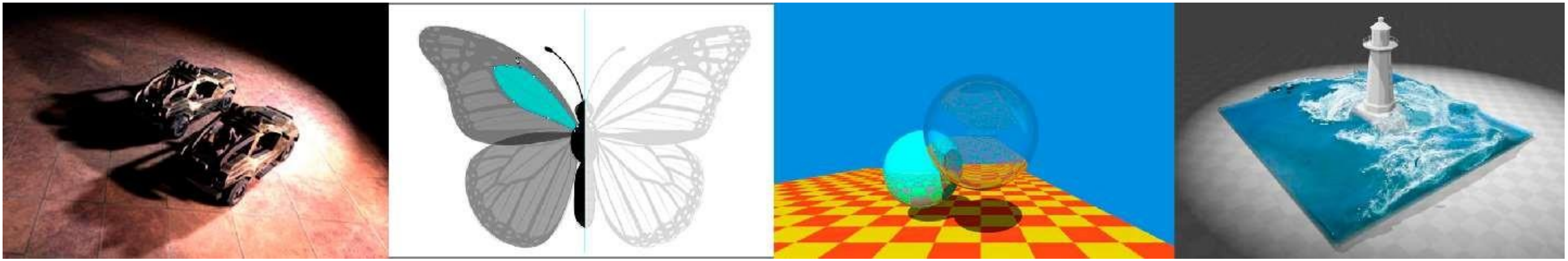
Cameras, Lenses and Light Fields



Last Lecture

- Using AABBs to accelerate ray tracing
  - Uniform grids
  - Spatial partitions
- Basic radiometry （辐射度量学）
  - Advertisement: new topics from now on, scarcely covered in other graphics courses

Reviewing Concepts

辐射能

Radiant energy $Q \; [\mathrm{J} = \mathrm{Joule}]$ (barely used in CG)

- the energy of electromagnetic radiation

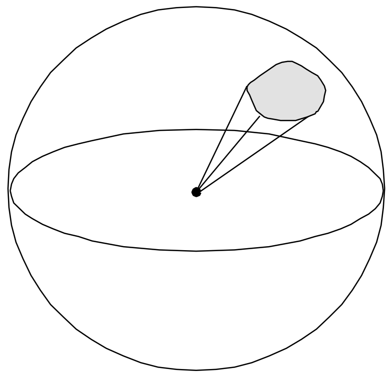
辐射通量

Radiant flux (power) $\Phi \equiv \frac{\mathrm{d}Q}{\mathrm{d}t} \; [\mathrm{W} = \mathrm{Watt}] \; [\mathrm{lm} = \mathrm{lumen}]$

- Energy per unit time

辐射强度

Radiant intensity $I(\omega) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\omega}$



- power per unit solid angle

立体角

Solid Angle $\Omega = \frac{A}{r^2}$

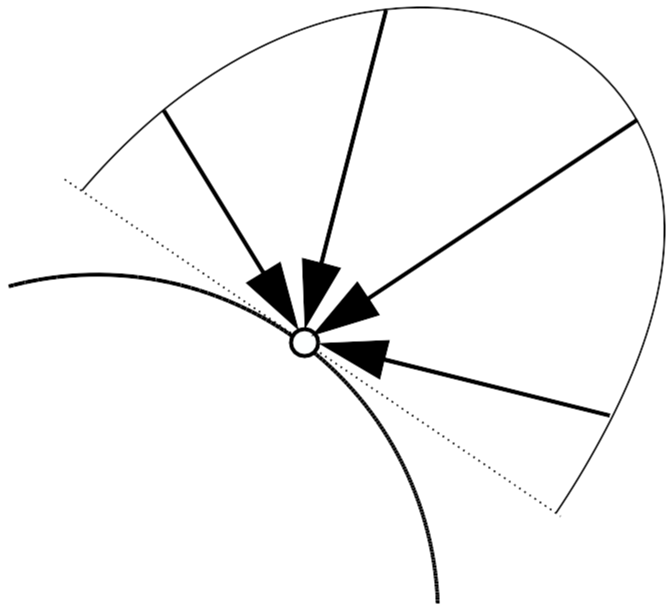
- ratio of subtended area on sphere to radius squared

Irradiance 辐照度

Definition: The irradiance is the power per unit area incident on a surface point.

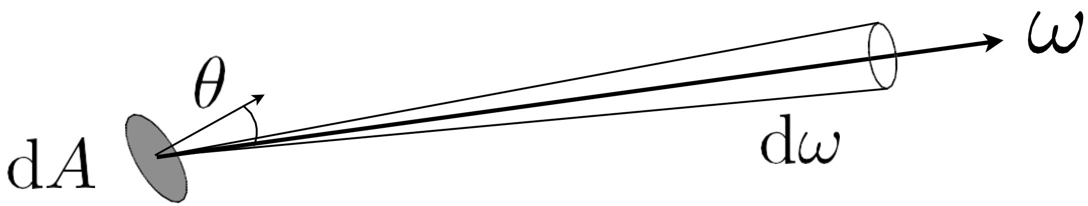
$$E(\mathbf{x}) \equiv \frac{\mathrm{d}\Phi(\mathbf{x})}{\mathrm{d}A}$$

$$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \quad \left[\frac{\mathrm{lm}}{\mathrm{m}^2} = \mathrm{lux}\right]$$



Radiance 辐射

Definition: The radiance (luminance) is the power emitted, reflected, transmitted or received by a surface, per unit solid angle, per projected unit area.

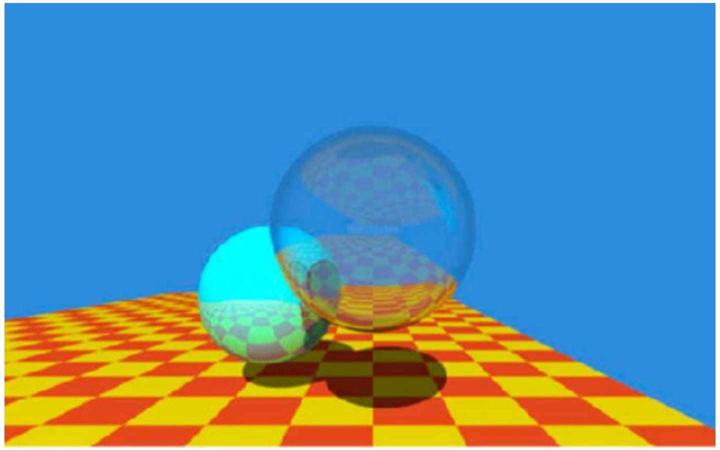


$$L(\mathrm{p}, \omega) \equiv \frac{\mathrm{d}^2\Phi(\mathrm{p}, \omega)}{\mathrm{d}\omega\, \mathrm{d}A \cos\theta}$$

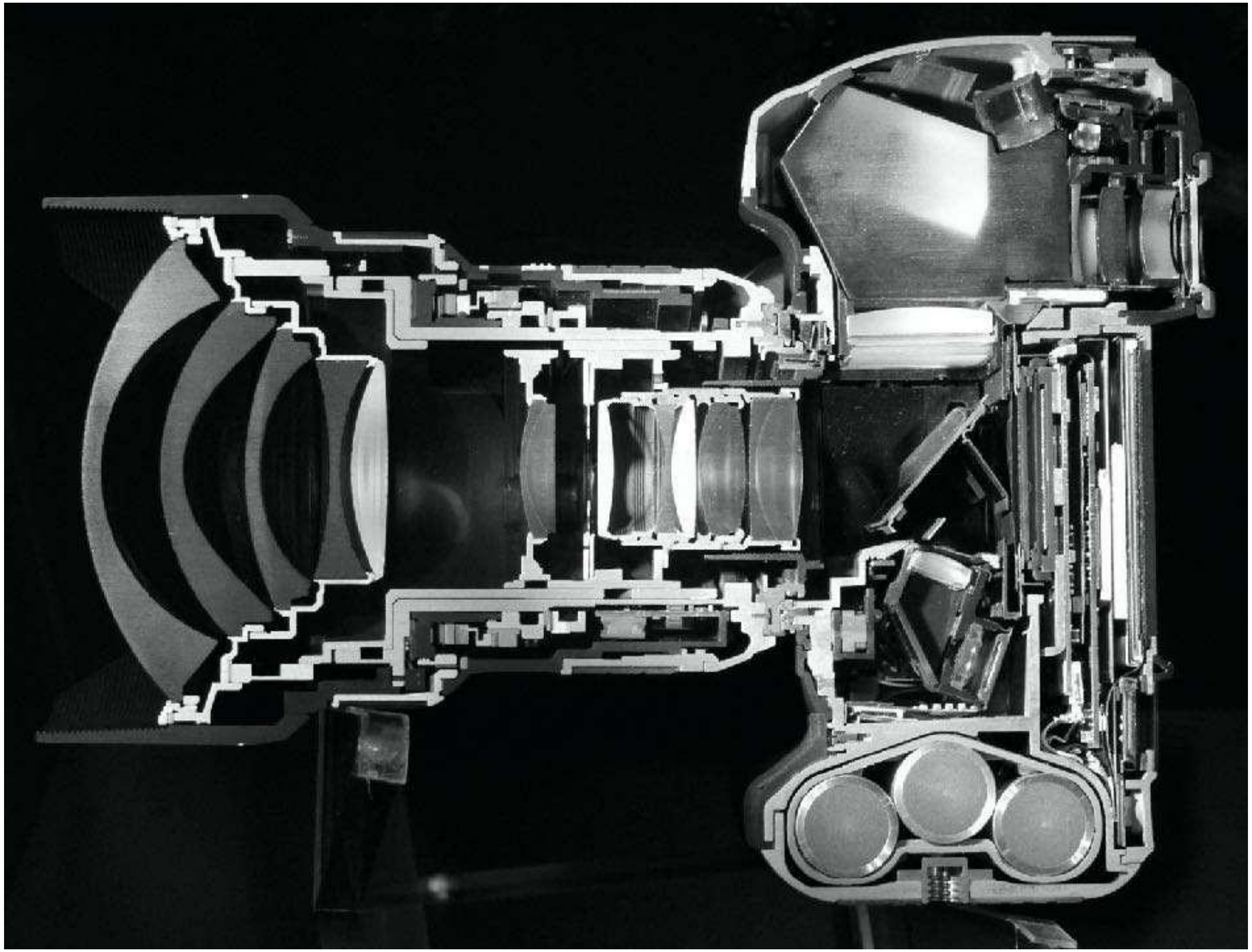
$\cos\theta$ accounts for projected surface area

$$\left[\frac{\mathrm{W}}{\mathrm{sr\,m^2}}\right] \quad \left[\frac{\mathrm{cd}}{\mathrm{m^2}} = \frac{\mathrm{lm}}{\mathrm{sr\,m^2}} = \mathrm{nit}\right]$$

Imaging = Synthesis + Capture



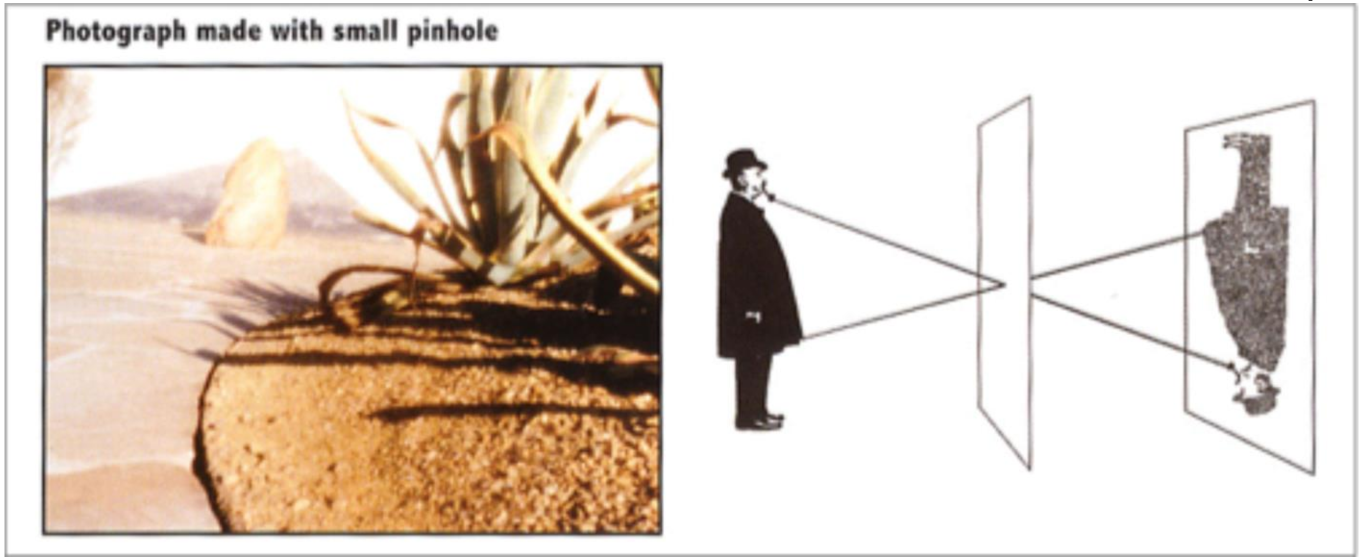
What's Happening Inside the Camera?

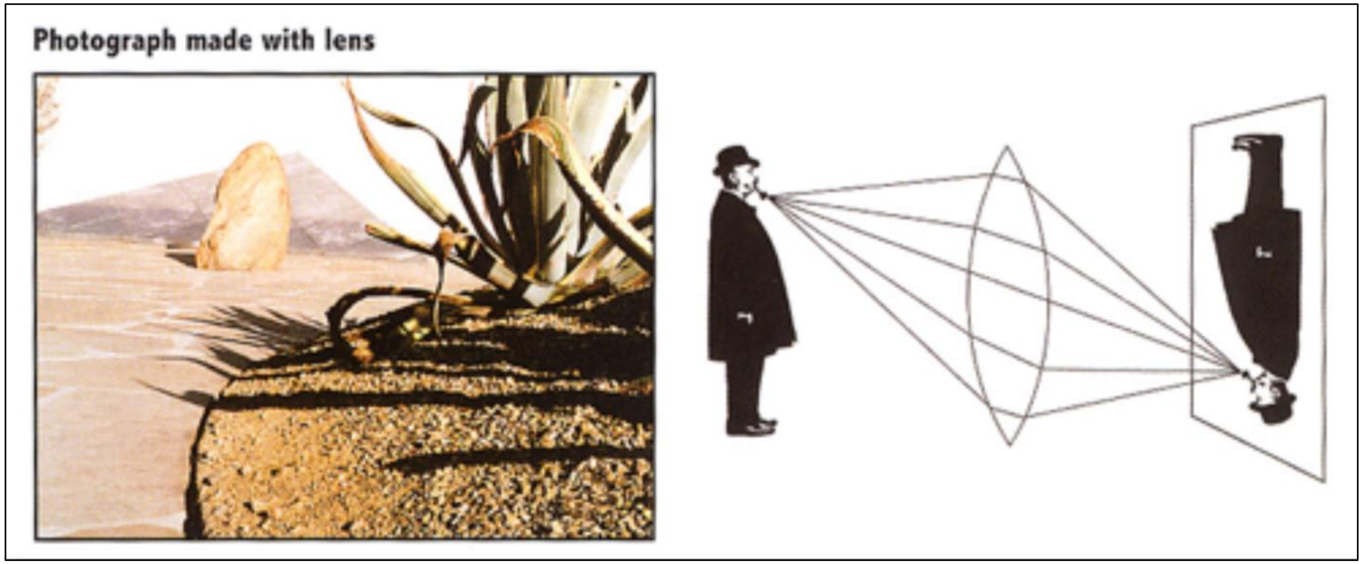


Cross-section of Nikon D3, 14-24mm F2.8 lens

Pinholes & Lenses Form Image on Sensor

(传感器)

