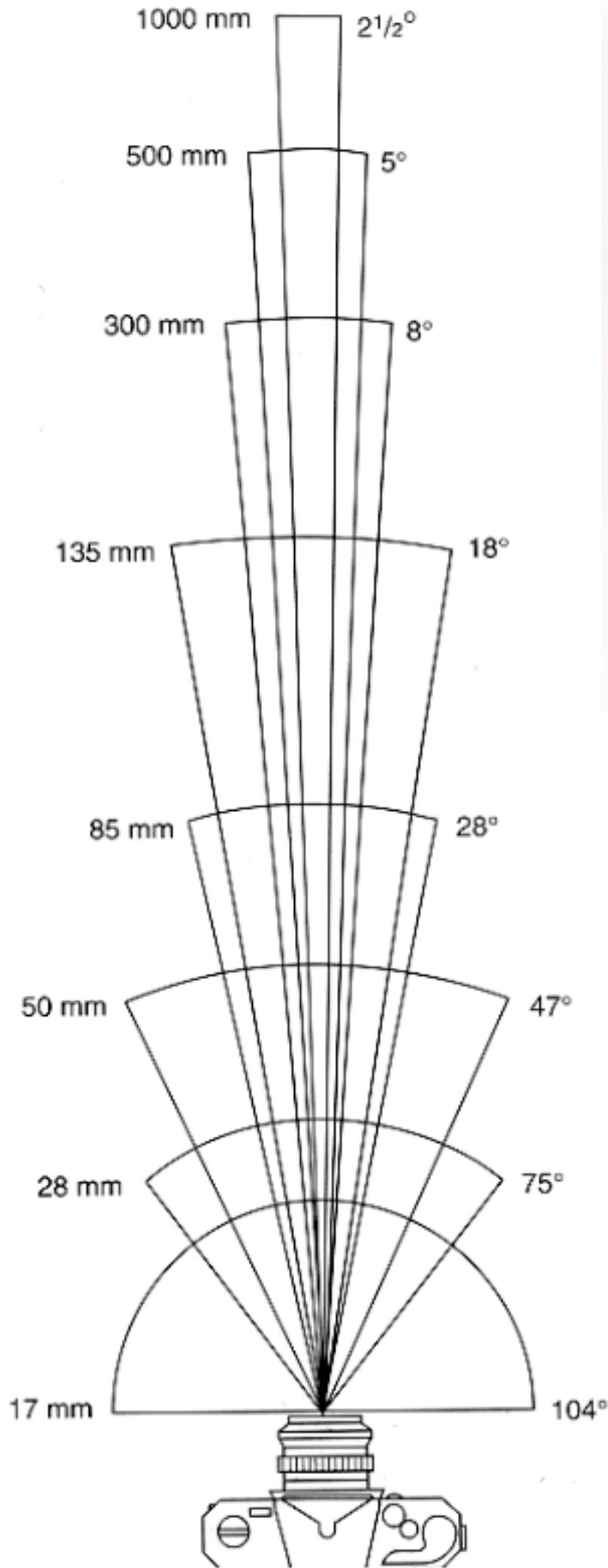
$$\text{FOV} = 2 \arctan\left(\frac{h}{2f}\right)$$

Focal Length v. Field of View
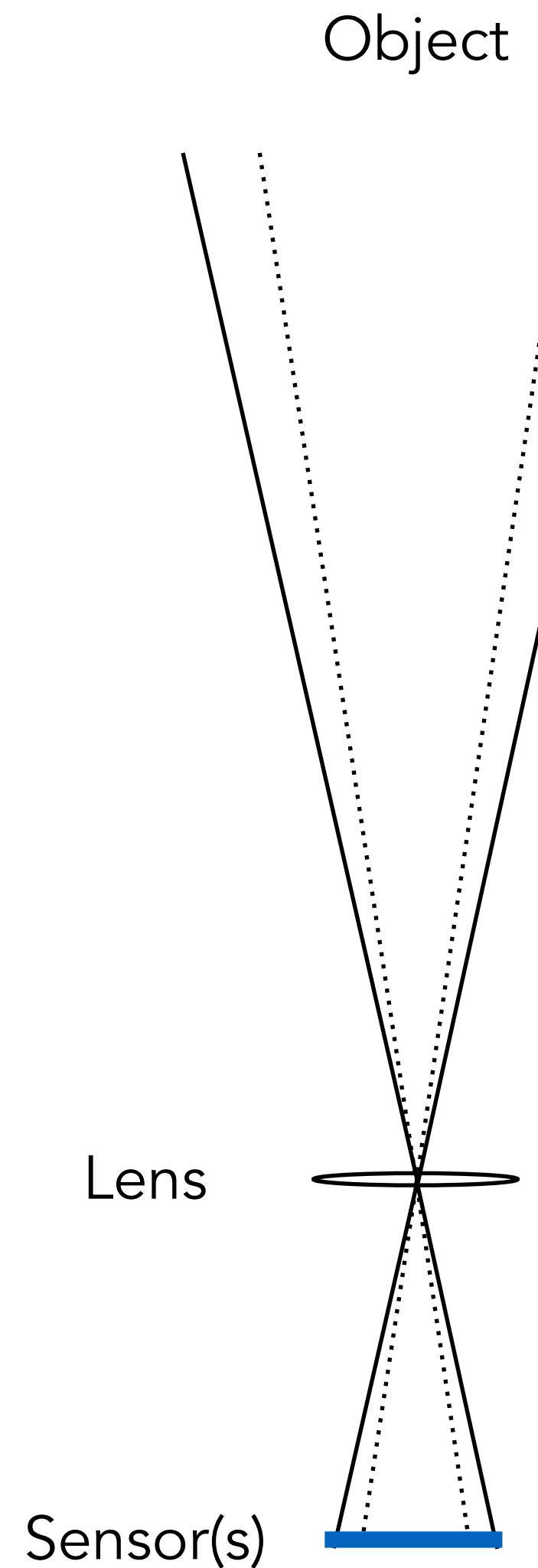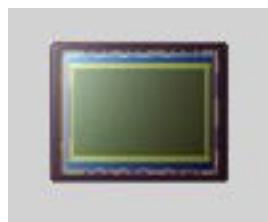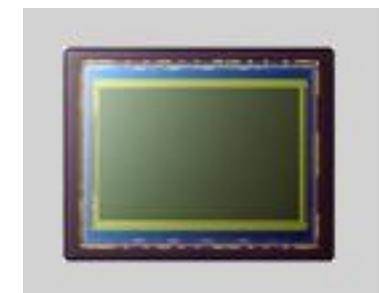

- For historical reasons, it is common to refer to angular field of view by focal length of a lens used on a 35mm-format film (36 x 24mm)

- 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.

Focal Length v. Field of View
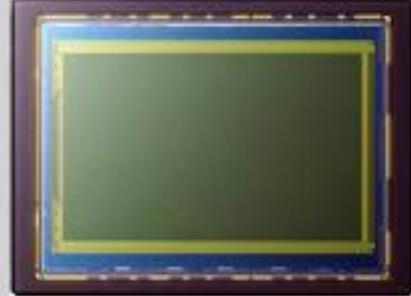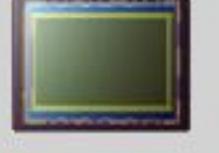
From London and Upton, and Canon EF Lens Work III

Effect of Sensor Size on FOV

APS-C

35mm Full Frame

Object

Lens
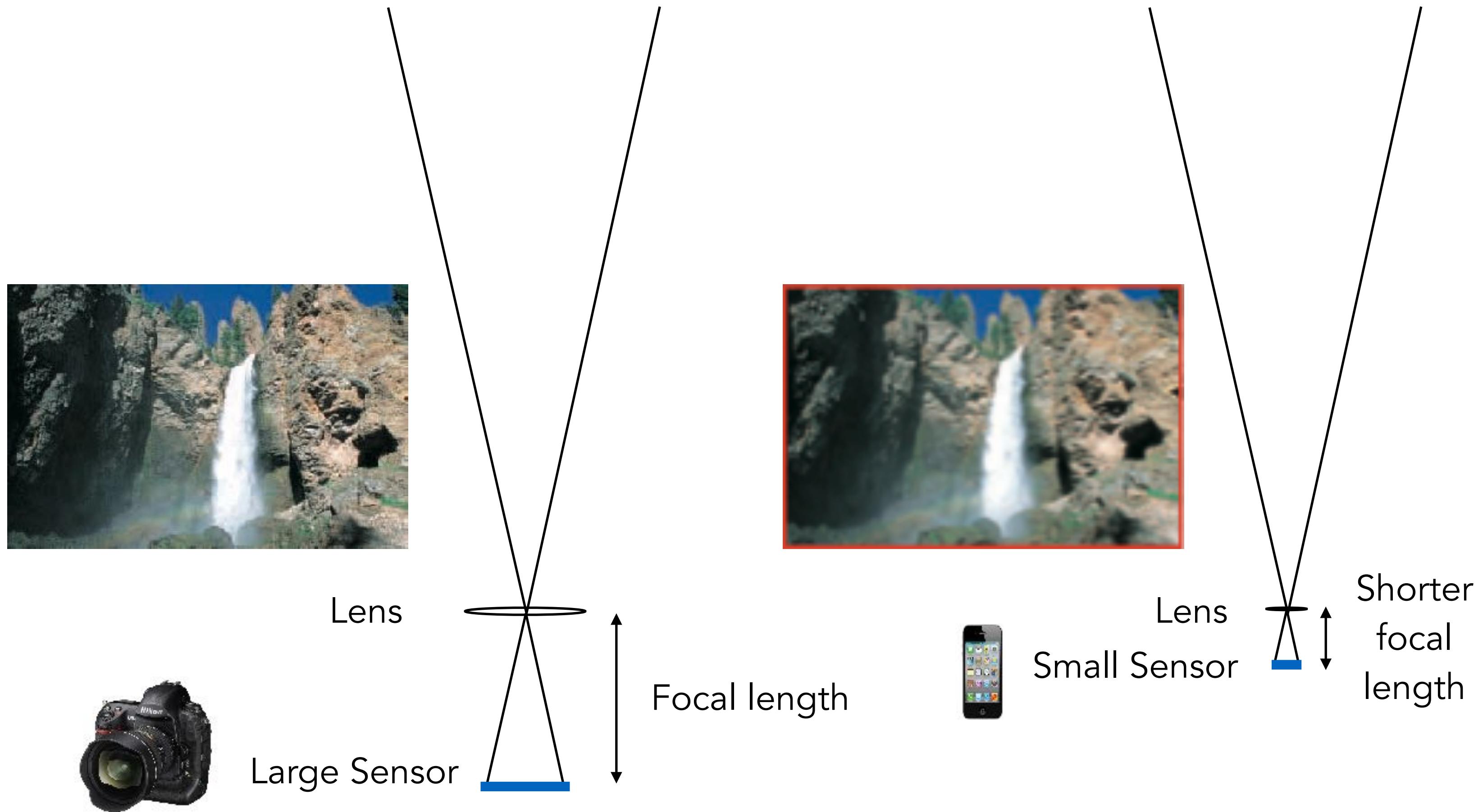
Sensor(s)

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									

Credit: lensvid.com

Maintain FOV on Smaller Sensor?

