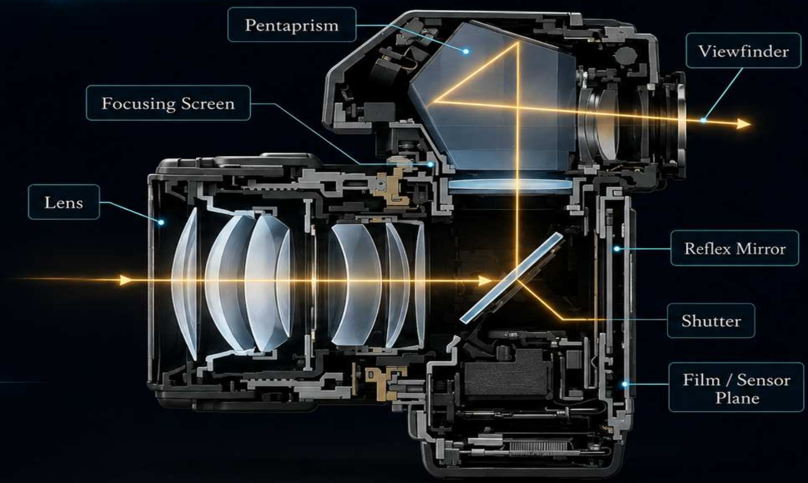
Single Lens Reflex Camera (SLR)

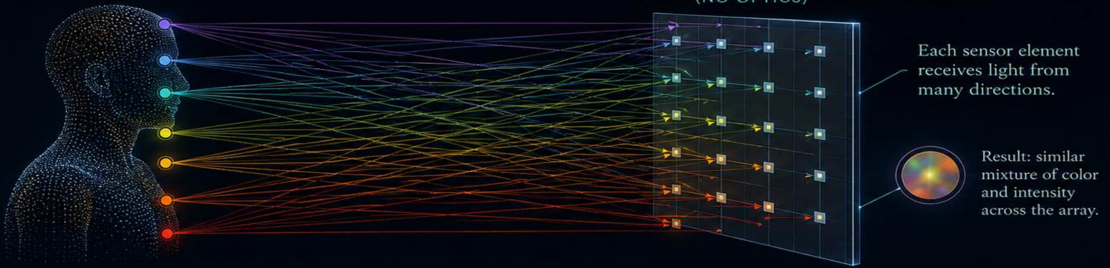
- One lens is used for both viewing and image capture.
- A mirror directs light to the optical viewfinder.
- During exposure, the mirror flips up and light reaches the film or sensor.



Example:

Nikon F4 (film camera)

Why Not Use Sensors Without Optics?

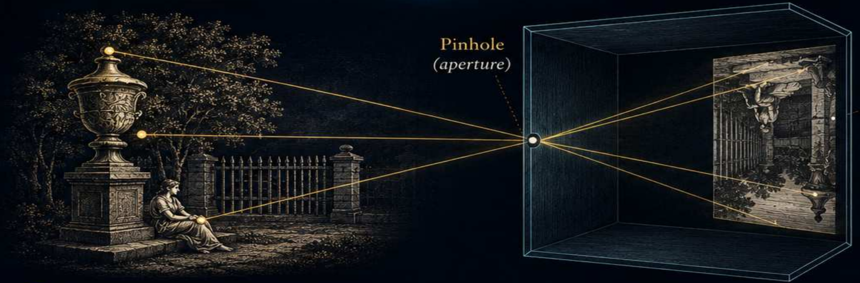


- Each sensor point would record the integral of light arriving from every point on the subject.
- Without optics, there is no mechanism to separate where light came from.
- As a result, most sensor points record similar mixtures of color and intensity.

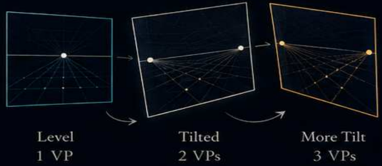
Optics are required to form a spatially meaningful image.