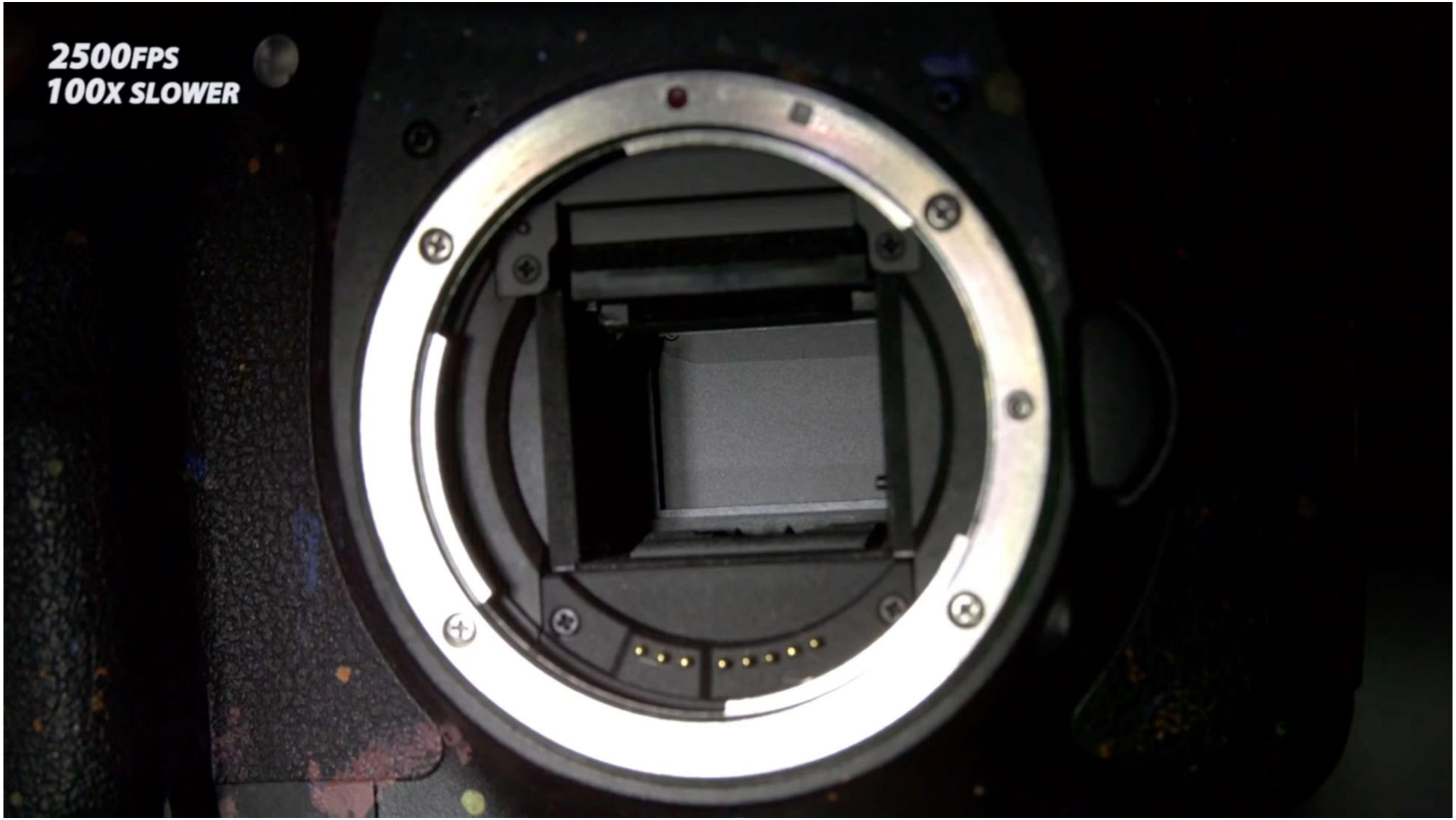




London and Upton

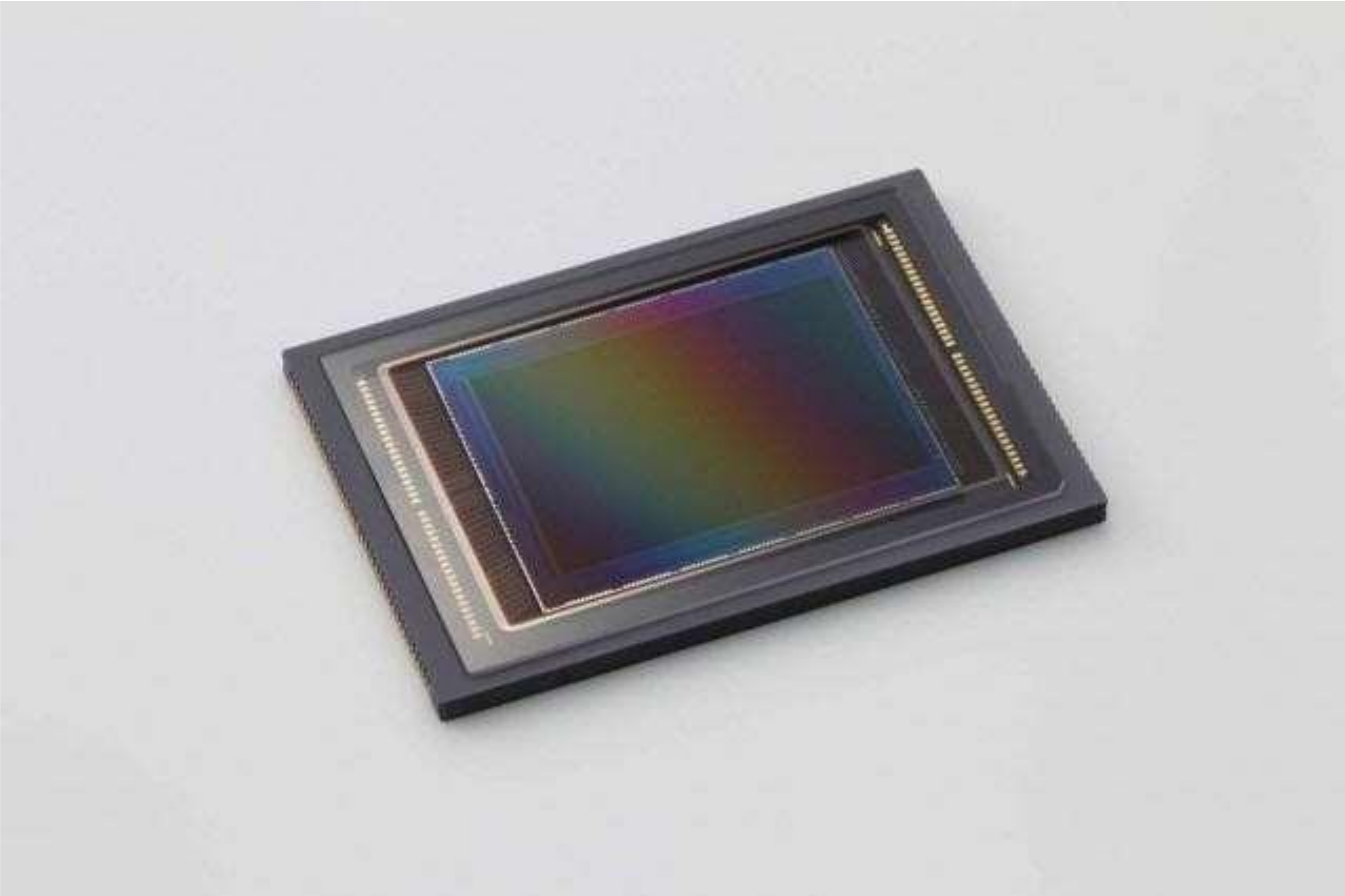
Shutter Exposes Sensor For Precise Duration

(快门)



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

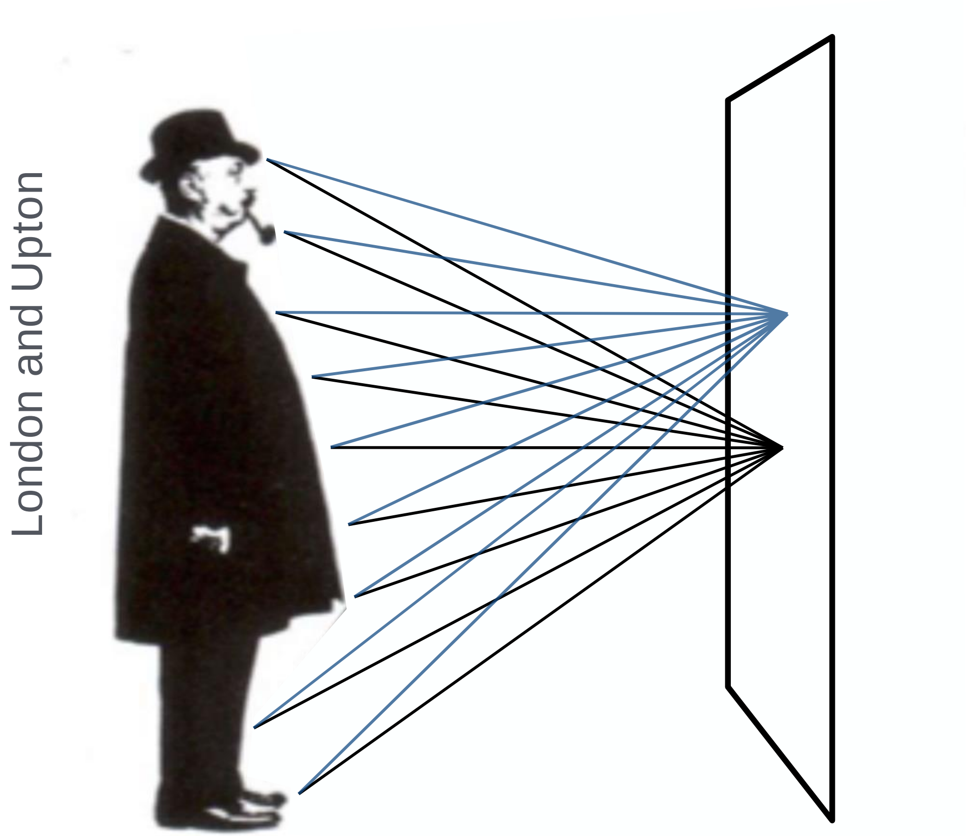
Sensor Accumulates Irradiance During Exposure



Why Not Sensors Without Lenses?

Each sensor point would integrate light from all points on the object, so all pixel values would be similar

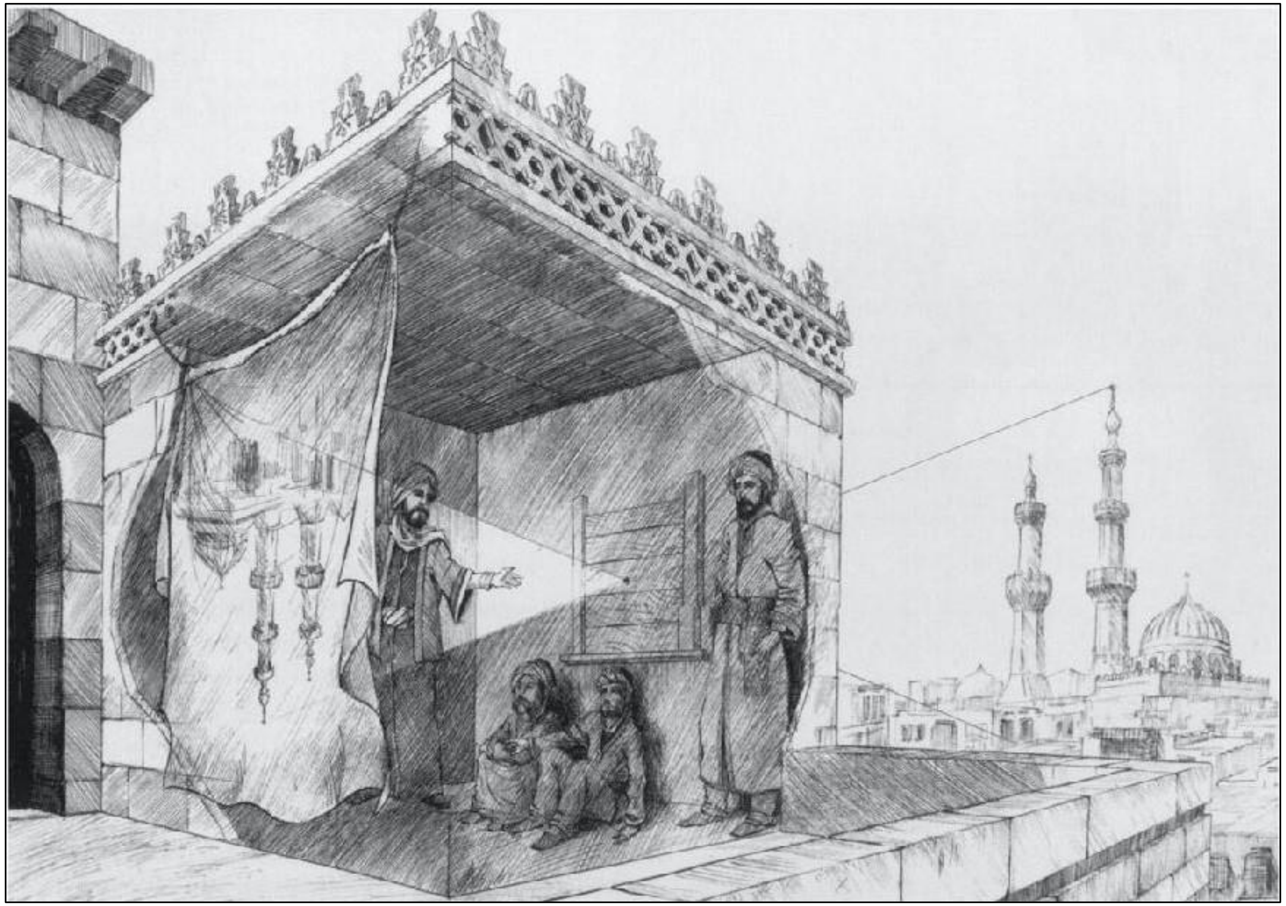
i.e. the sensor records irradiance



but there is computational imaging research…

Pinhole Image Formation

Pinhole Camera



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

Mo Tzu (c. 470–c. 390 BC)

Aristotle (384–322 BC)