Lens

Large Sensor

Focal length

Lens

Small Sensor

Shorter focal length

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

Exposure

Exposure

- H = T x 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 Controls in Photography

Aperture size

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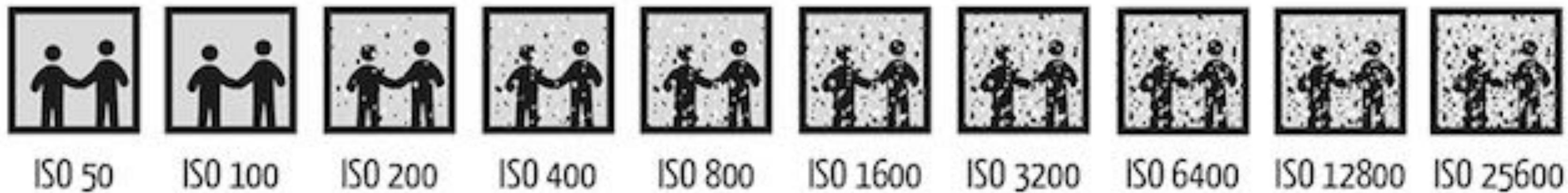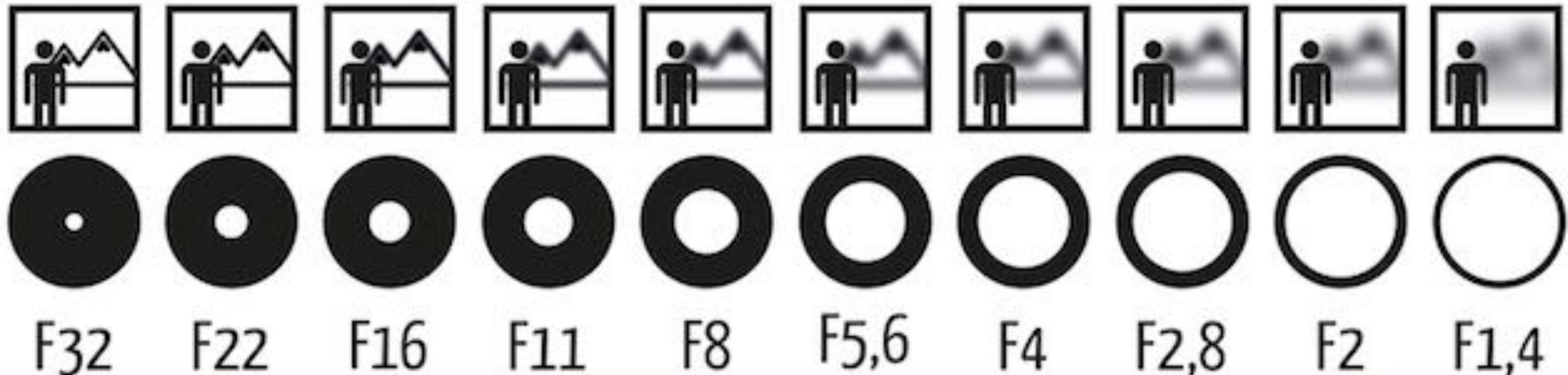
Shutter speed

- Change the duration the sensor pixels integrate light

ISO gain (感光度)

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

Exposure: Aperture, Shutter, Gain (ISO)

F32 F22 F16 F11 F8 F5,6 F4 F2,8 F2 F1,4

1/1000 1/500 1/250 1/125 1/60 1/30 1/15 1/8 1/4 1/2

ISO 50 ISO 100 ISO 200 ISO 400 ISO 800 ISO 1600 ISO 3200 ISO 6400 ISO 12800 ISO 25600

Photoblog Hamburg

ISO (Gain)
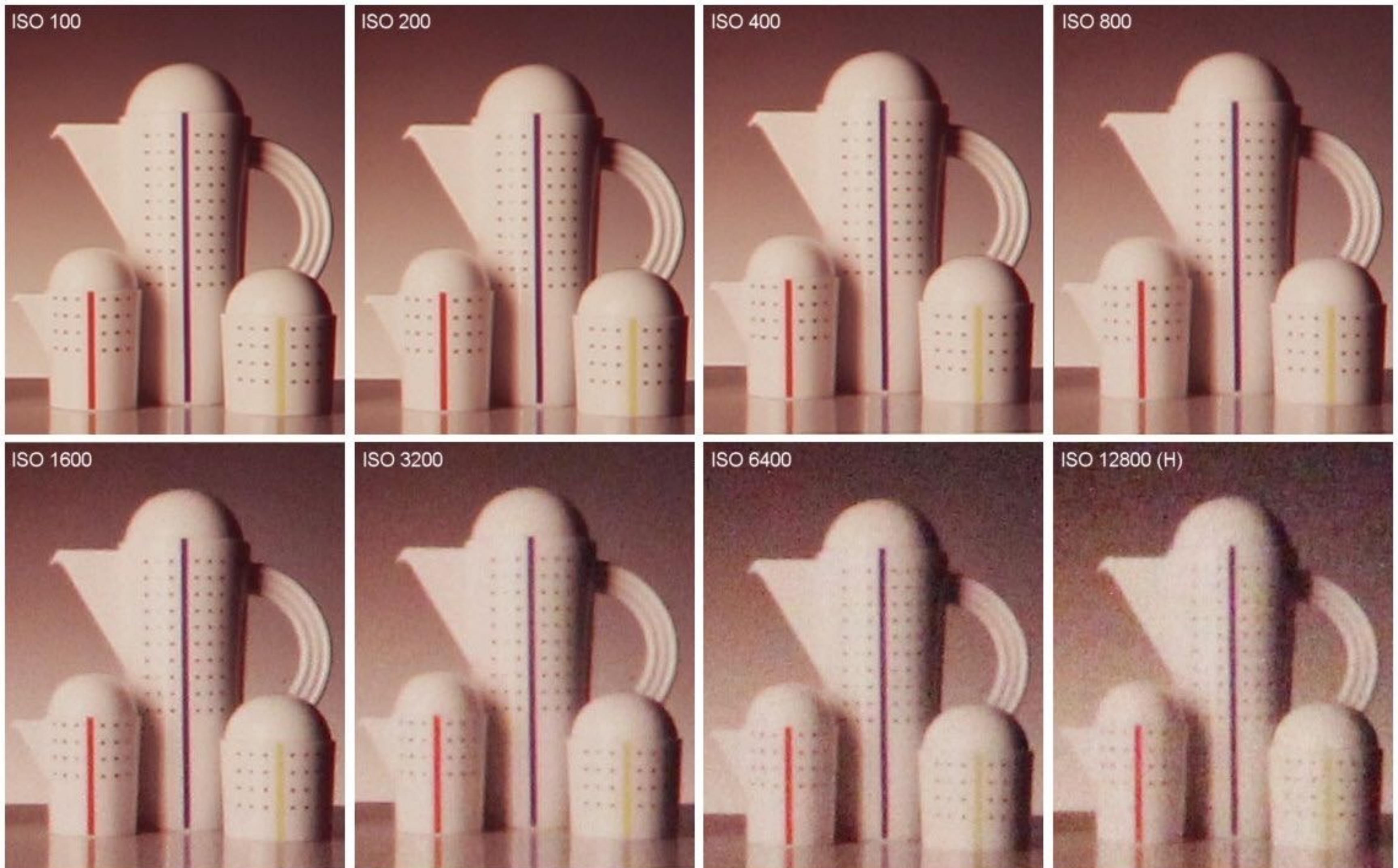
Third variable for exposure

Film: trade sensitivity for grain

Digital: 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: bobatkins.com

F-Number (F-Stop): Exposure Levels
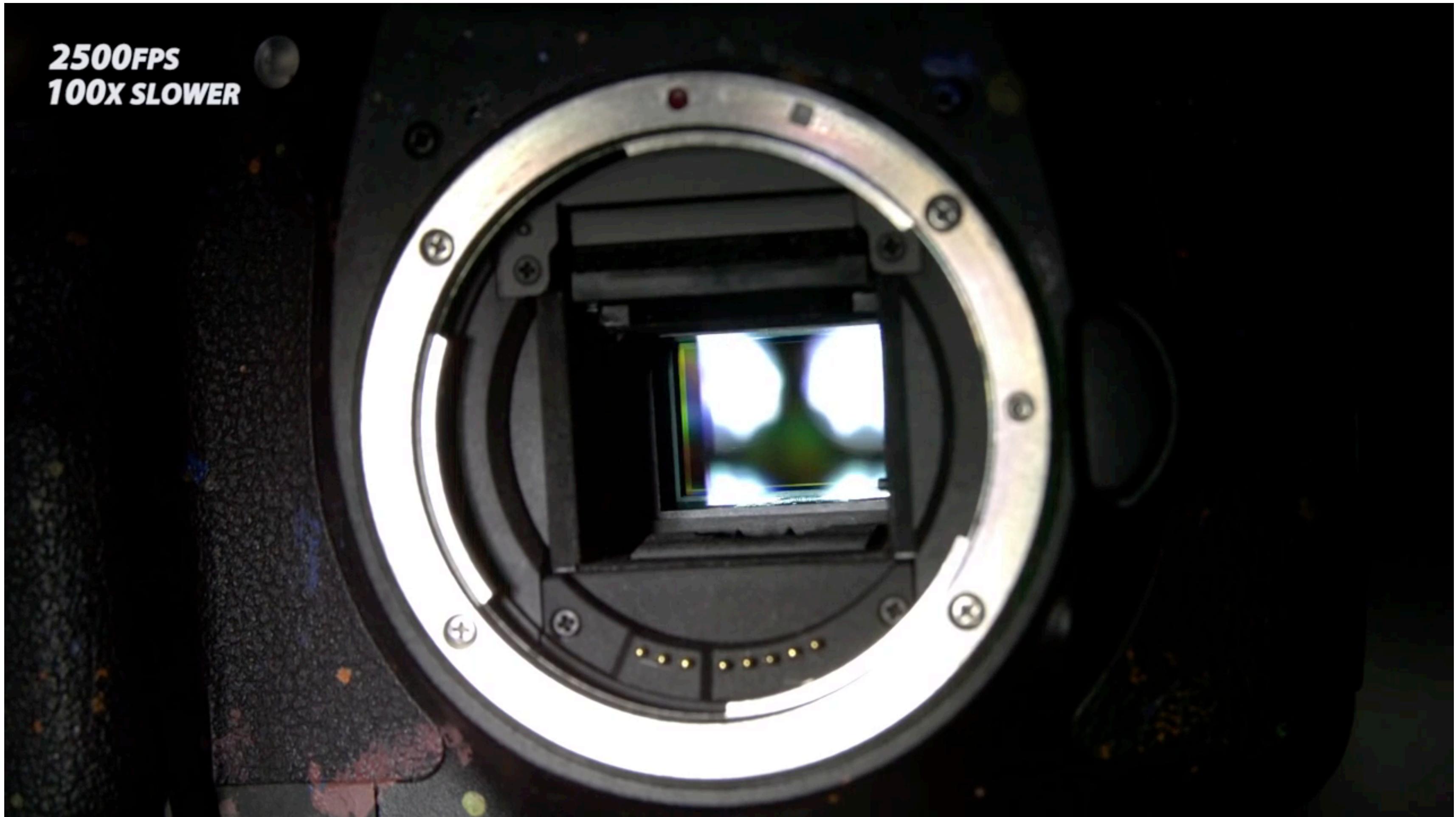
Written as F N or F/N. N is the f-number.

Informal understanding: the inverse-diameter of a round aperture

-1 Underexposure

Normal Exposure

+1 Overexposure

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

Physical Shutter (1/25 Sec Exposure)

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

Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur

1/125th Sec @65mm
f/8   ISO200

1/60th Sec @65mm
f/8   ISO100

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

Gavin Hoey

Side Effect of Shutter Speed

Note: motion blur is not always bad!

Tip: think about anti-aliasing

London

Side Effect of Shutter Speed

Rolling shutter: different parts of photo taken at different times

https://www.premiumbeat.com/blog/3-tips-for-dealing-with-rolling-shutter/

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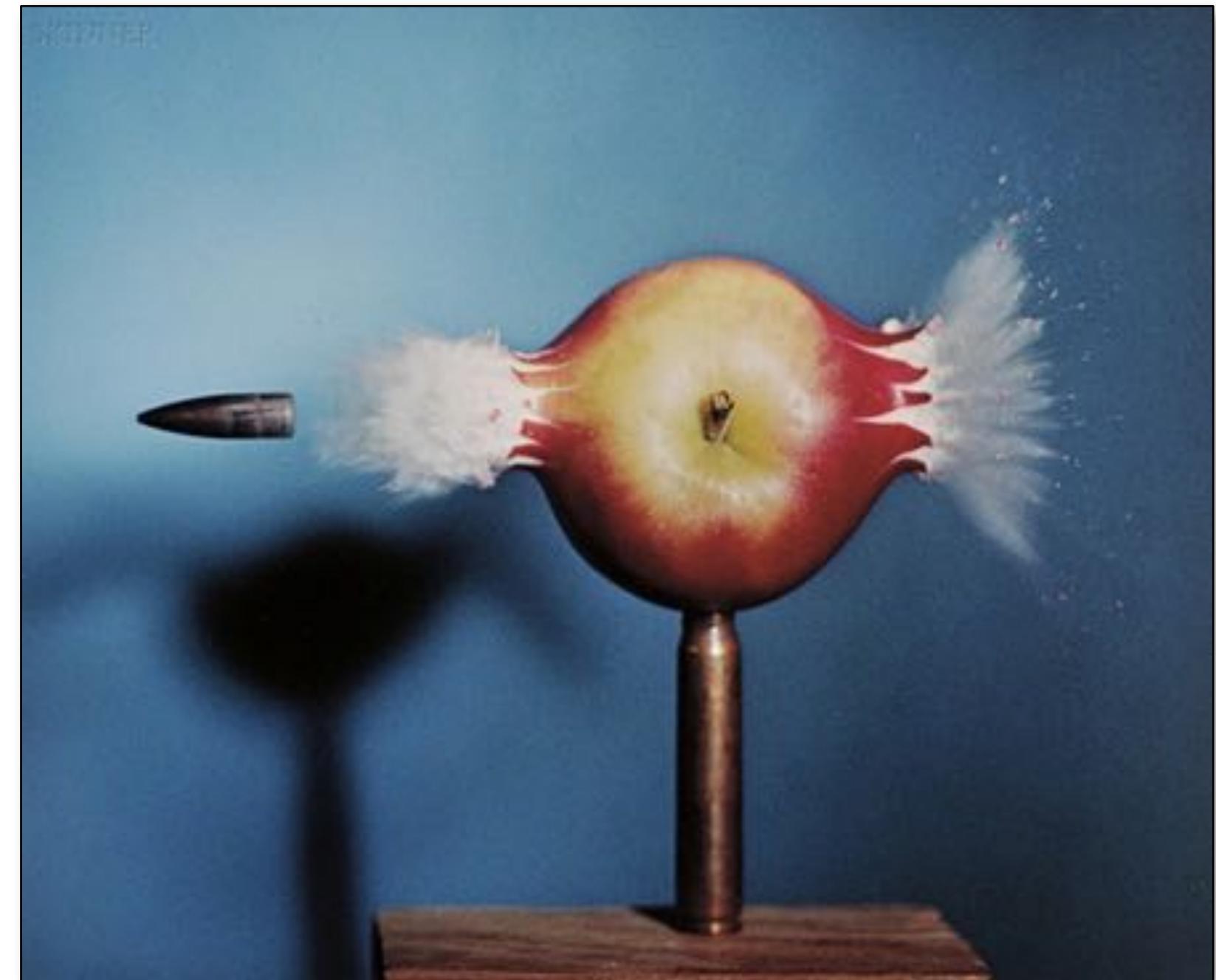
If the exposure is too bright/dark, may need to adjust f-stop and/or shutter up/down.