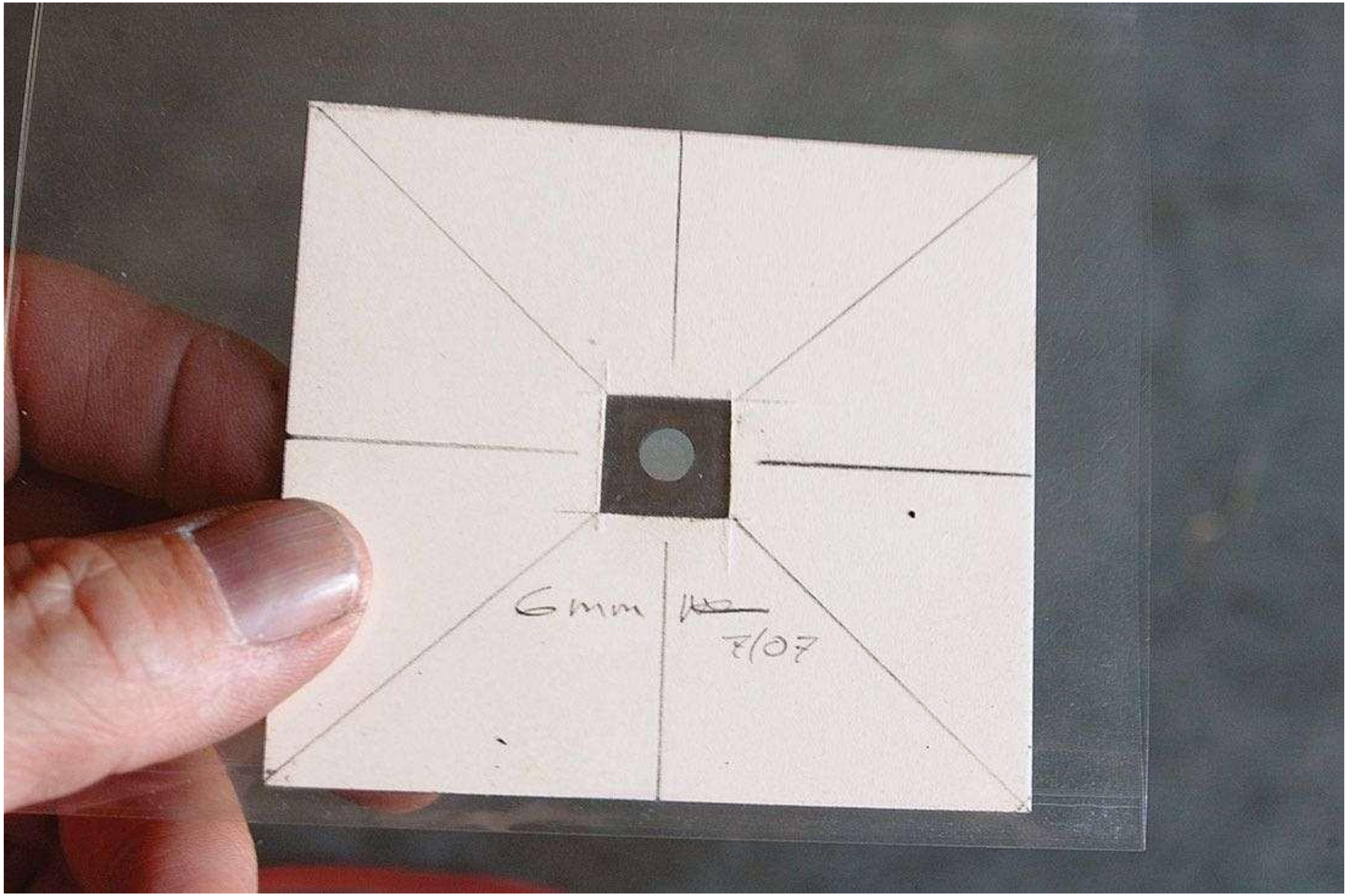
Ibn al-Haytham (965–1040)

Shen Kuo (1031–1095)

Roger Bacon (c. 1214–1294)

Johannes Kepler (1571–1630)

Largest Pinhole Photograph



legacyphotoproject.com

Largest Pinhole Photograph

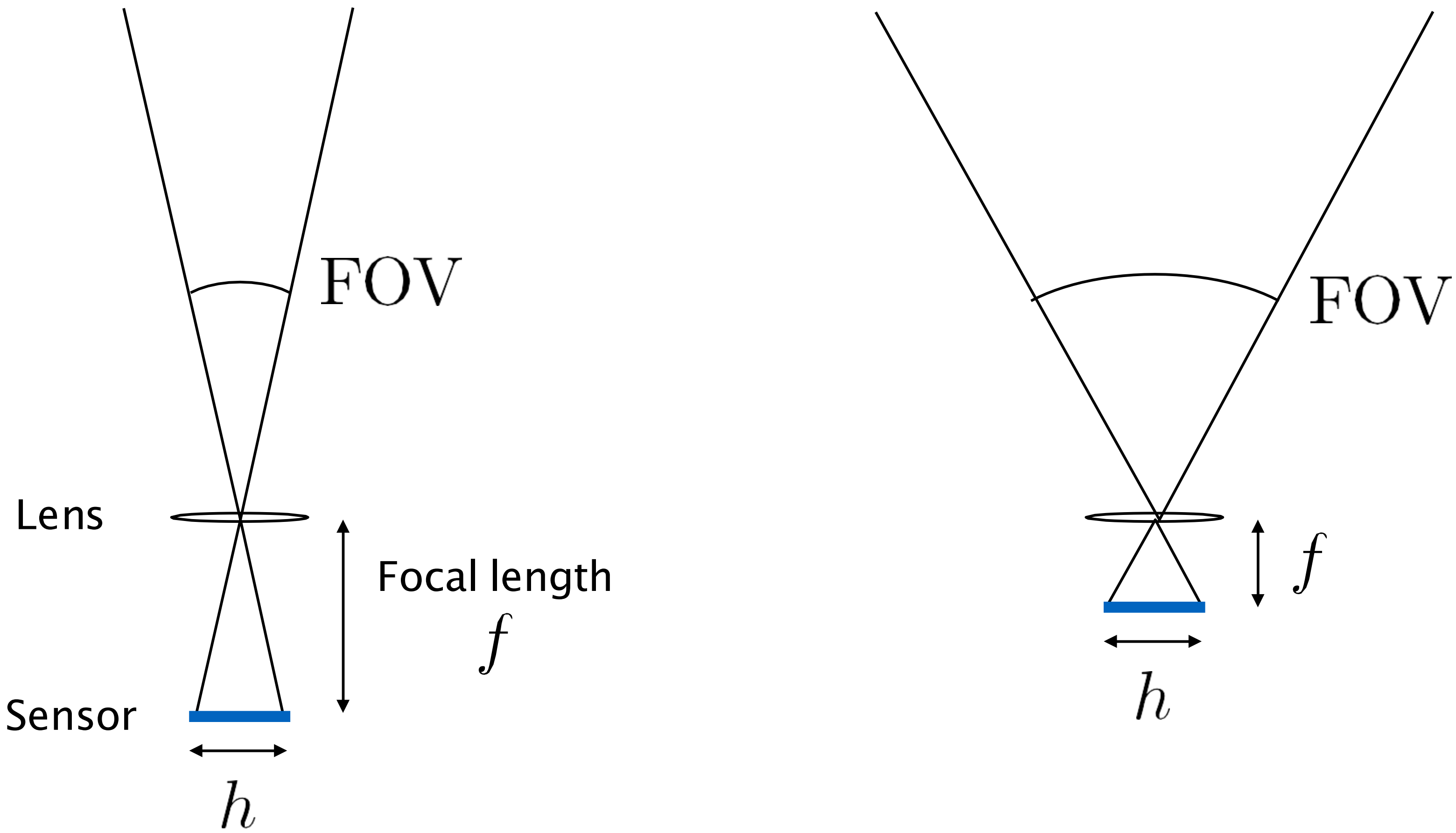
legacyphotoproject.com

Field of View (FOV)

(视场)

Effect of Focal Length on FOV

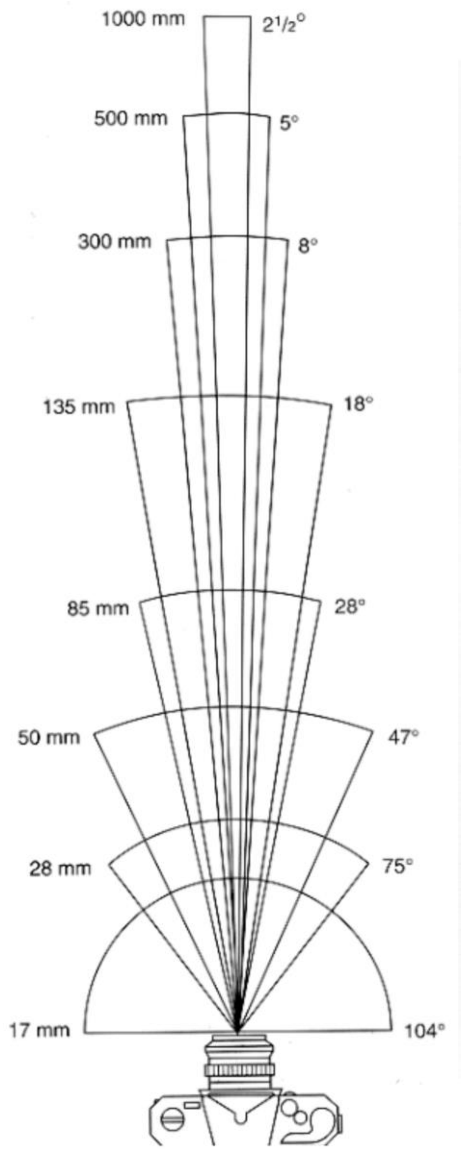
(焦距)



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

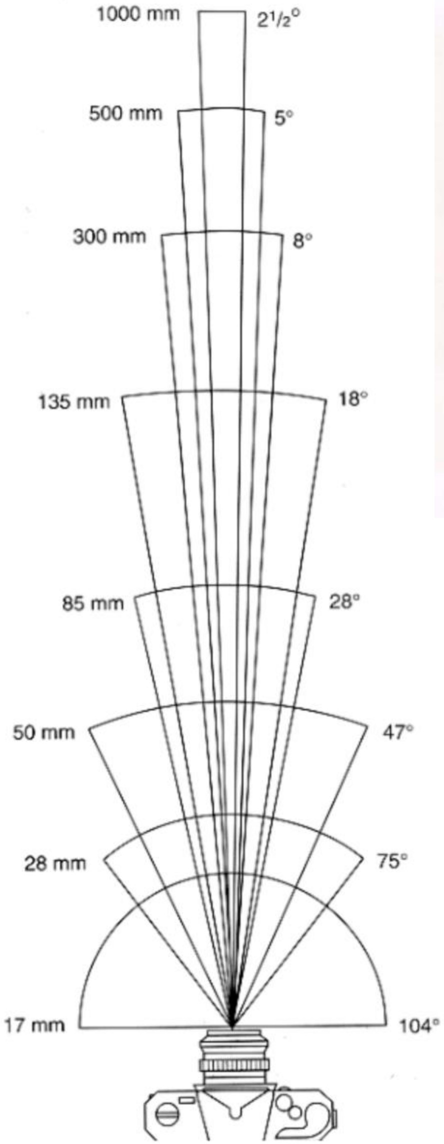
$$\mathrm{FOV} = 2\ \arctan\left(\frac{h}{2f}\right)$$

Focal Length v. Field of View



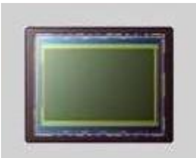
- For historical reasons, it is common to refer to angular field of view by focal length of a lens used on a 35mm-format film (36 x 24mm)
- Examples of focal lengths on 35mm format:
  - 17mm is wide angle 104°
  - 50mm is a "normal" lens 47°
  - 200mm is telephoto lens 12°
- Careful! When we say current cell phones have approximately 28mm "equivalent" focal length, this uses the above convention.

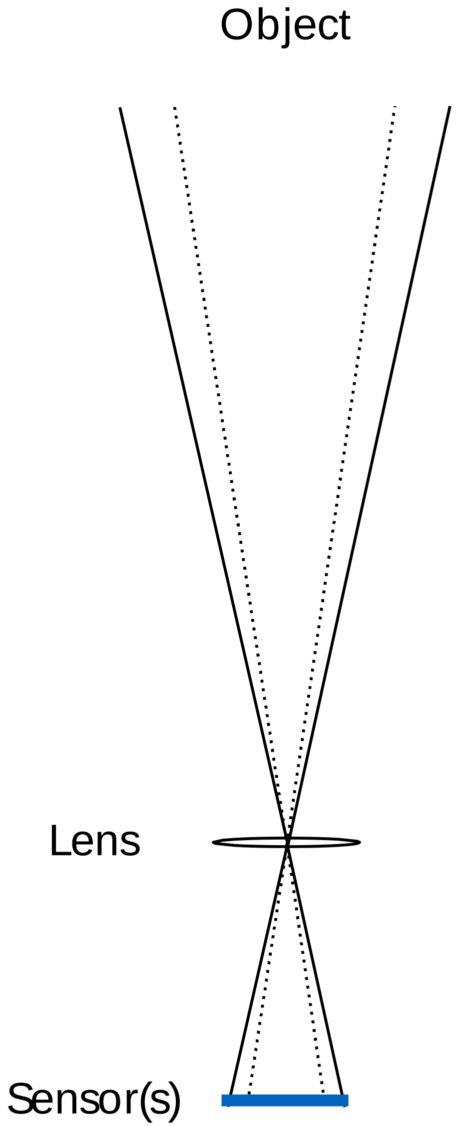
Focal Length v. Field of View



From London and Upton, and Canon EF Lens Work III

Effect of Sensor Size on FOV





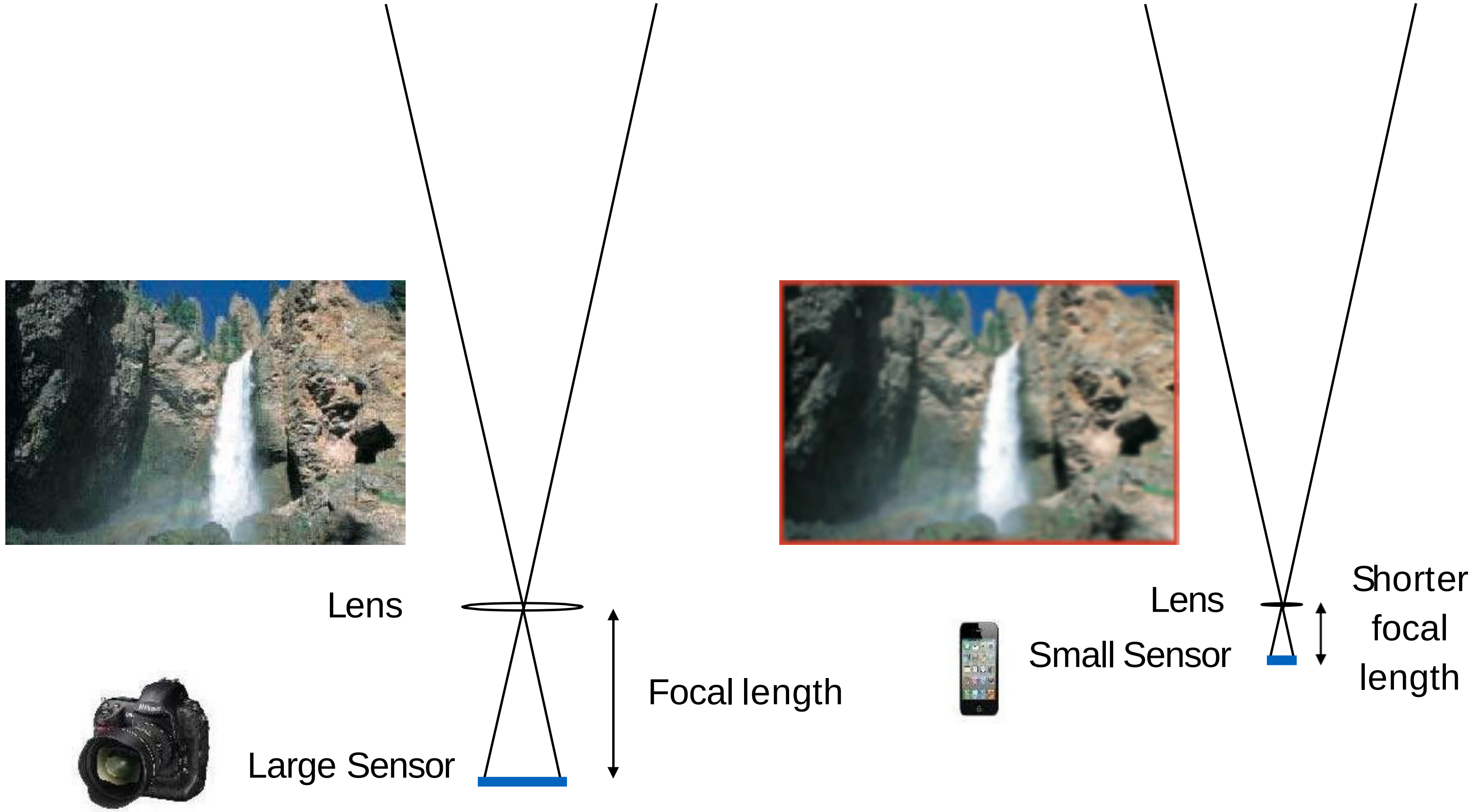
Sensor Sizes

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

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 (光圈)

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

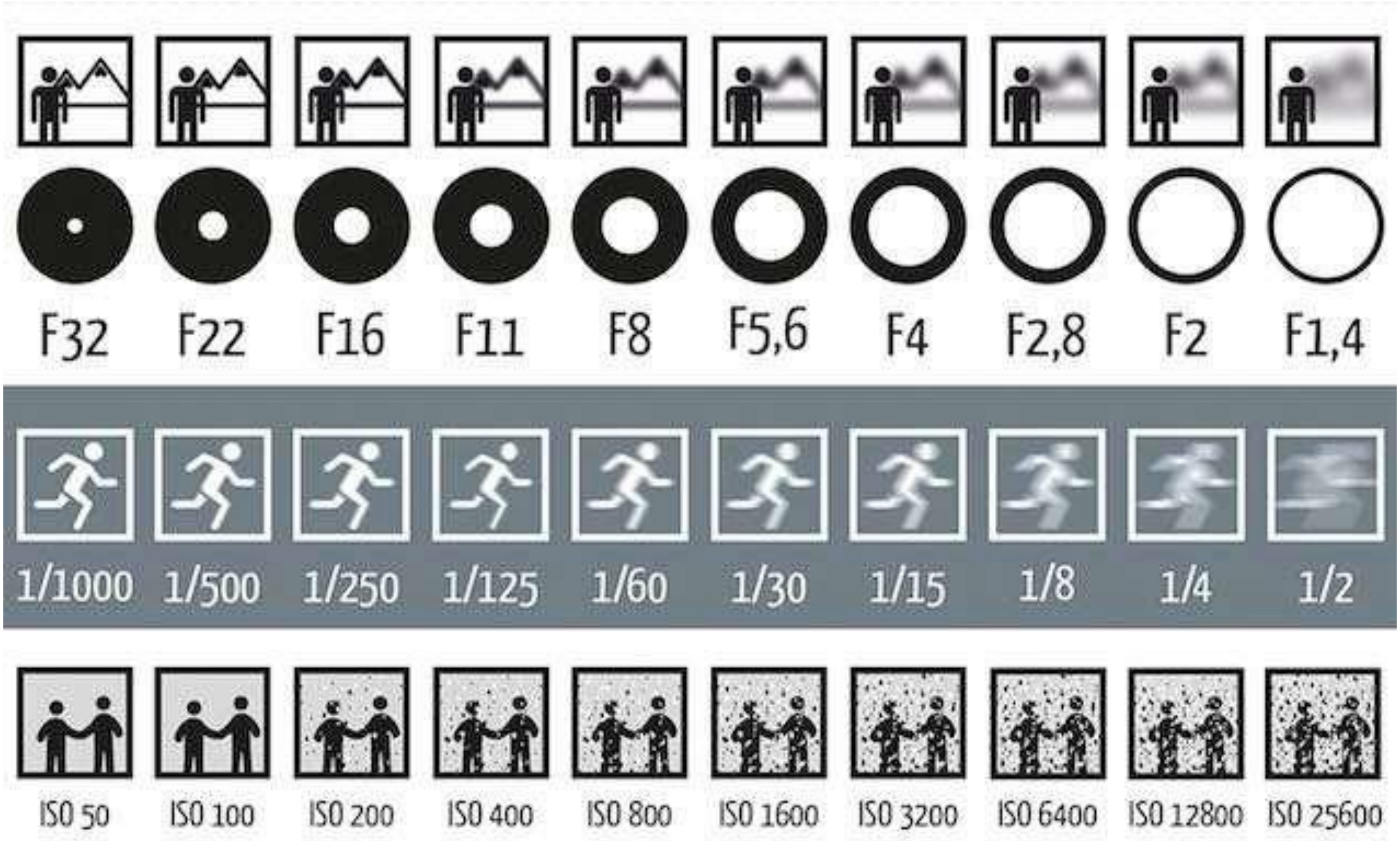
Shutter speed (快门)

- 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)



Photoblog Hamburg

ISO (Gain，增益)

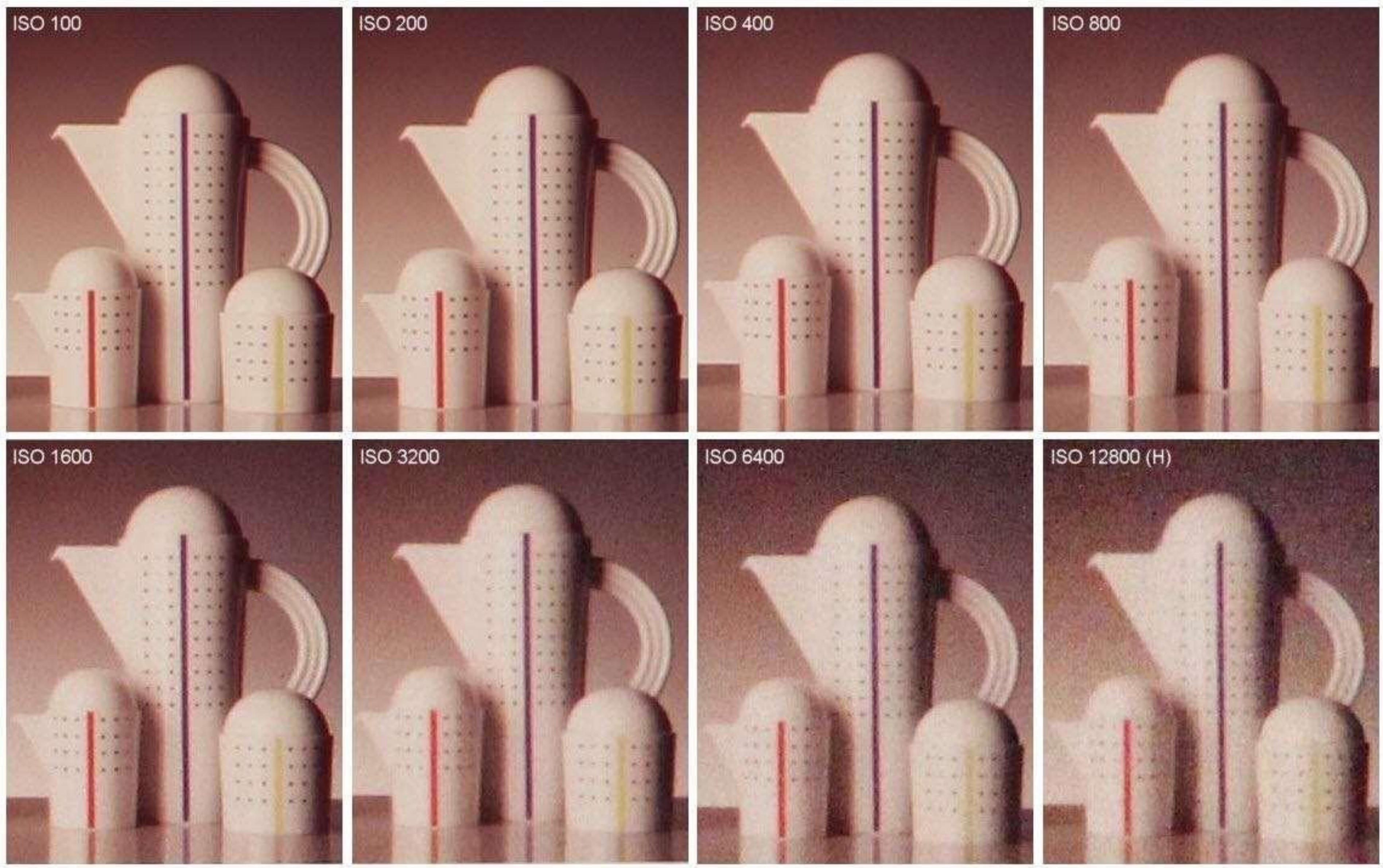
Third variable for exposure

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

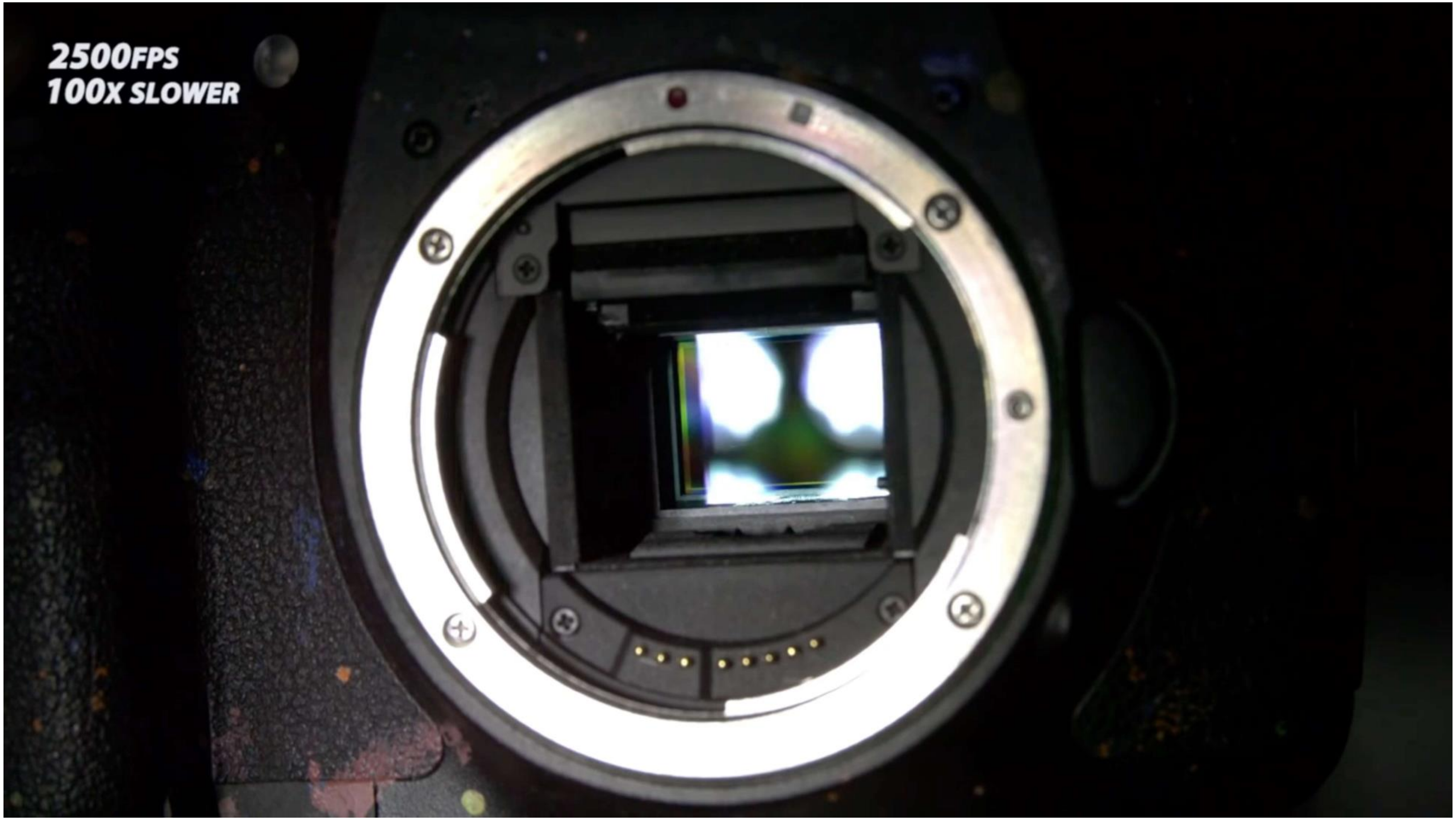
F-Number (F-Stop): Exposure Levels

Written as FN or F/N. N is the f-number.