- Photographers must trade off depth of field (?) and motion blur for moving subjects　　(景深)

Fast and Slow Photography

High-Speed Photography

Normal exposure =
extremely fast shutter speed x
(large aperture and/or high ISO)
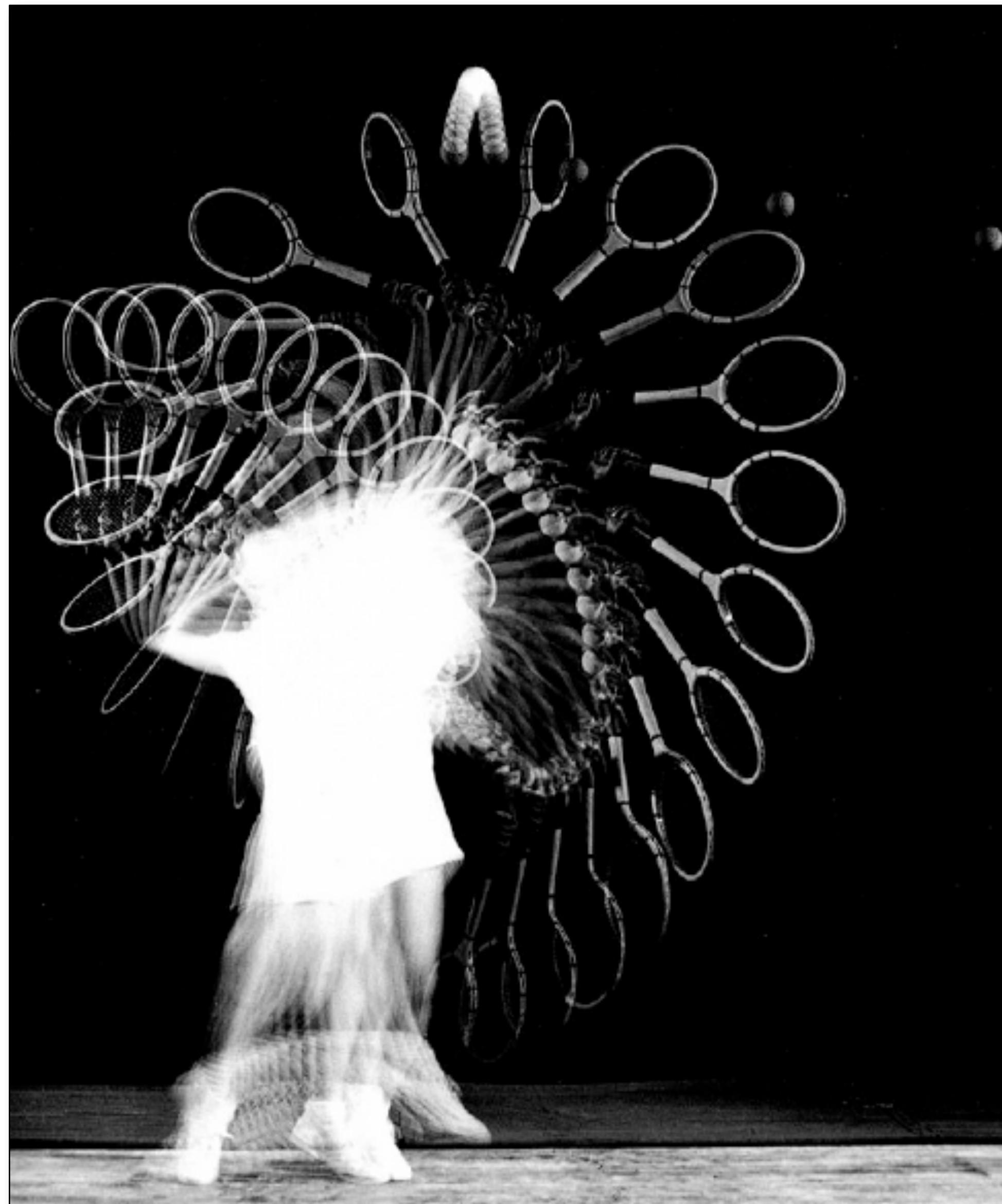
Harold Edgerton
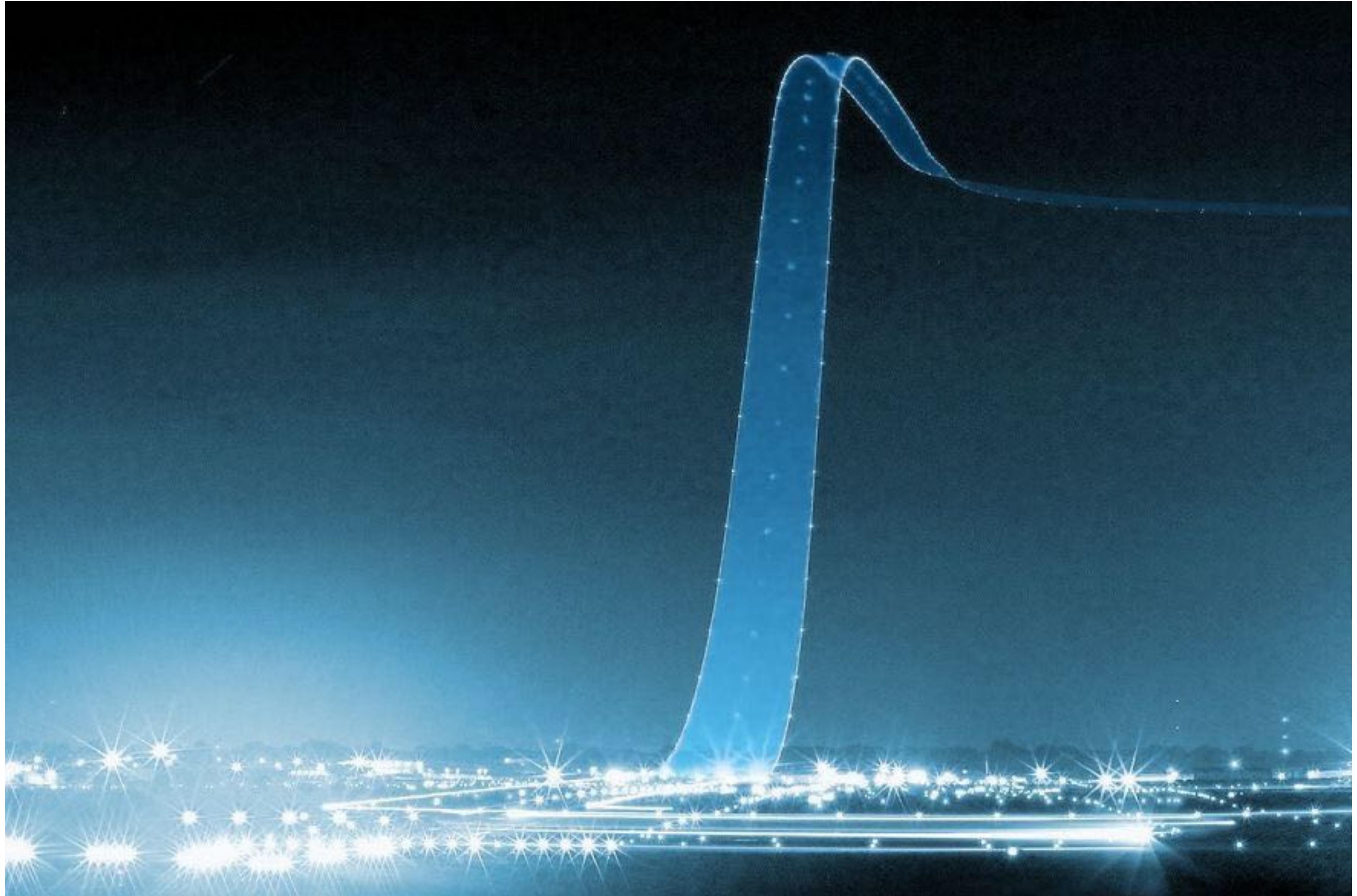
Slide courtesy L. Waller

Mark Watson

High-Speed Photography
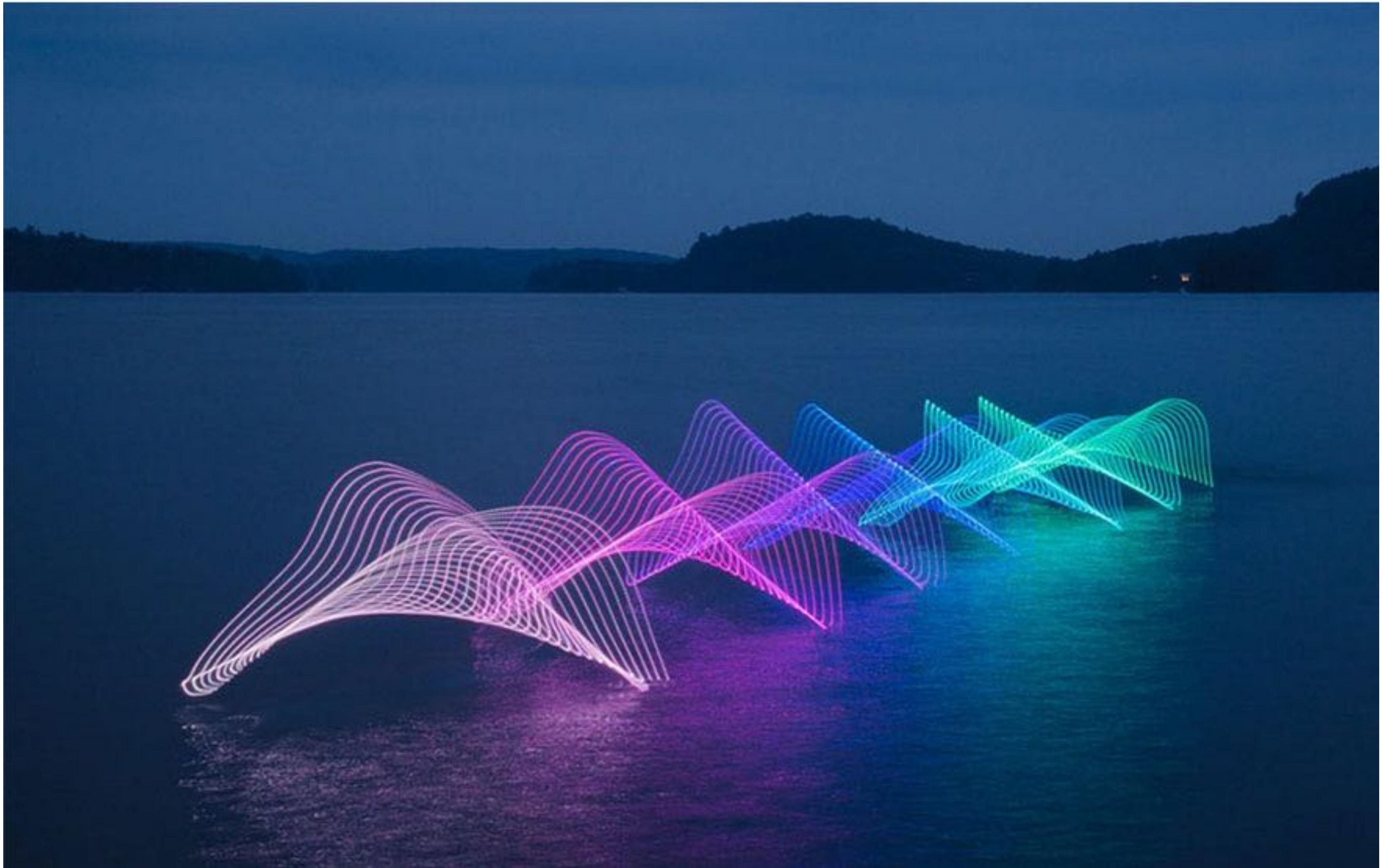
34   Harold Edgerton   Lingqi Yan, UC Santa Barbara