Informal understanding: the inverse-diameter of a round aperture

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

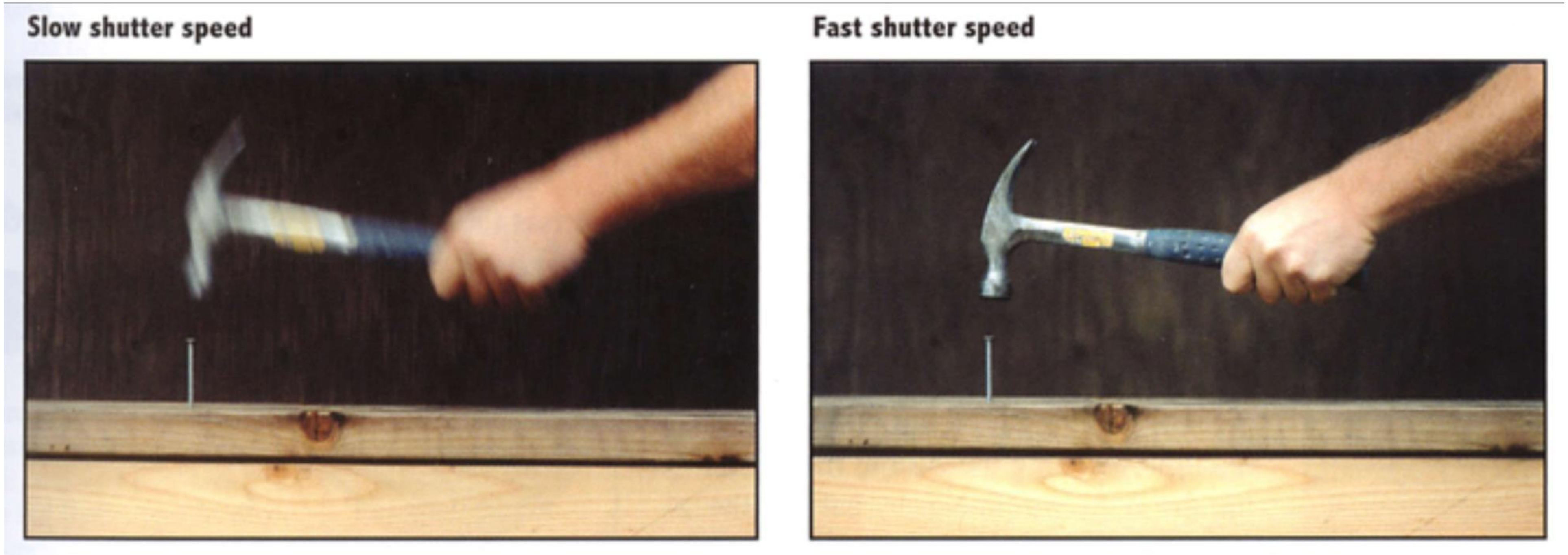
http://www.gavtrain.com/?p=3960

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

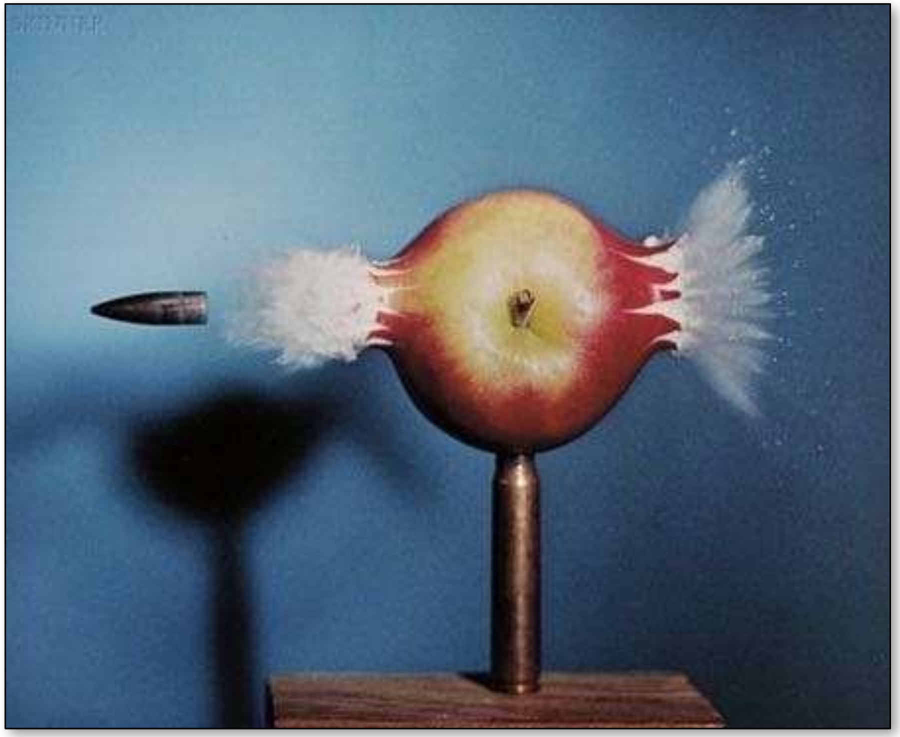
If the exposure is too bright/dark, may need to adjust f-stop and/or shutter up/down.

- 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)

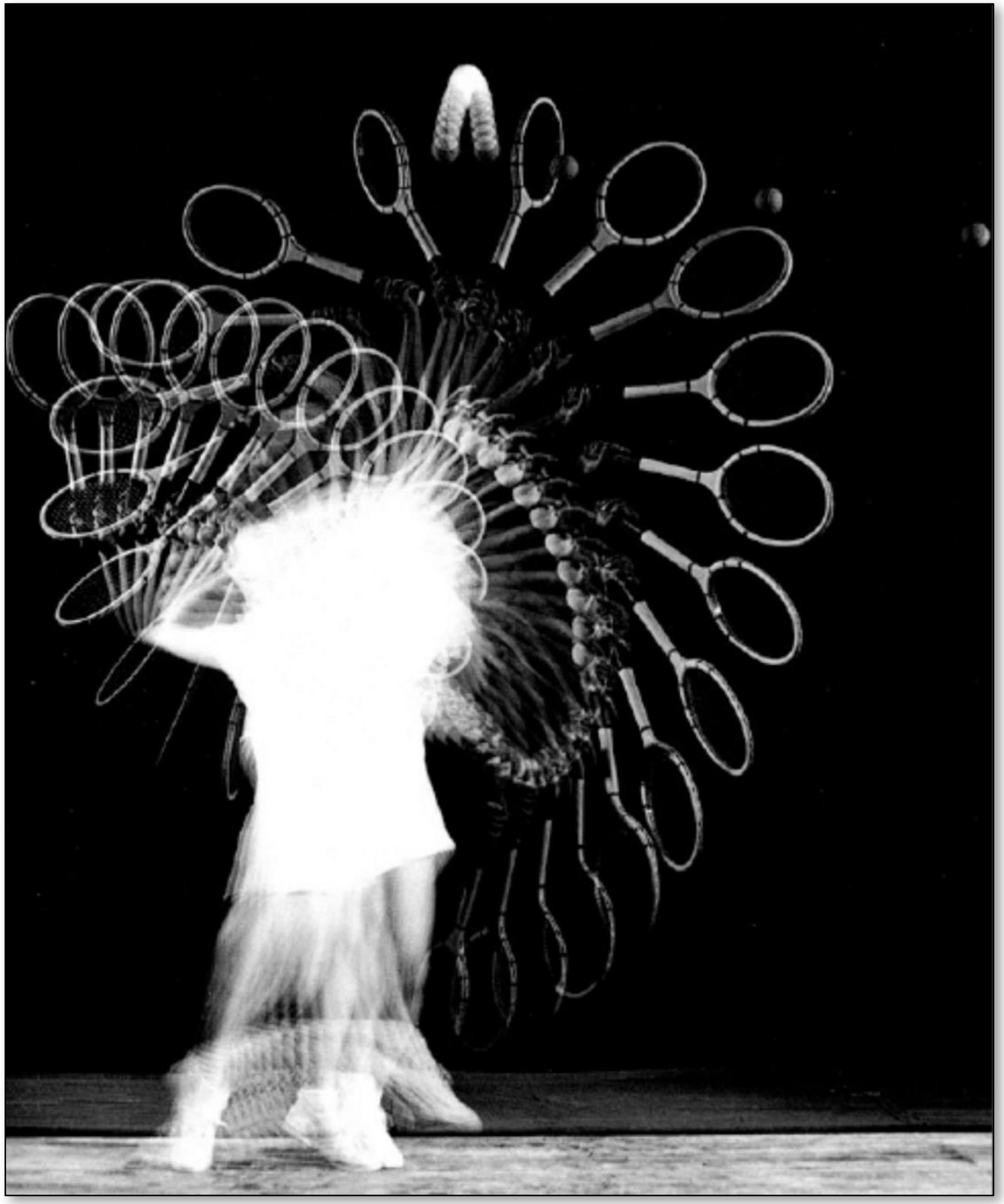


Harold Edgerton

Mark Watson

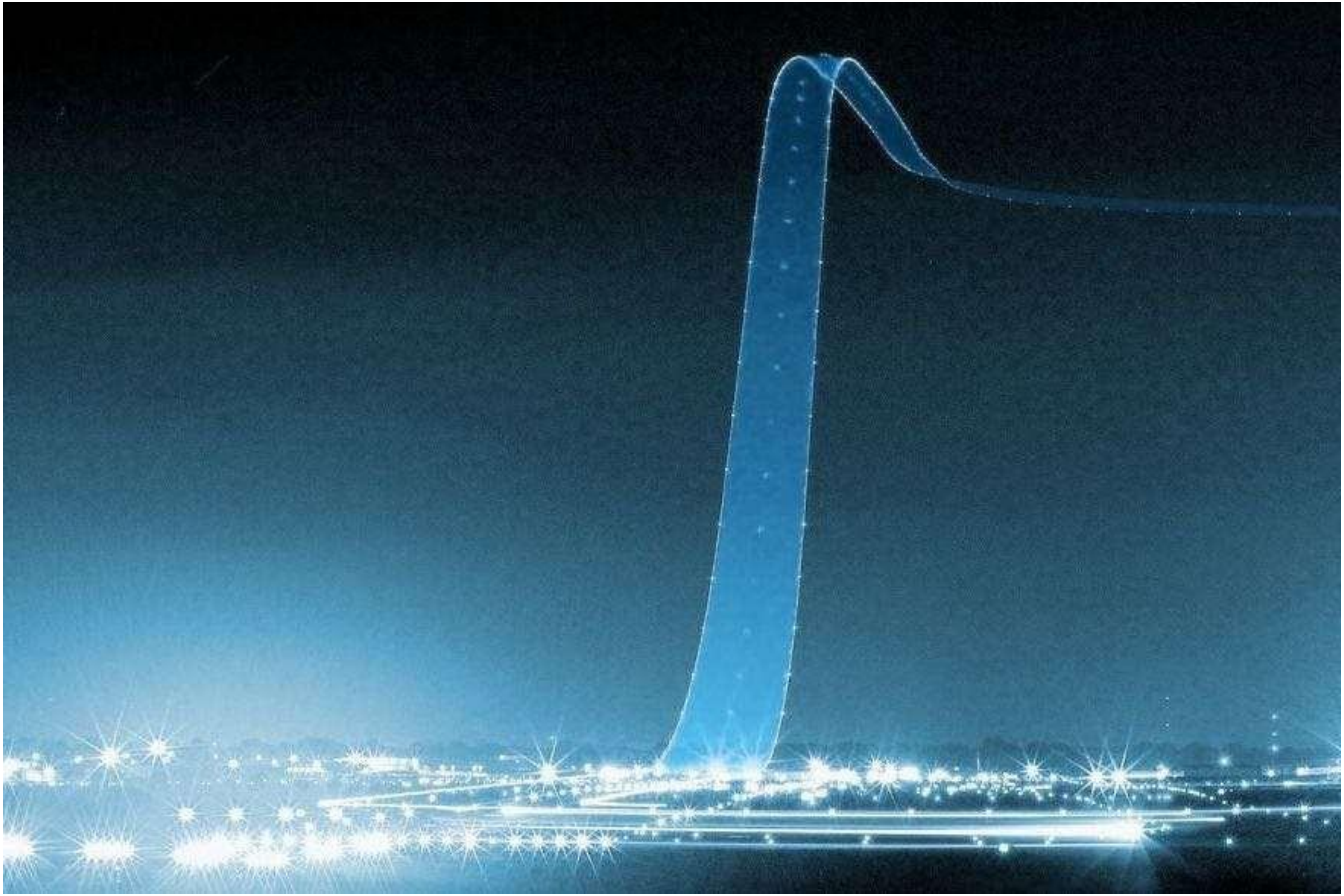
Slide courtesy L. Waller

High-Speed Photography



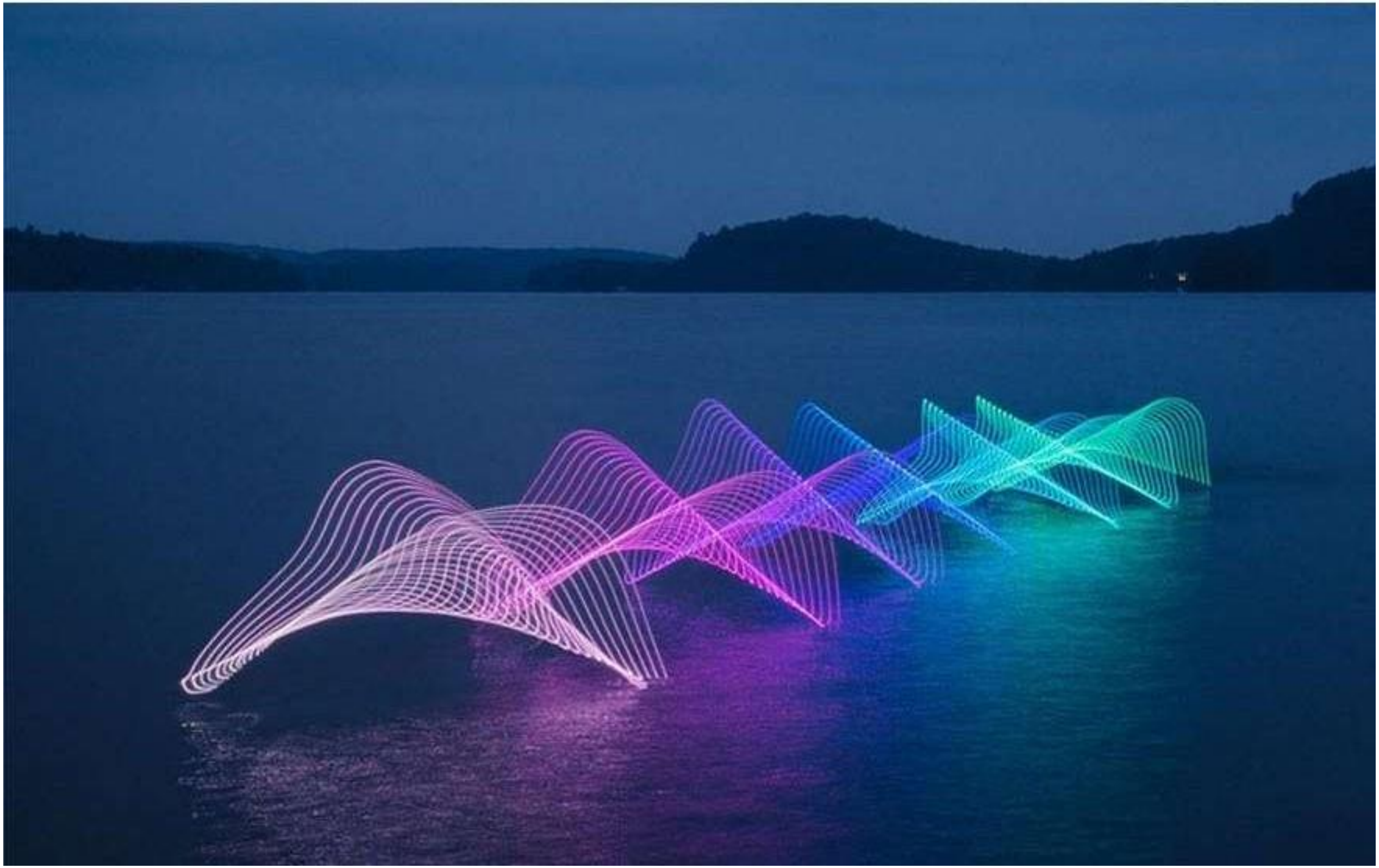
Harold Edgerton

Long-Exposure Photography



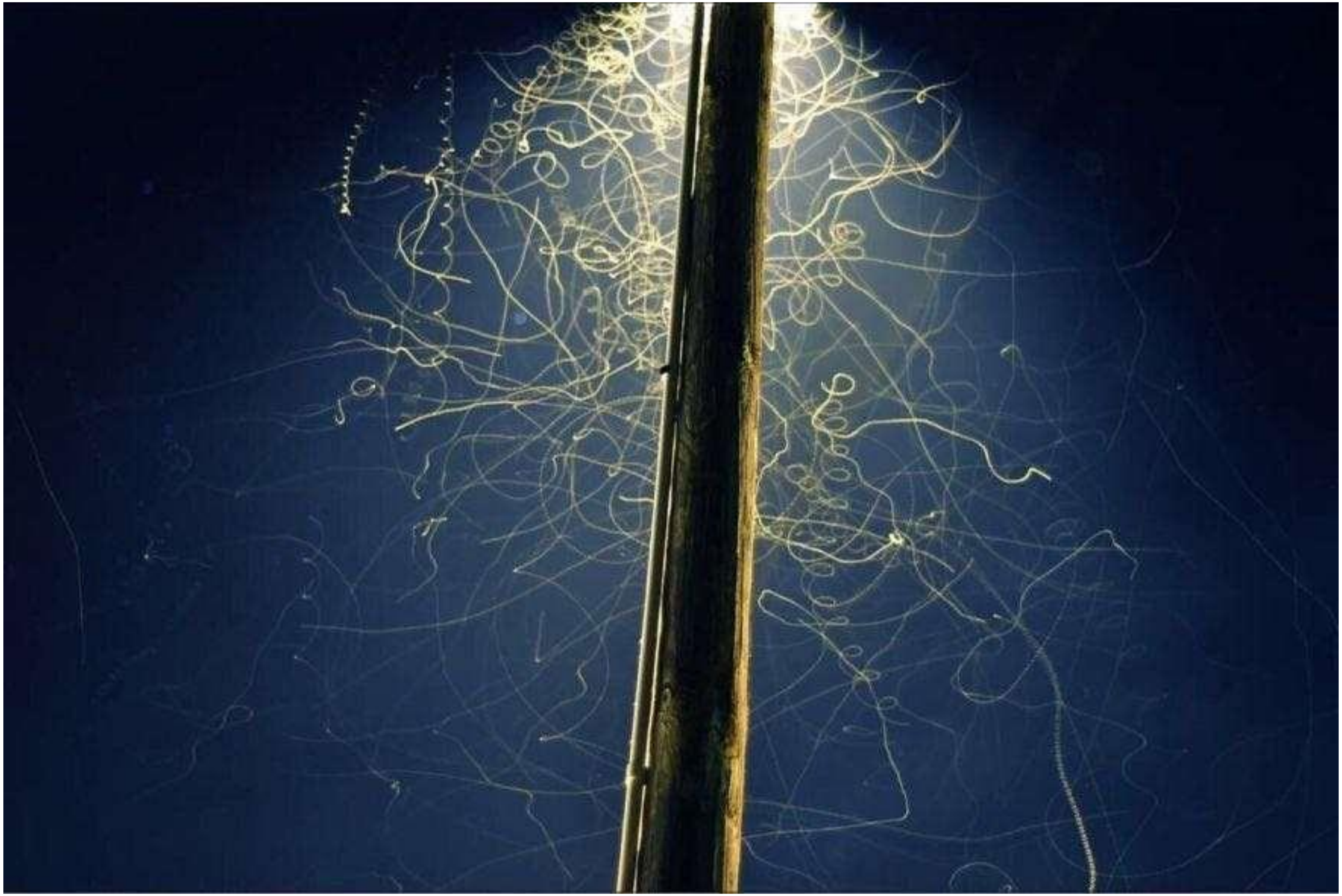
https://www.demilked.com/best-long-exposure-photos/