Long-Exposure Photography

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

Long-Exposure Photography

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

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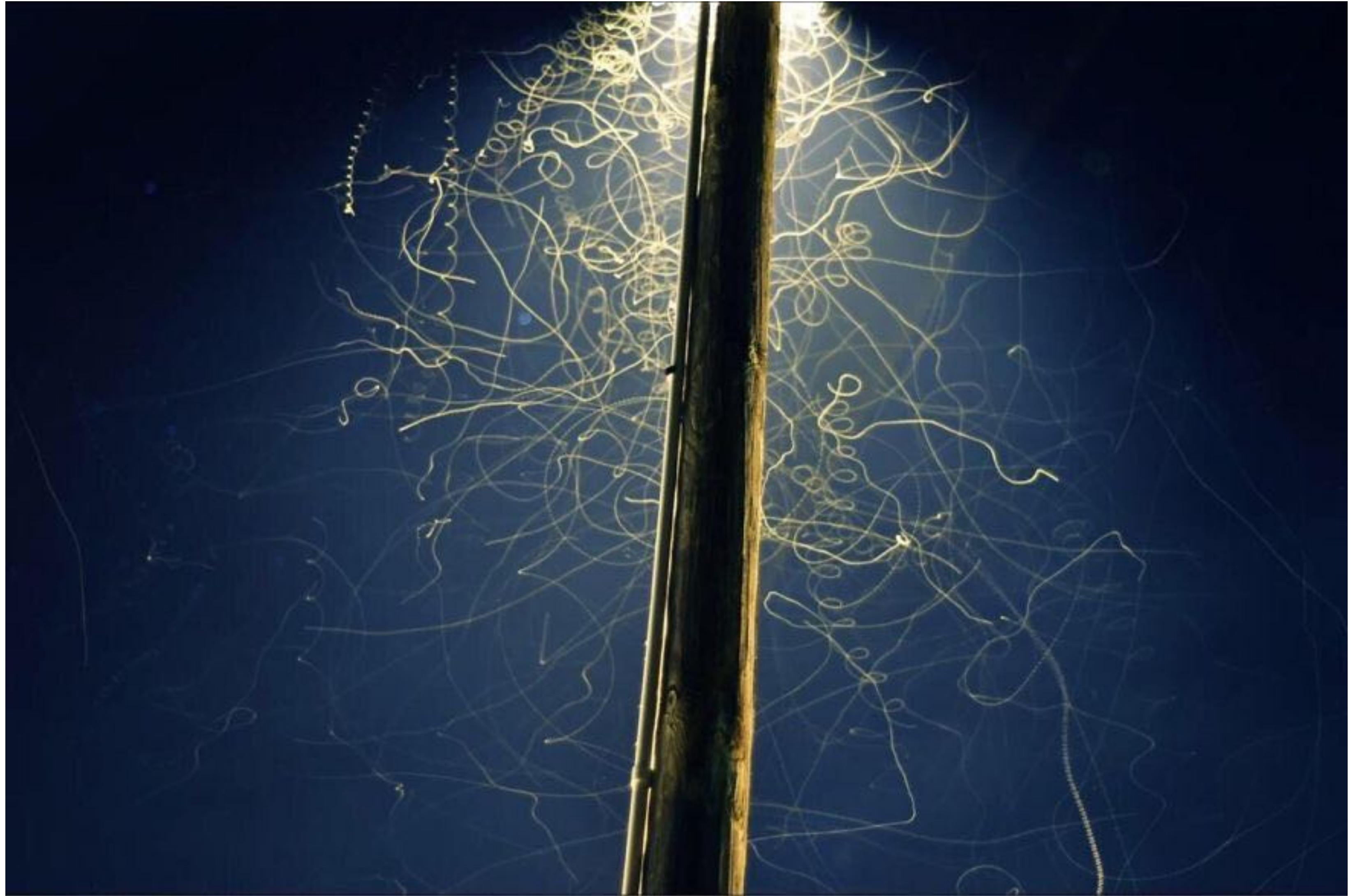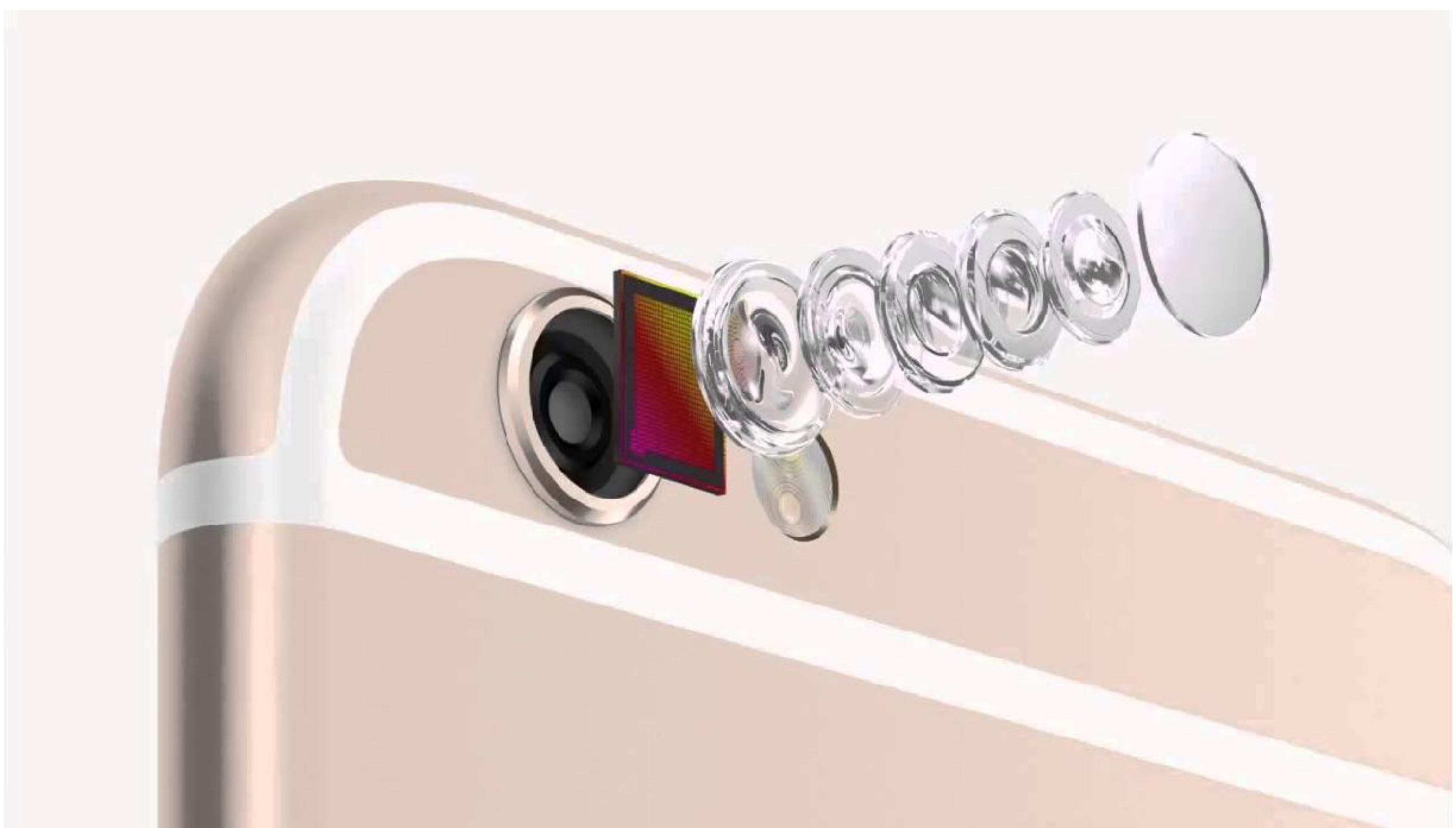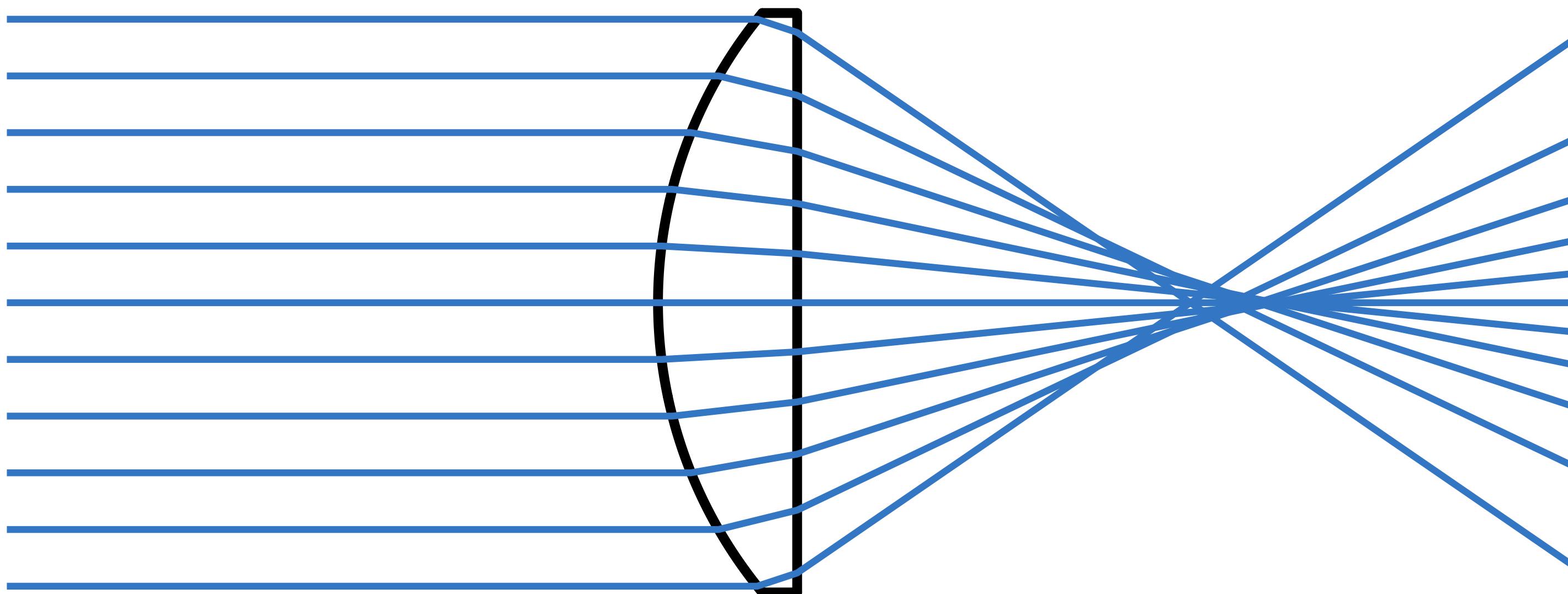
Thin Lens Approximation

# Real Lens Designs Are Highly Complex
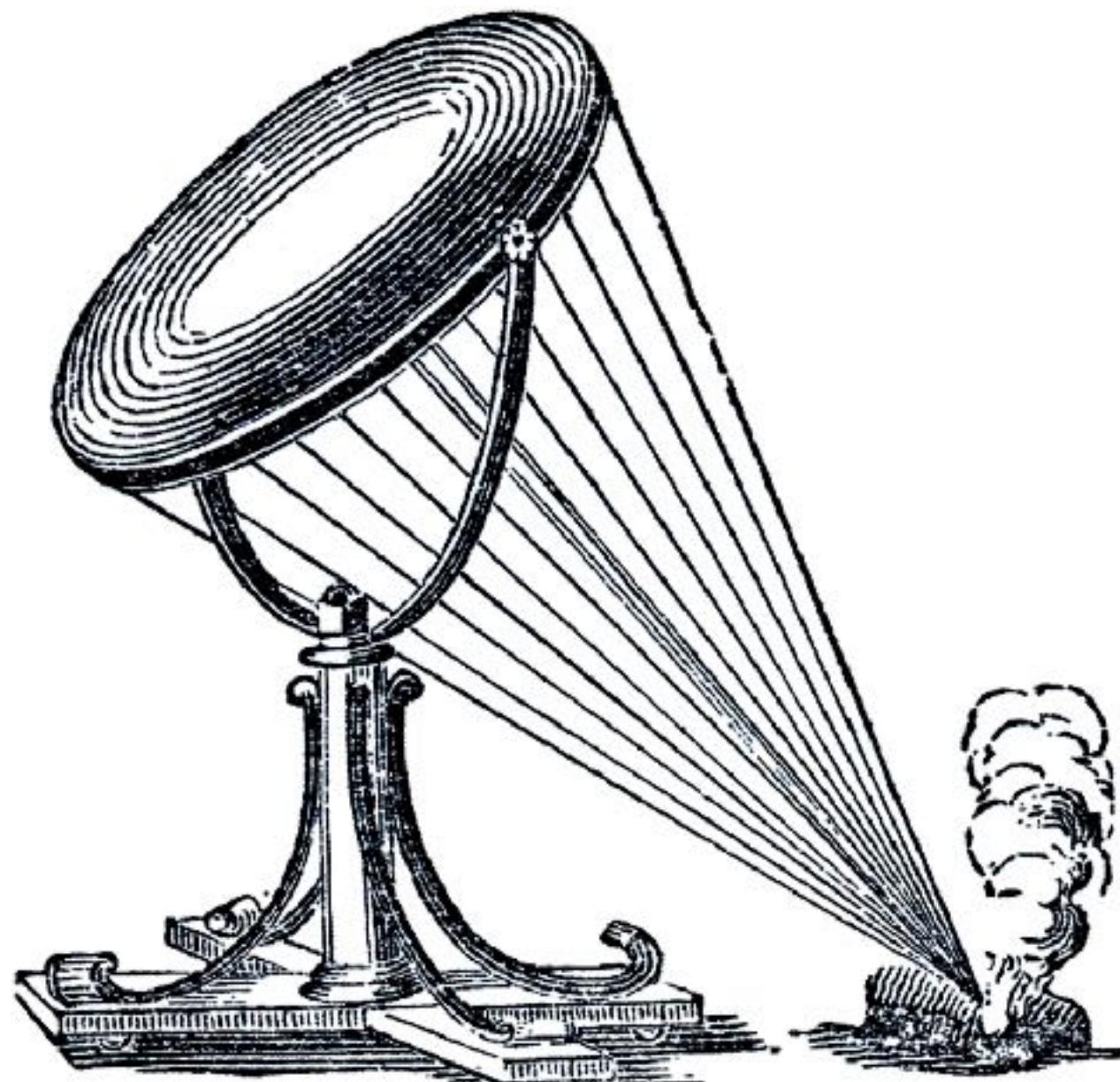
[Apple]

# Real Lens Elements Are Not Ideal – Aberrations
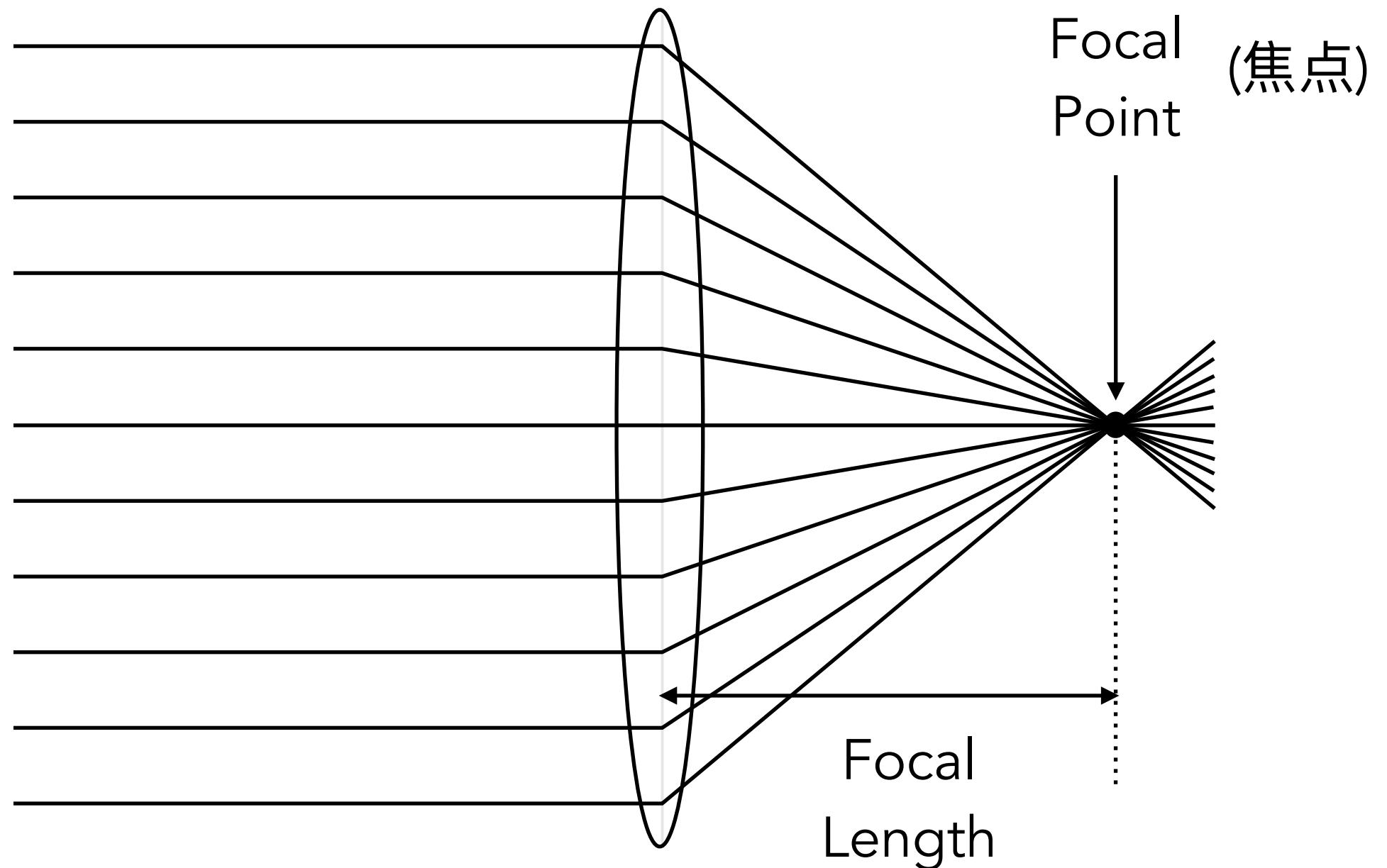
Real plano-convex lens (spherical surface shape).
Lens does not converge rays to a point anywhere.

Ideal Thin Lens – Focal Point

Credit: Karen Watson
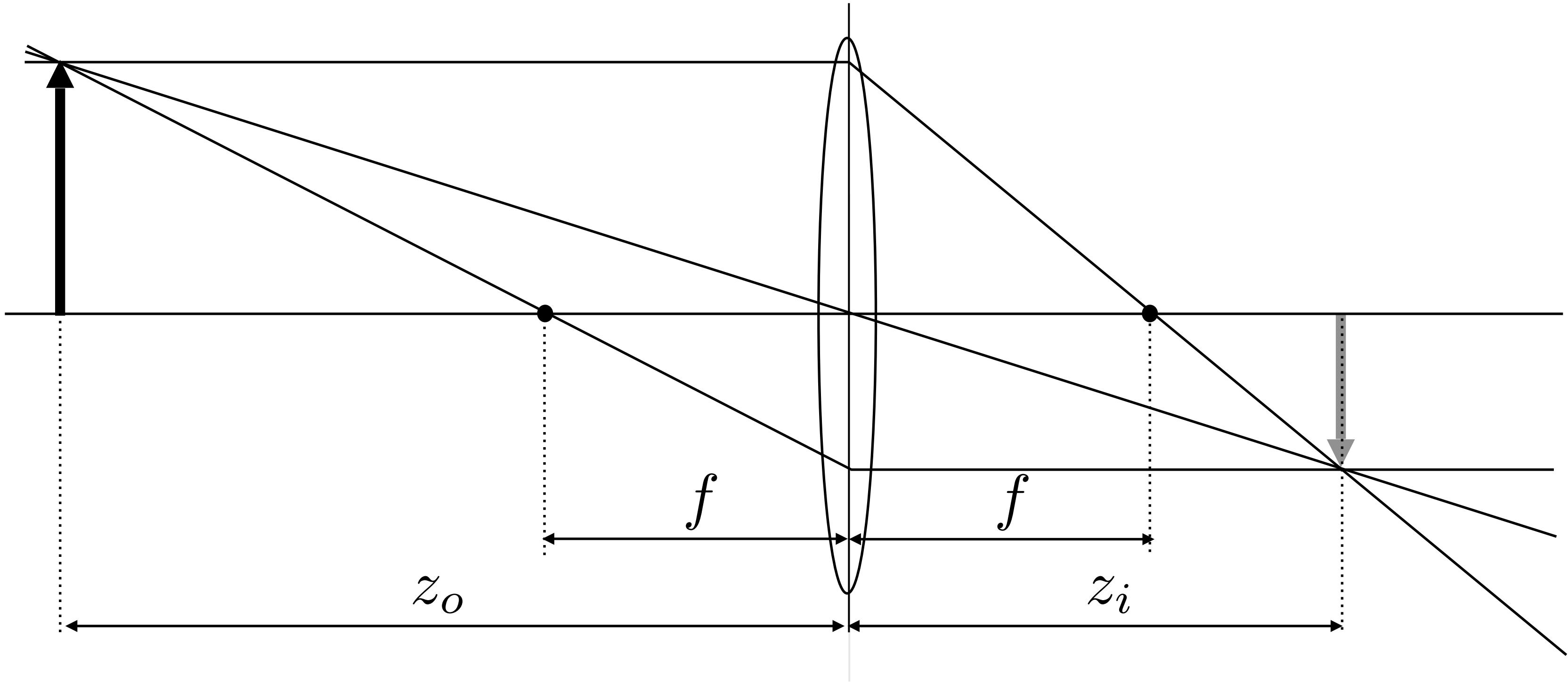
Focal Point (焦点)
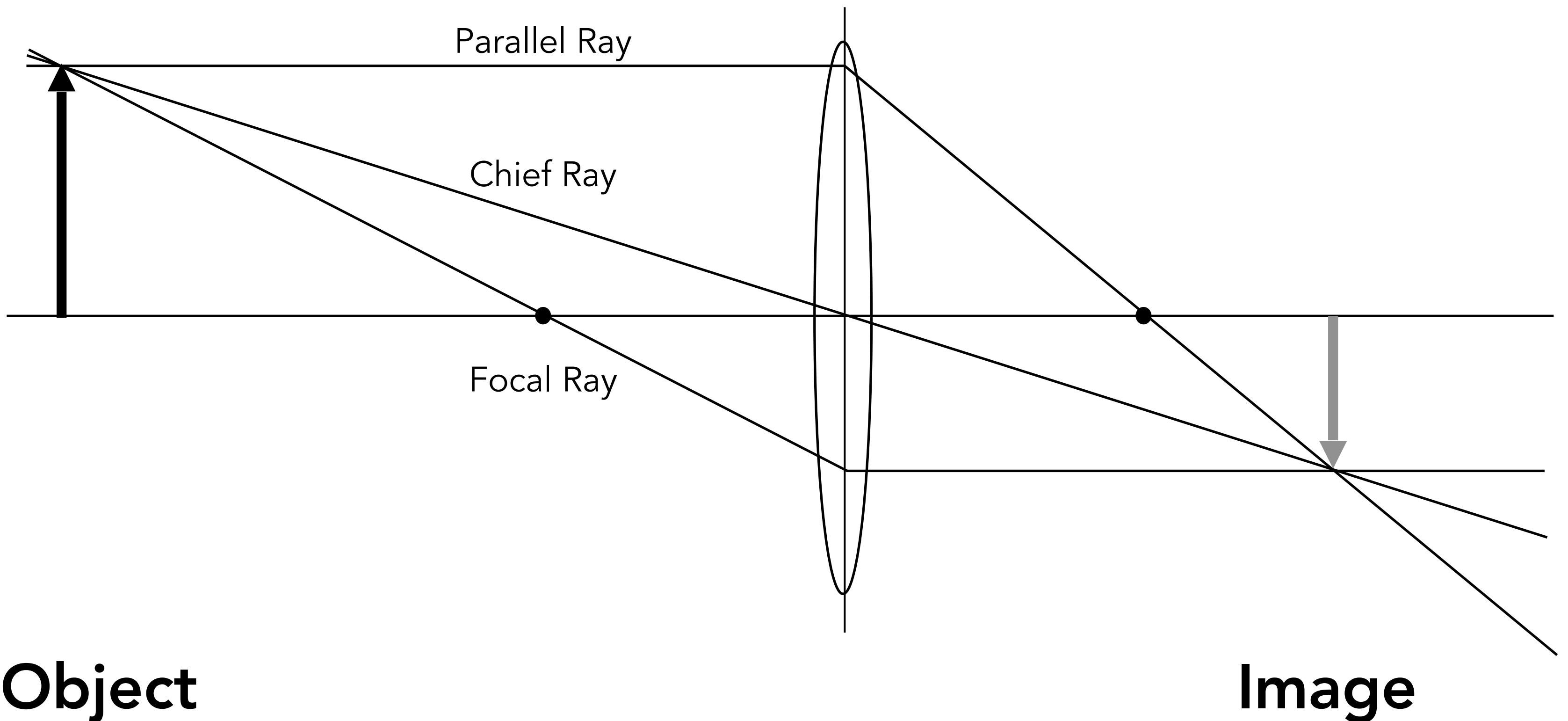
Focal Length

(1) All parallel rays entering a lens pass through its focal point.
(2) All rays through a focal point will be in parallel after passing the lens.
(3) Focal length can be arbitrarily changed (in reality, yes!).