Long-Exposure Photography



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

Long-Exposure Photography



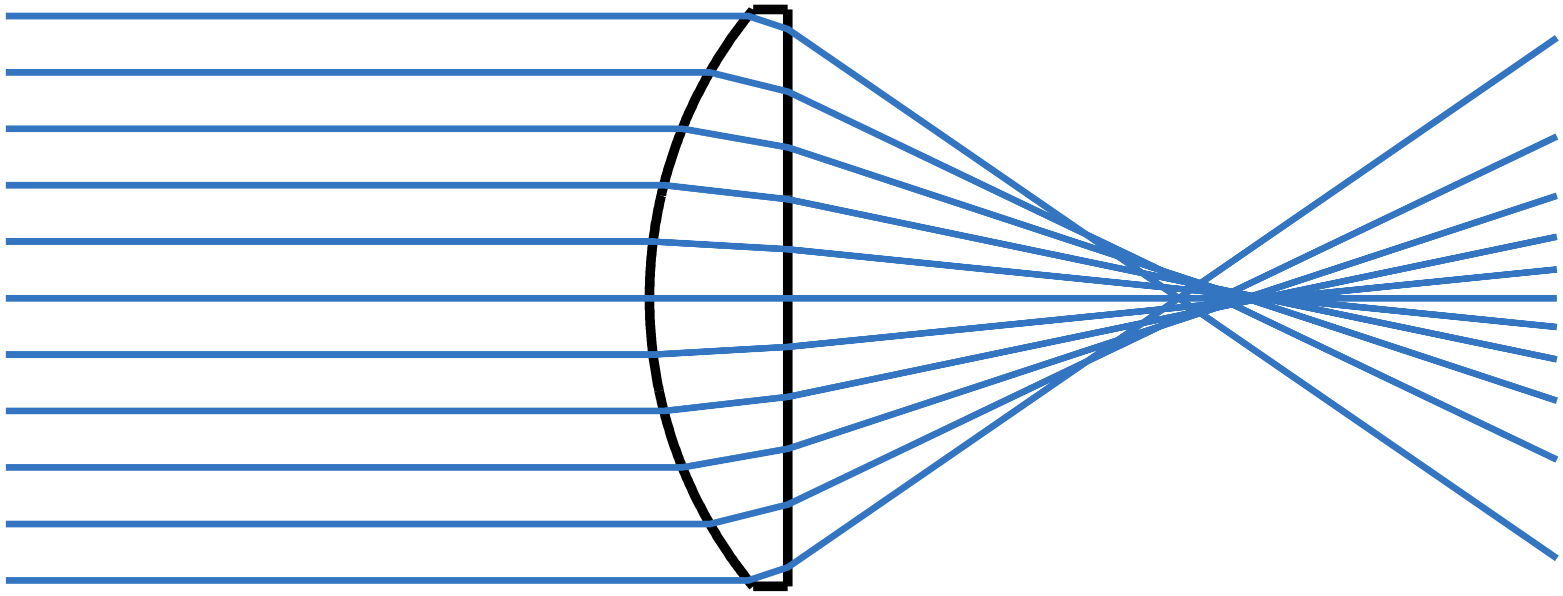
https://www.demilked.com/best-long-exposure-photos/

Thin Lens Approximation

Real Lens Designs Are Highly Complex

[Apple]

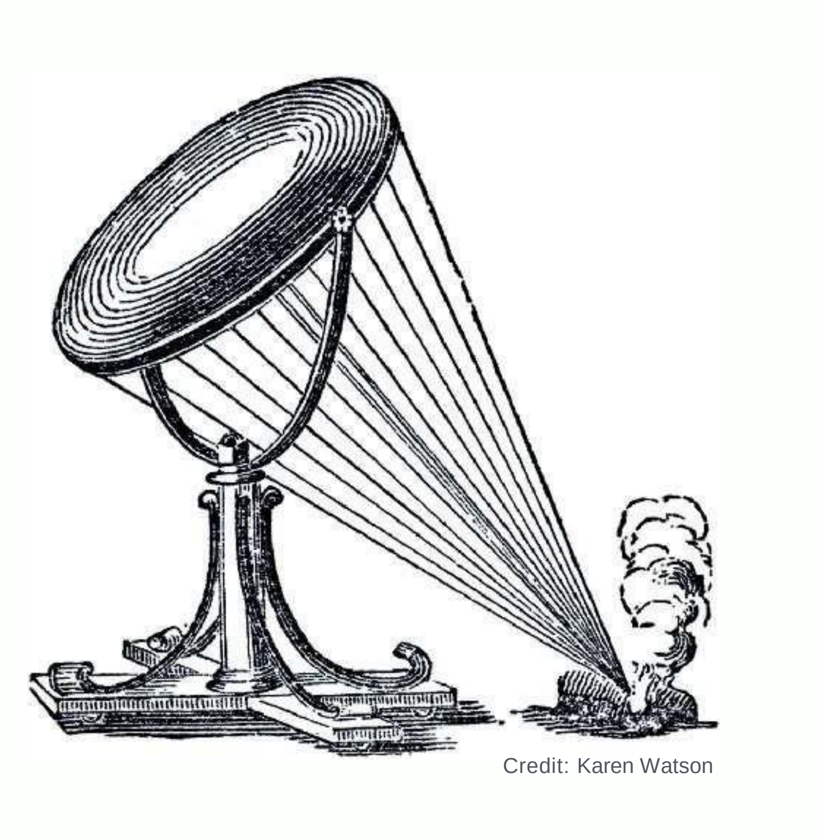
Real Lens Elements Are Not Ideal – Aberrations

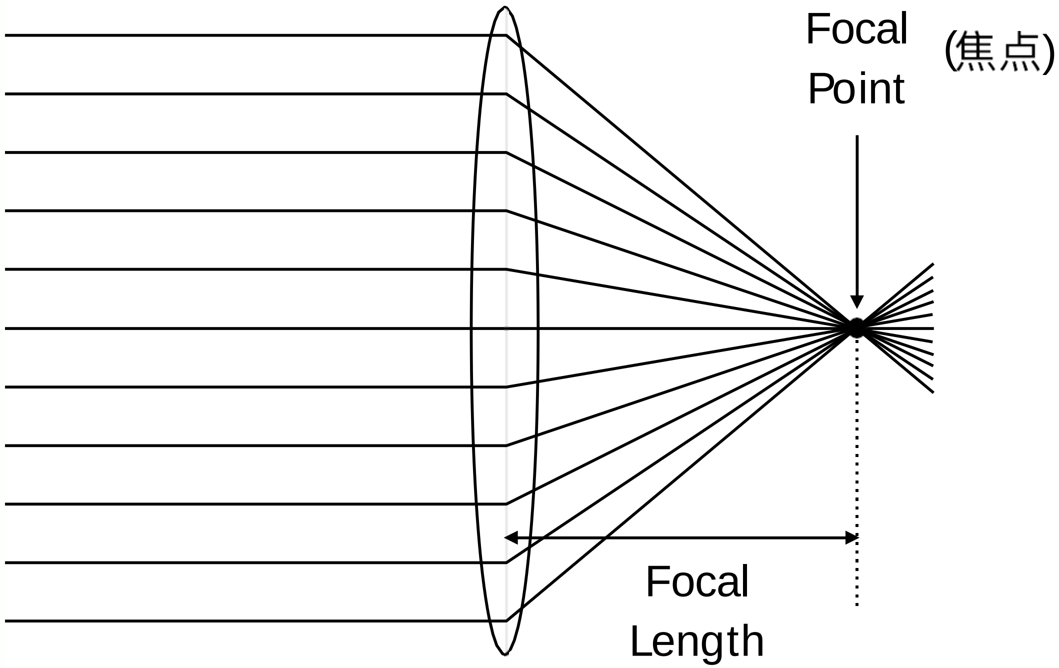


Real plano-convex lens (spherical surface shape).

Lens does not converge rays to a point anywhere.

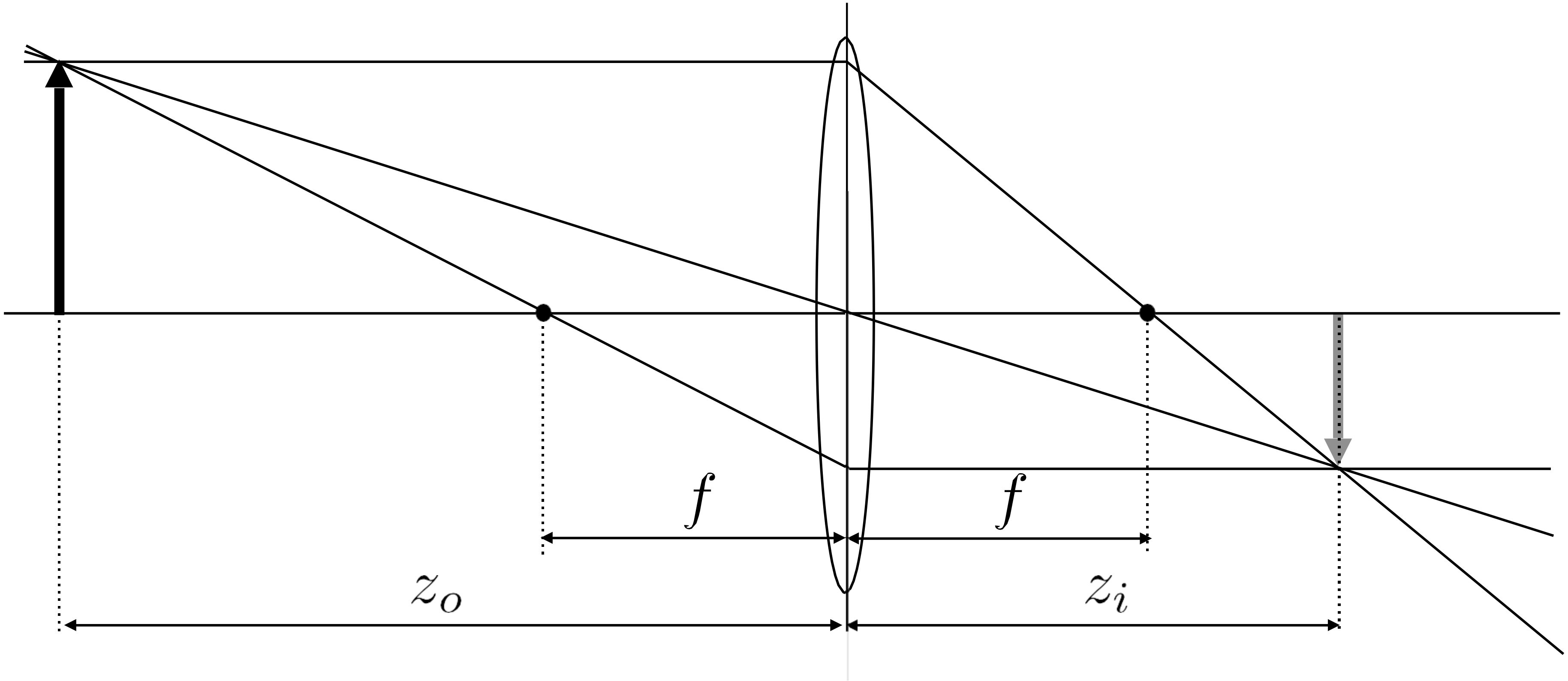
Ideal Thin Lens – Focal Point





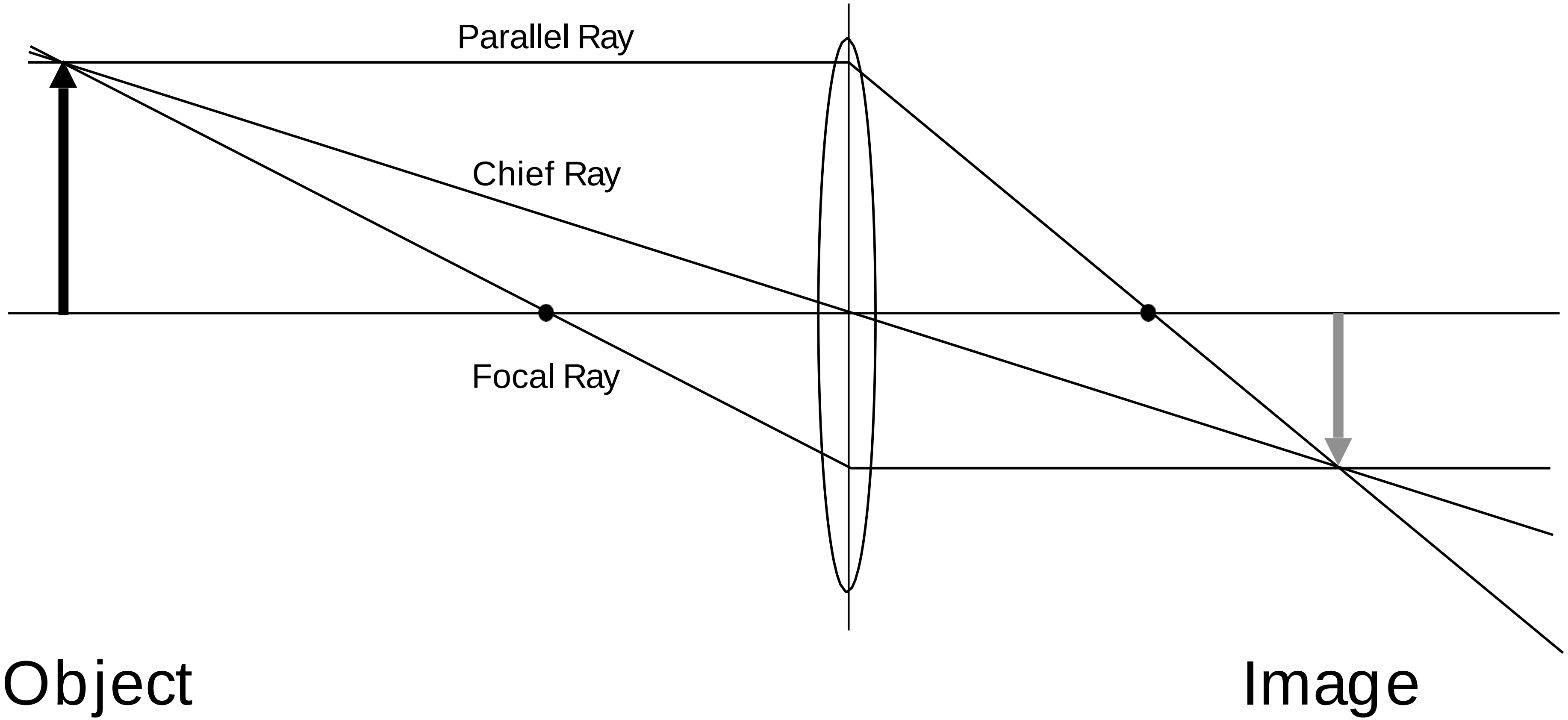
(1) All parallel rays entering a lens pass through its focal point.
(2) All rays through a focal point will be in parallel after passing the lens.
(3) Focal length can be arbitrarily changed (in reality, yes!).

The Thin Lens Equation

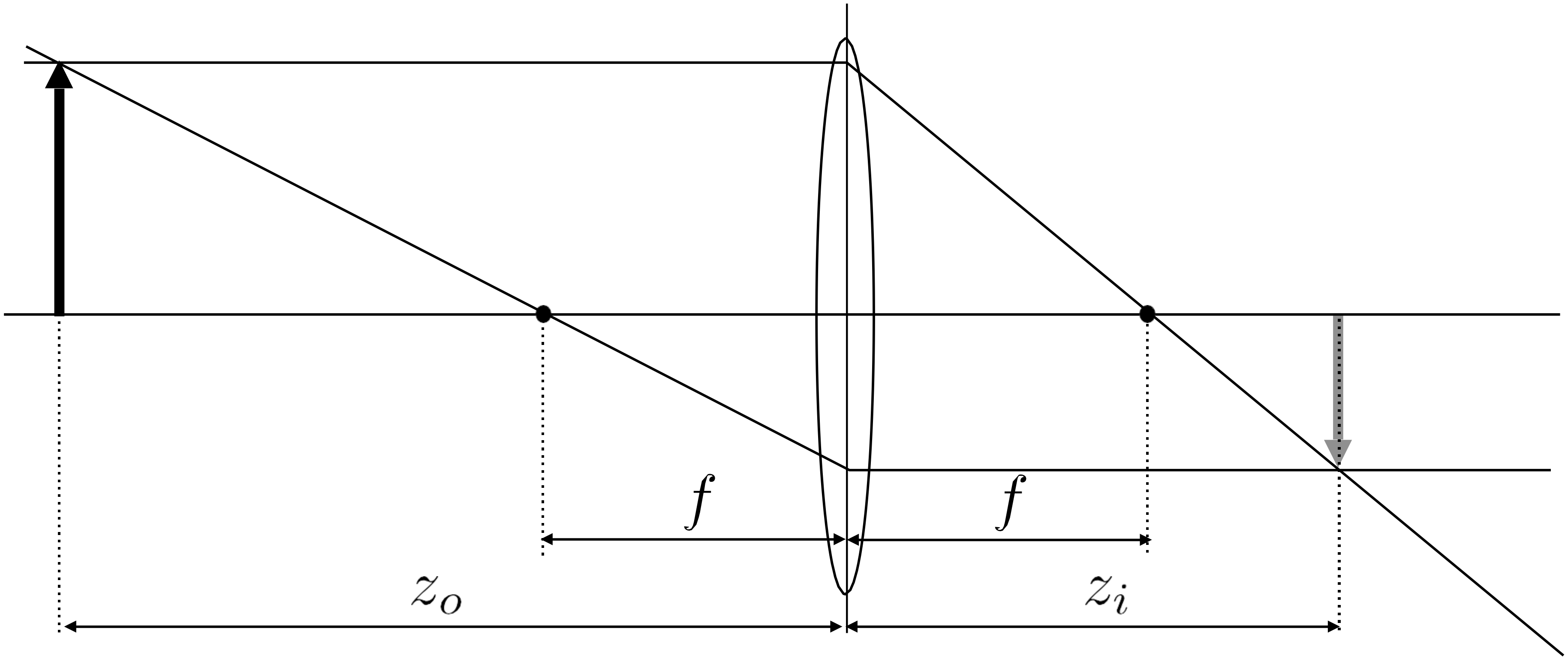


$$\boxed{\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}}$$

Gauss' Ray Diagrams

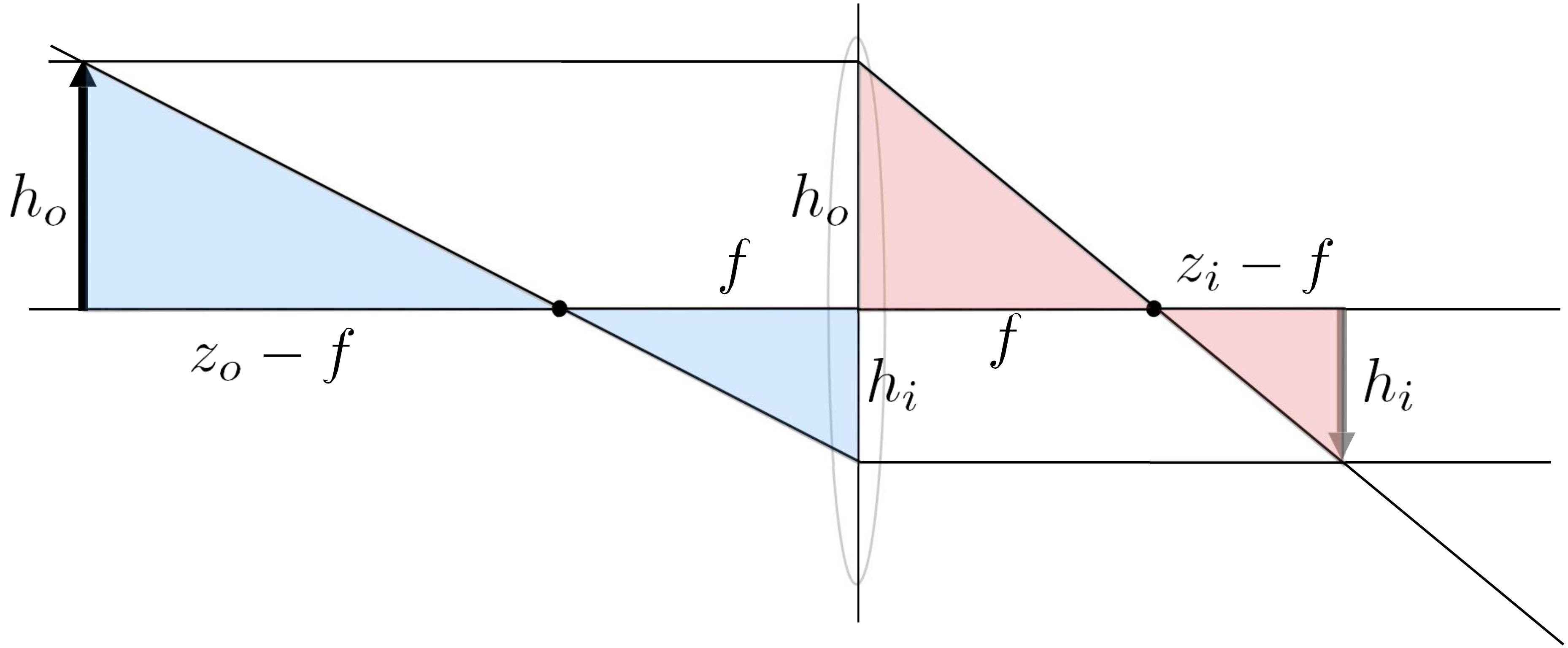


Gauss' Ray Tracing Construction



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

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

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

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

Object / image heights factor out - applies to all rays

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

Newtonian Thin Lens Equation

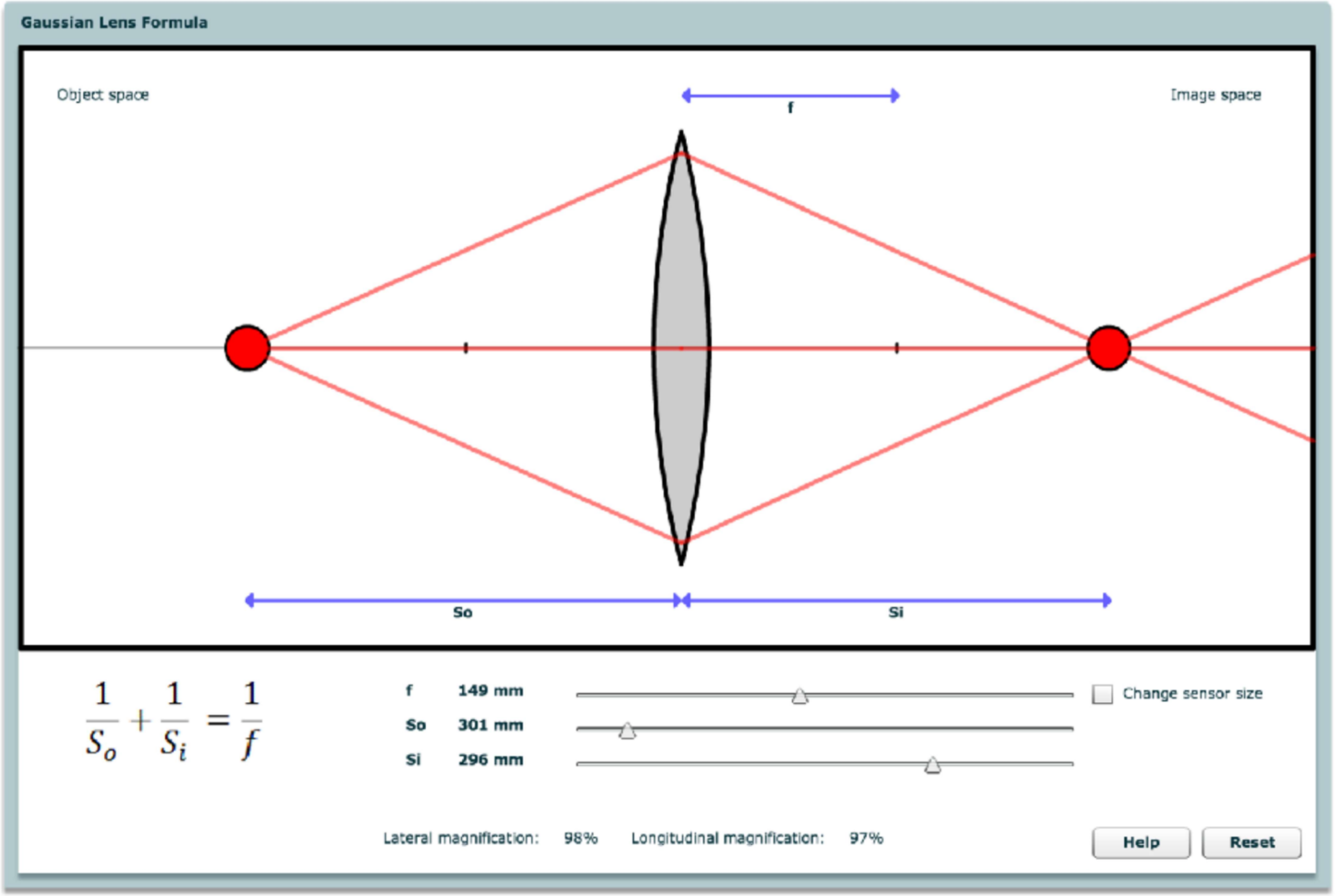
$$z_o z_i - (z_o + z_i)f + f^2 = f^2$$

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

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

Gaussian Thin Lens Equation

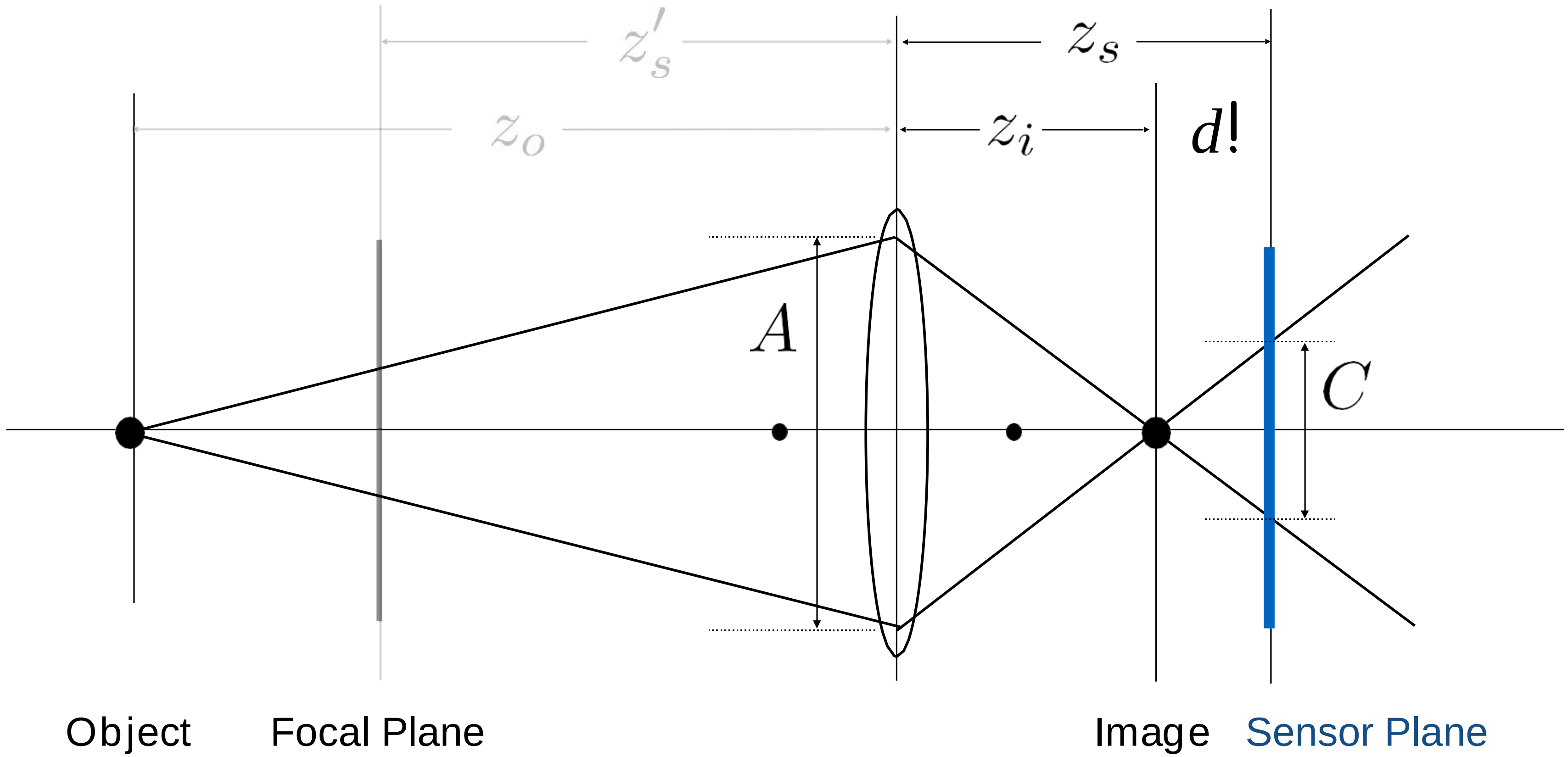
Thin Lens Demonstration



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

Defocus Blur
&
Depth of Field

Computing Circle of Confusion (CoC) Size



Circle of confusion is proportional to the size of the aperture

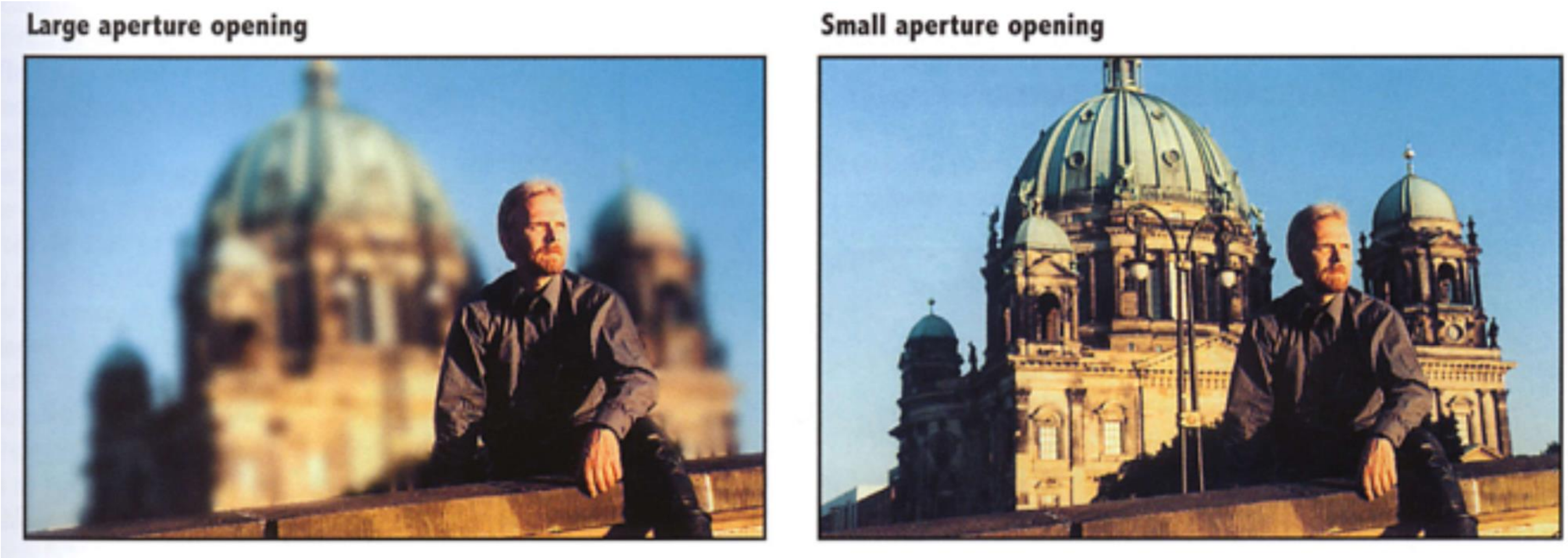