The Thin Lens Equation
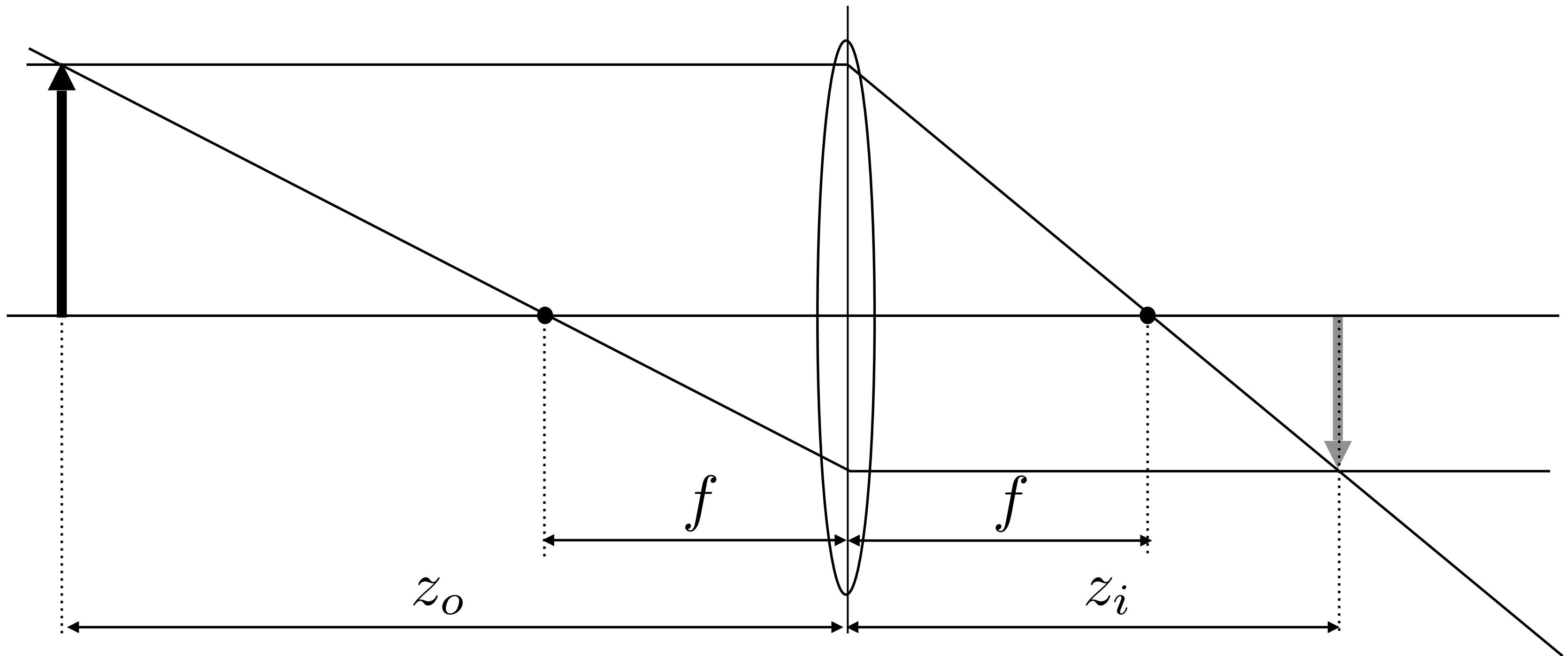

$$\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}$$

Gauss' Ray Diagrams

Parallel Ray

Chief Ray

Focal Ray
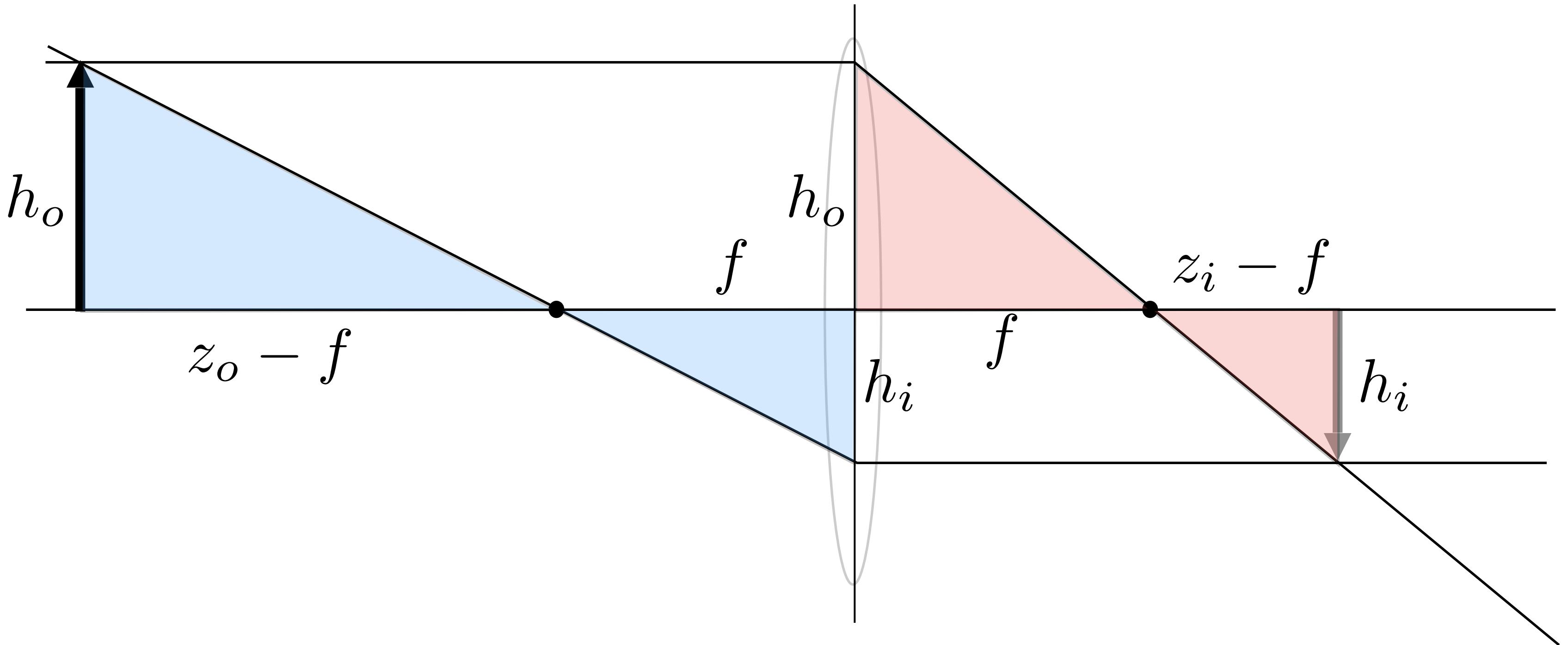
Object

Image

Gauss' Ray Tracing Construction

What is the relationship between conjugate depths z_o, z_i ?

Gauss' Ray Tracing Construction

h_o

$z_o - f$

f

h_o

h_i

f

f

$z_i - f$

h_i

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

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

Gauss' Ray Tracing Construction

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

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

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

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

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

Object / image heights
factor out - applies to all rays

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

Newtonian Thin Lens Equation
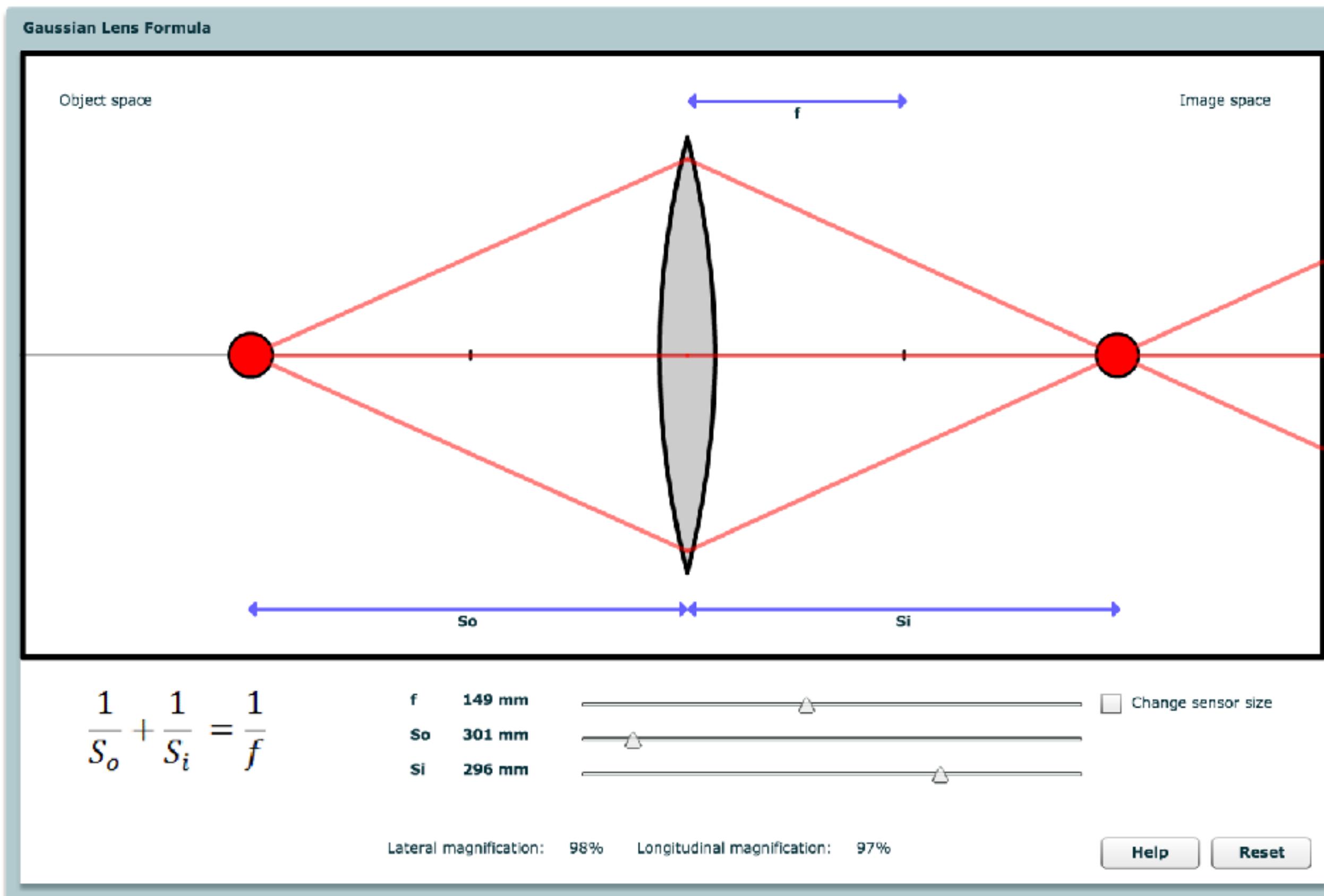
$$z_o z_i - (z_o + z_i)f + f^2 = f^2$$