$$\frac{C}{A} = \frac{d'}{z_i} = \frac{|z_s - z_i|}{z_i}$$

CoC vs. Aperture Size

A side note: hilarious Google translate…

"Circle of confusion" 在中文中翻译为「弥散圆」或「模糊圈」。它是摄影和光学中的一个术语，指的是光学系统无法将点光源精确聚焦到图像平面时，在图像平面上形成的模糊光斑。弥散圆的大小与焦距、光圈大小和焦点距离有关，它是衡量图像清晰度的重要参数之一。

Depth of Field

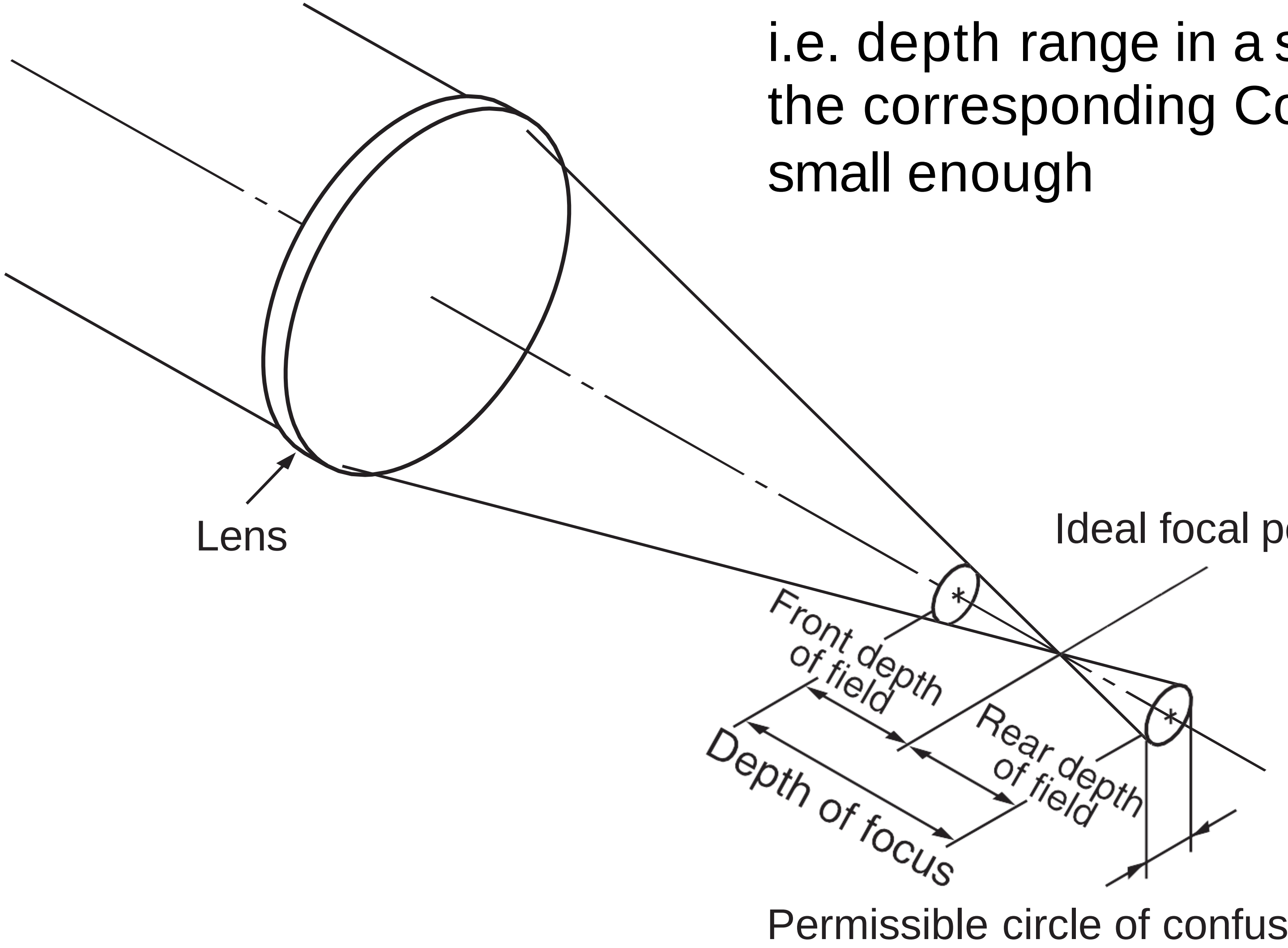


From London and Upton

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

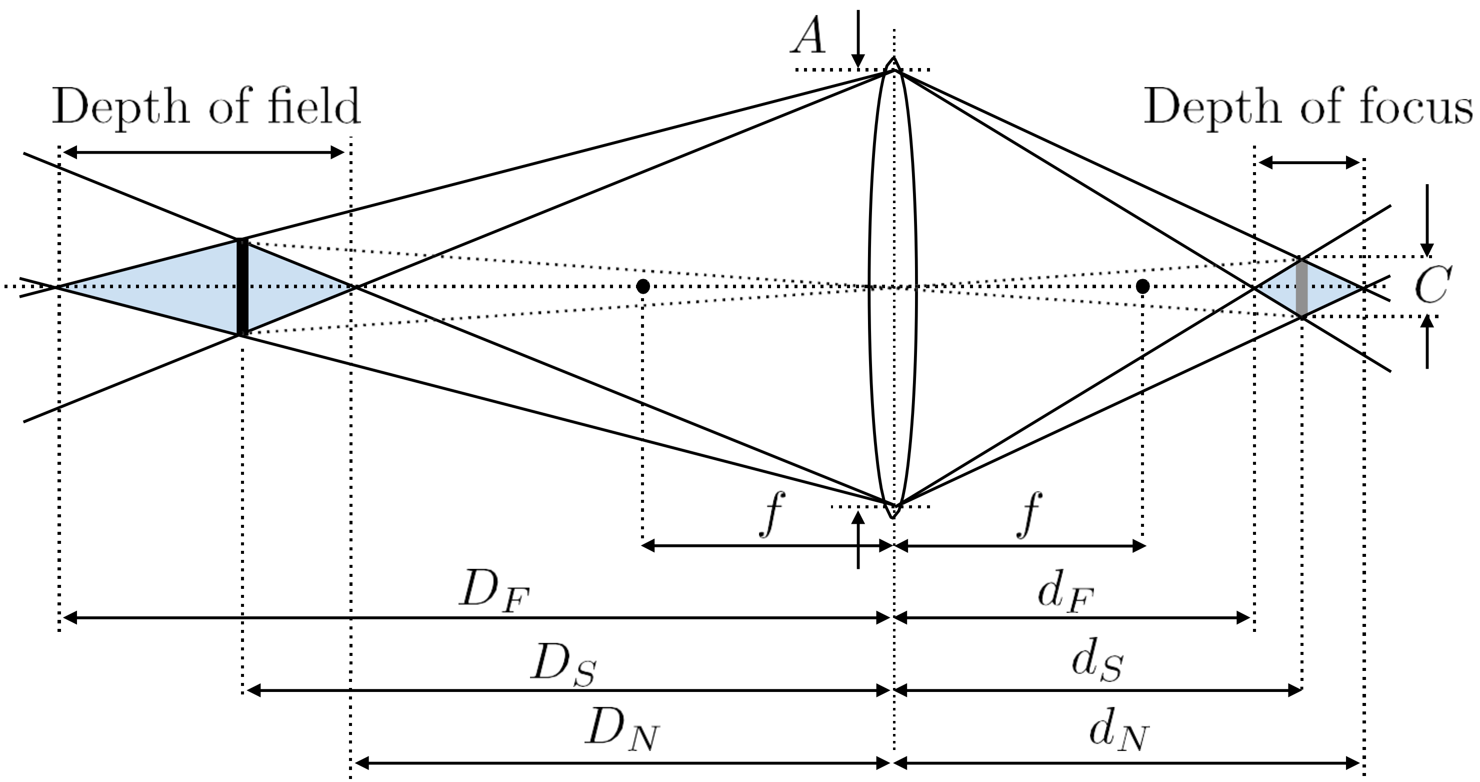
Circle of Confusion for Depth of Field

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



[Canon, EF Lens Work III]

Depth of Field (FYI)



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

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

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

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

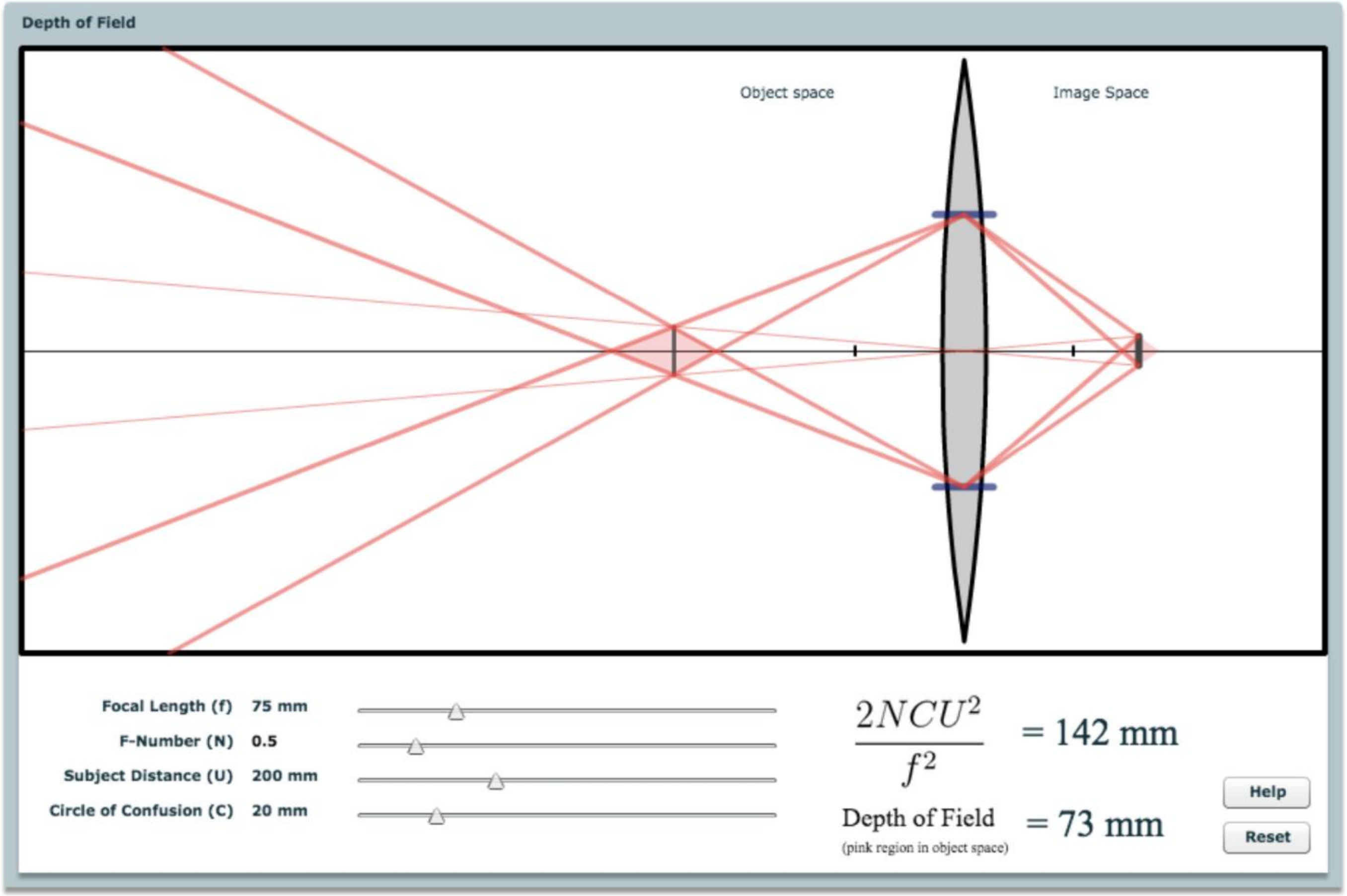
$$\frac{1}{D_S} + \frac{1}{d_S} = \frac{1}{f}$$

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

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

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

DOF Demonstration (FYI)



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

Thank you!