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

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

Gaussian Thin Lens Equation
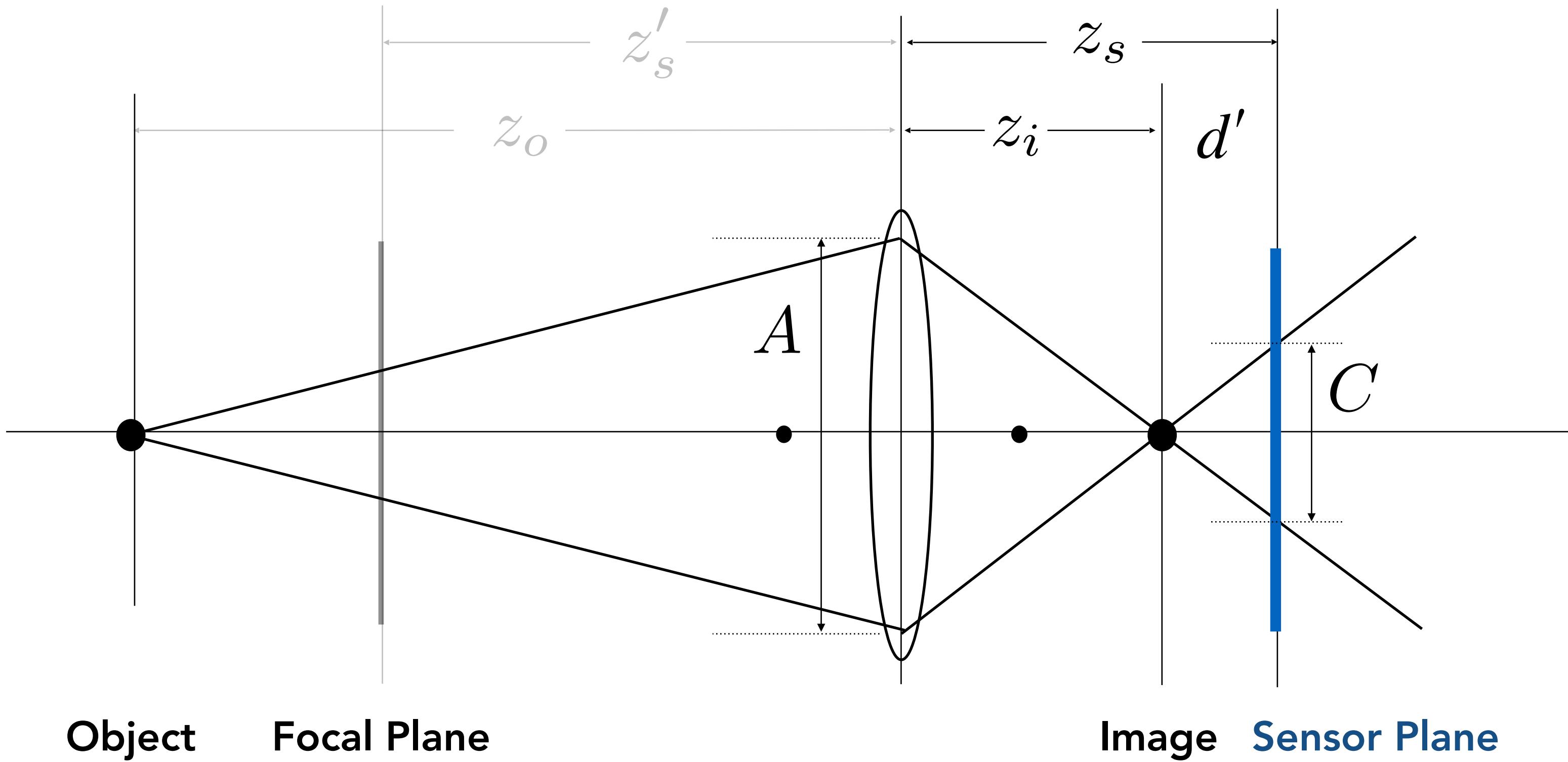
Thin Lens Demonstration

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

Defocus Blur

Computing Circle of Confusion (CoC) Size

Object   **Focal Plane**   **Image**   **Sensor Plane**

Circle of confusion is proportional to the size of the aperture

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

CoC vs. Aperture Size

f/1.4

f/22

English - detected ▾   ⇄   Chinese ▾

circle of
confusion   ✕   混乱的圈子
   Hǔnluàn de quānzi

Open in Google Translate   Feedback
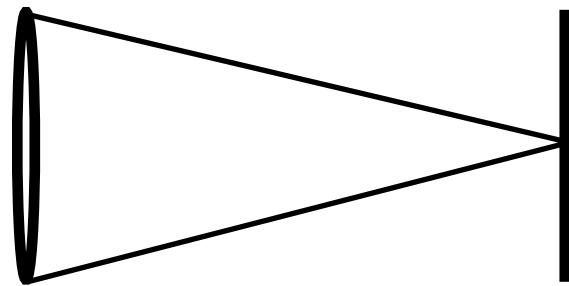
A side note: hilarious Google translate…

Revisiting F-Number (a.k.a. F-Stop)

- Formal definition: 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

- An f-stop of 2 is sometimes written f/2, reflecting the fact that the absolute aperture diameter (A) can be computed by dividing focal length (f) by the relative aperture (N).
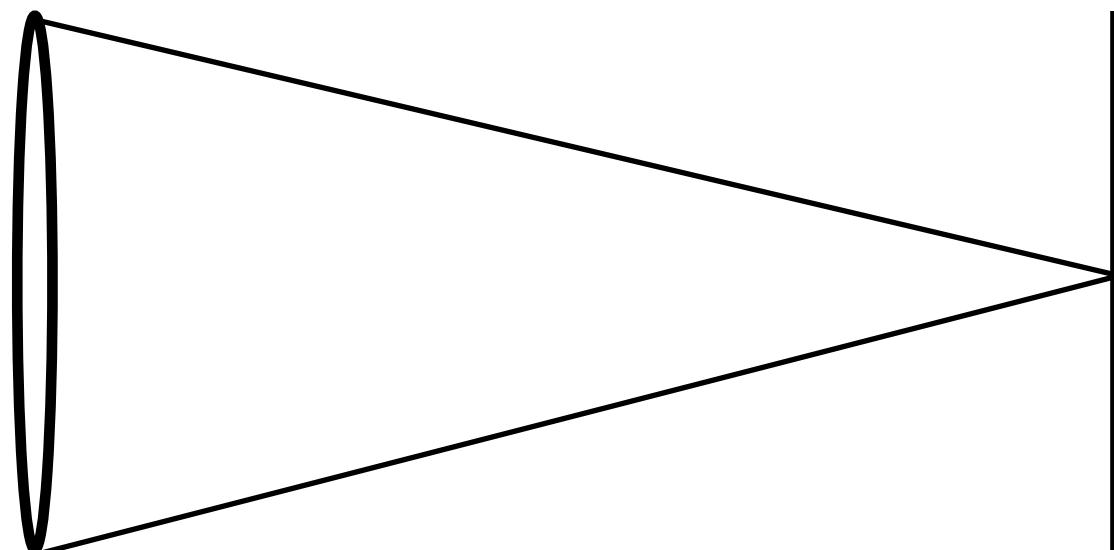
Example F-Stop Calculations
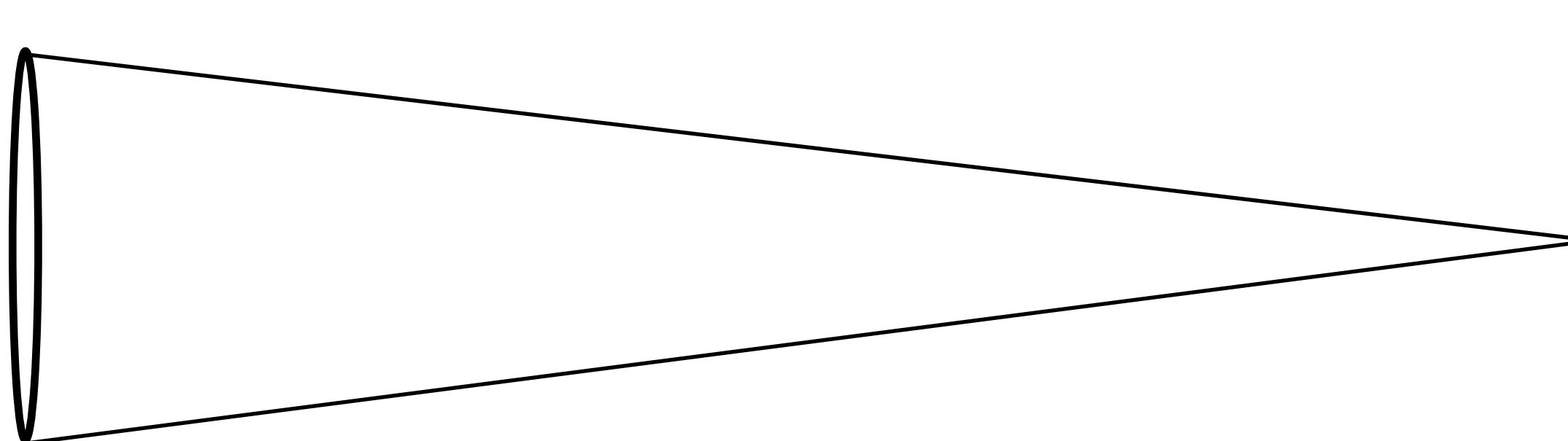
$$D = 50\,\mathrm{mm}$$
$$f = 100\,\mathrm{mm}$$
$$N = f/D = 2$$

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

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

Size of CoC is Inversely Proportional to F-Stop

R. Berdan, canadiannaturephotographer.com

F2.8

F16

$$C = A\frac{|z_s - z_i|}{z_i} = \frac{f}{N}\frac{|z_s - z_i|}{z_i}$$
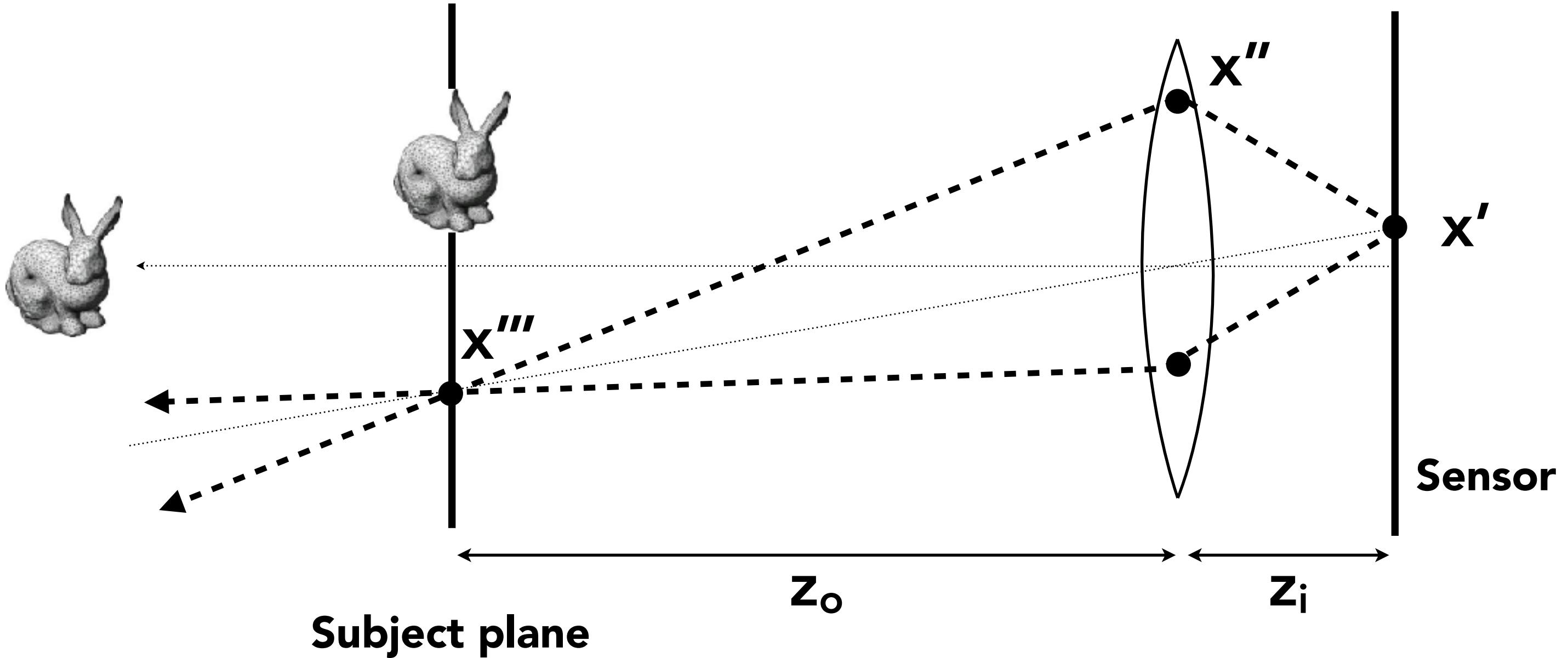
Ray Tracing Ideal Thin Lenses

Examples of Renderings with Lens Focus


Pharr and Humphreys
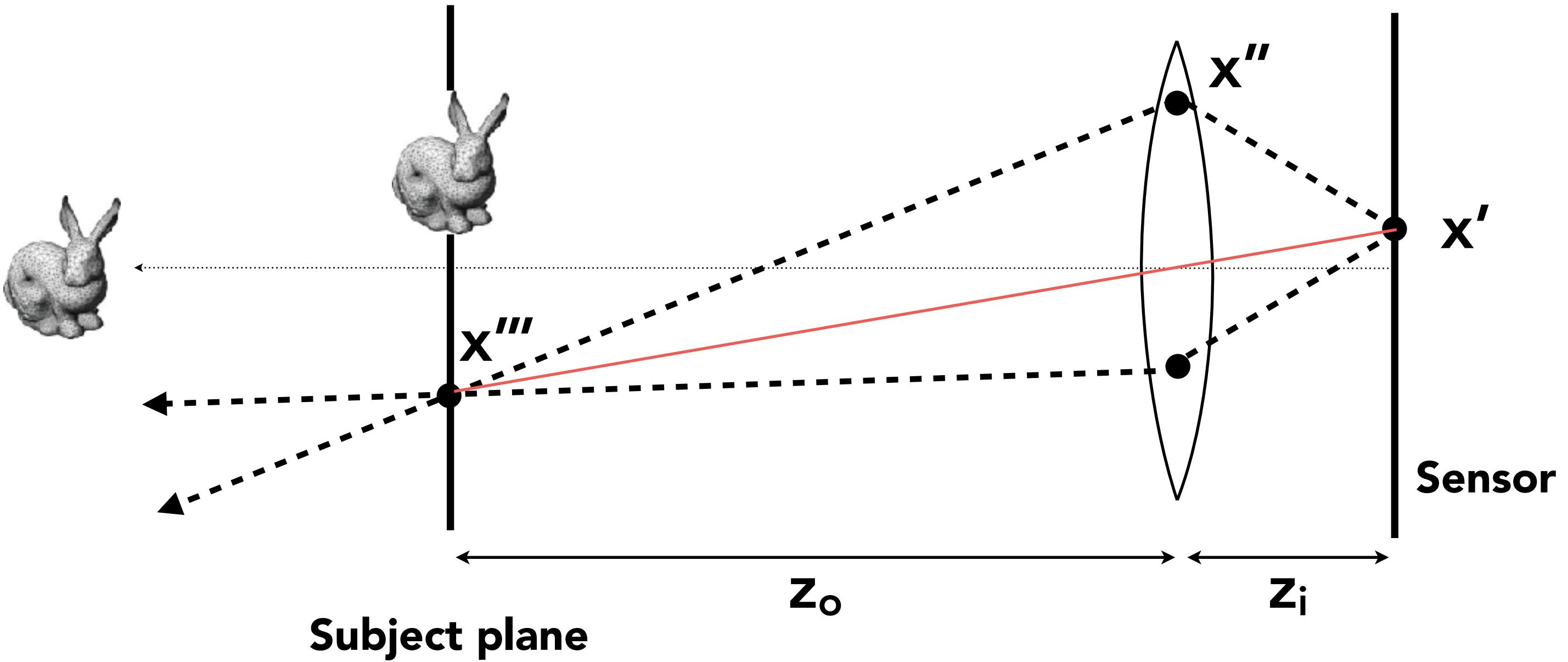
Ray Tracing for Defocus Blur (Thin Lens)

(One possible) 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

Ray Tracing for Defocus Blur (Thin Lens)

Sensor

z_o

z_i

Subject plane

Rendering:
- For each pixel x' on the sensor (actually, film (胶片))
- Sample random points x'' on lens plane
- You know the ray passing through the lens will hit x'''
  (because x''' is in focus, consider virtual ray (x', center of the lens))
- Estimate radiance on ray x'' -> x'''

Depth of Field

Depth of Field

Large aperture opening
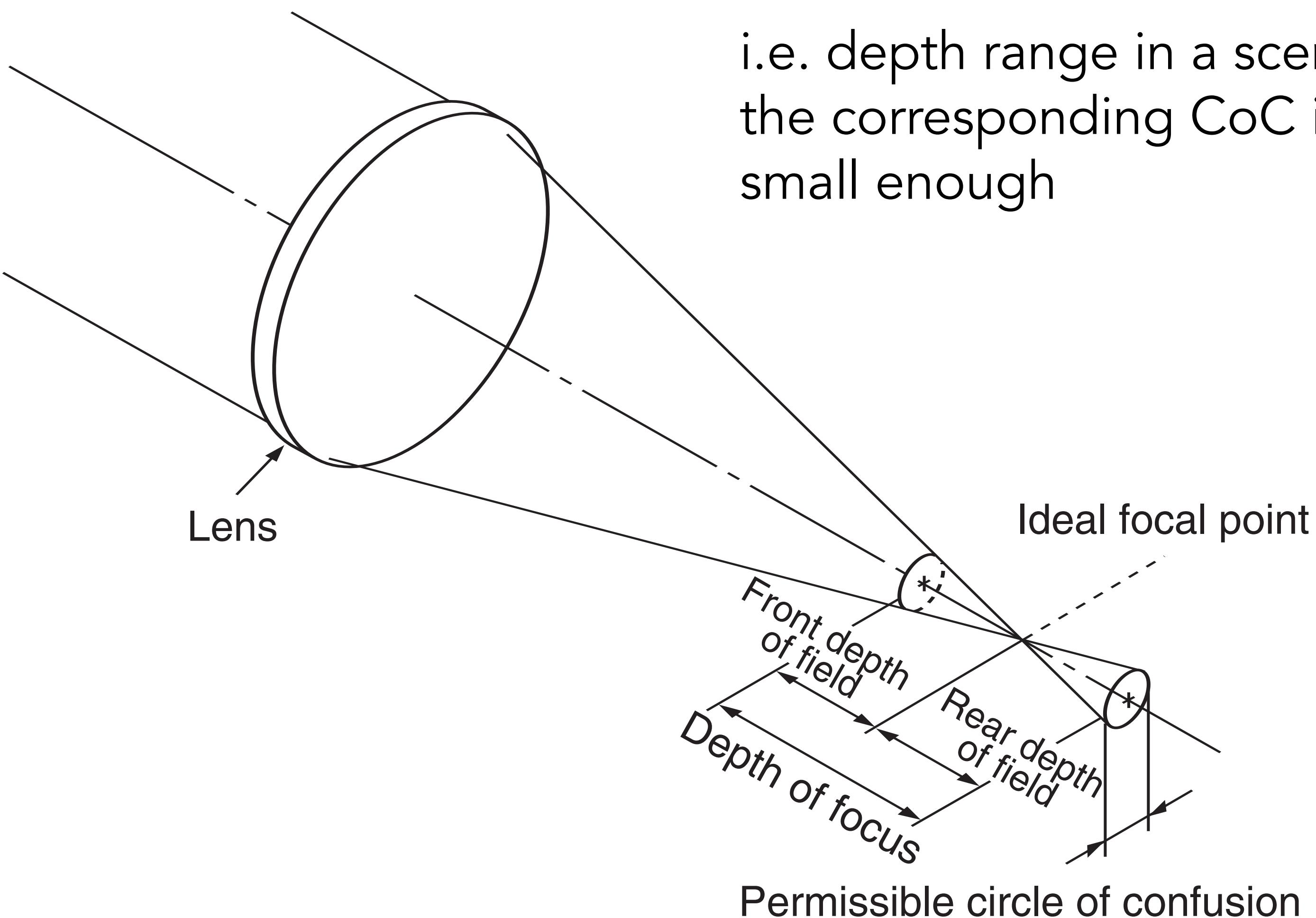
Small aperture opening
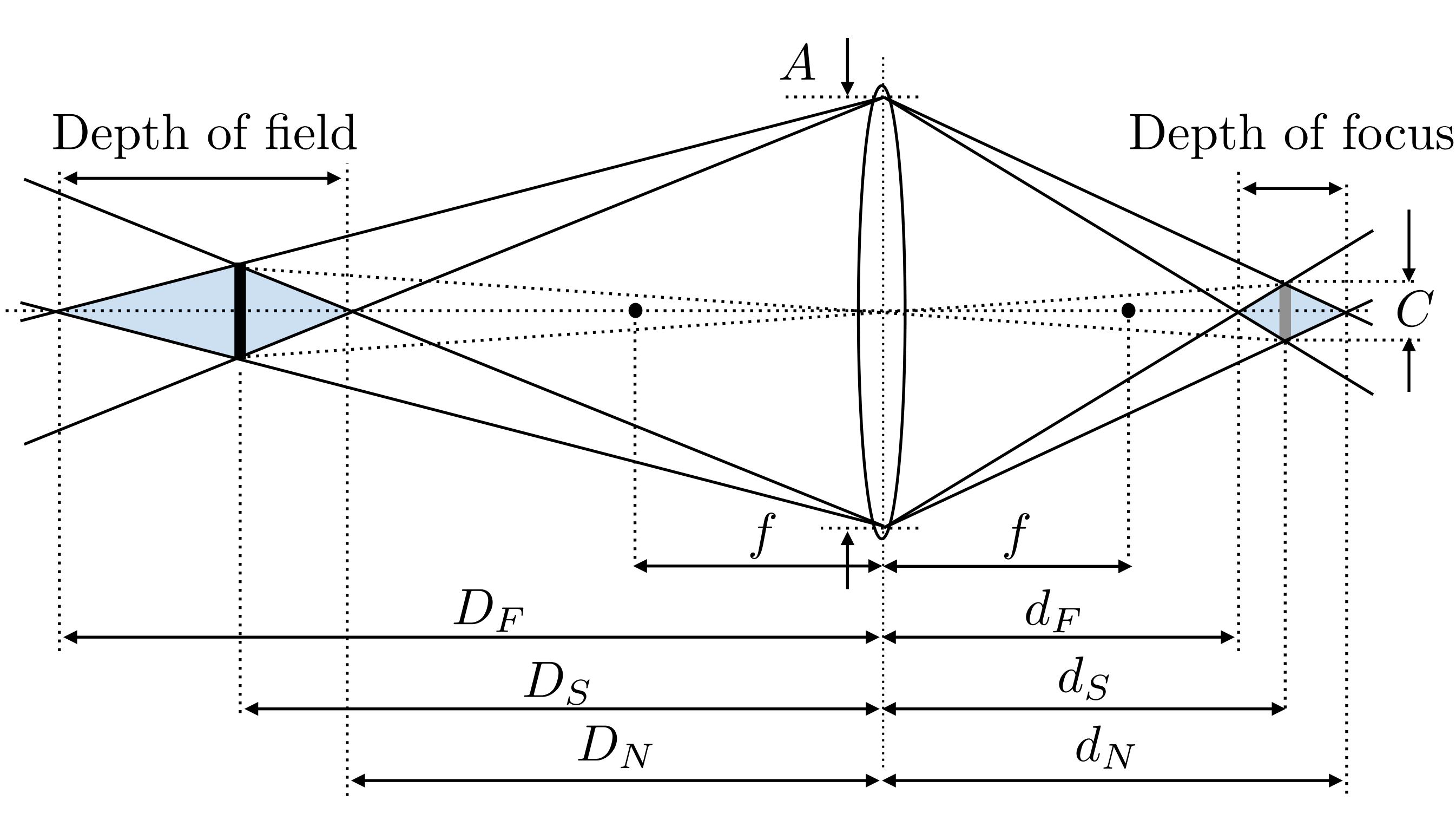
From London and Upton

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

Circle of Confusion for Depth of Field

i.e. depth range in a scene where
the corresponding CoC is considered
small enough

Lens

Ideal focal point

Front depth of field

Rear depth of field

Depth of focus

Permissible circle of confusion

Depth of Field (FYI)

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

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

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

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

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

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

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

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

DOF Demonstration (FYI)

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

Thank you!

(And thank Prof. Ren Ng for many of the slides!)