Pinhole Camera
(Camera Obscura)

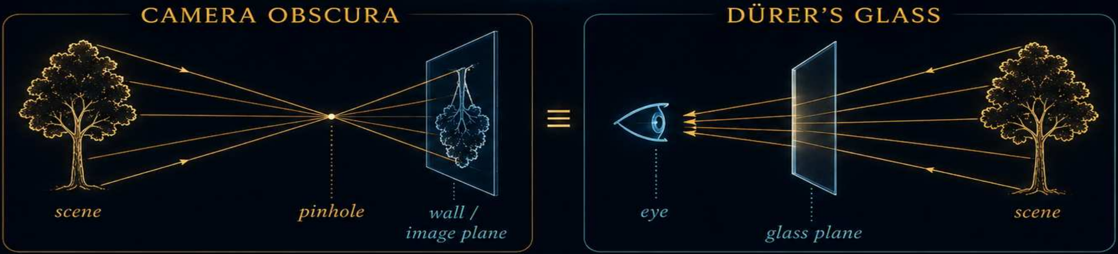
2D planar geometric projection



- **Linear perspective** is formed with the **viewpoint** at the **pinhole**.
- A pinhole camera produces an **inverted image** on the image plane.
- Tilting the picture plane changes the number and location of **vanishing points**.



Equivalence of Dürer's Glass and Camera Obscura



Both devices compute the *same* projective geometry;
the images differ only in scale and by a reflection / inversion.

- Both are 2D planar geometric projections.
- Projections are along straight lines through a single point (the pinhole / the eye).
- Projections land on a plane (wall / image plane or glass plane).

Imaging & Deep Learning

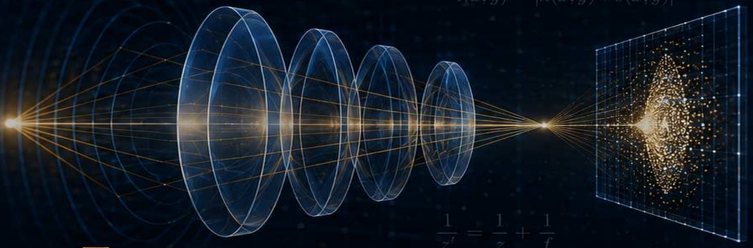
Gonzalo R. Arce

Department of Electrical and Computer Engineering

University of Delaware

$$h(\mathbf{r}) * o(\mathbf{r}) = i(\mathbf{r})$$

$$i(x,y) = |h(x,y) * o(x,y)|^2$$



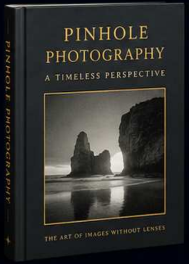
$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f}$$

$$\mathrm{MTF}(f) = \left|\mathcal{F}\{h(x,y)\}\right|$$

Chapter I: Image Formation

Pinhole Photography

- no distortion
  - straight lines remain straight
- infinite depth of field
  - everything is in focus

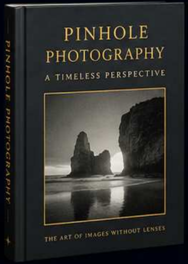


Pinhole images may exhibit diffraction artifacts, but not chromatic aberration, which is produced by lenses.

Pinhole photograph by Gonzalo R. Arce

Pinhole Photography

- no distortion
  - straight lines remain straight
- infinite depth of field
  - everything is in focus



Pinhole images may exhibit diffraction artifacts, but not chromatic aberration, which is produced by lenses.

Pinhole photograph by Gonzalo R. Arce

Camera Obscura

An inverted world projected through a tiny aperture.

Effect of Pinhole Size

Photograph made with small pinhole

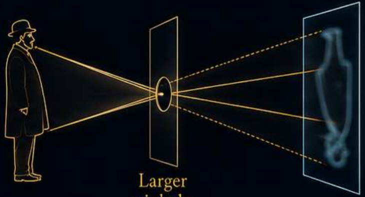
- Sharper geometry
- Lower light

Sharper, well-defined inverted image

Less light reaches the image plane

Photograph made with larger pinhole

- More light
- More blur



Brighter inverted image

More blur (lower spatial resolution)

Increasing pinhole size brightens the image but spreads each scene point over a larger region on the image plane.

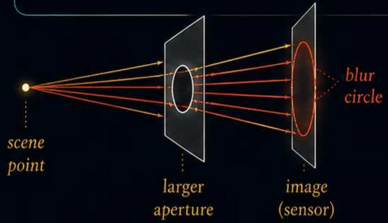
Gonzalo R. Arce | Department of Electrical and Computer Engineering

Pinhole Size Tradeoff

Photograph made with small pinhole

Photograph made with larger pinhole

A larger aperture allows multiple rays from a single scene point to hit different sensor locations, creating blur.



Sharpness vs brightness tradeoff.

Smaller pinholes → sharper images but dimmer.

Larger pinholes → brighter images but blurrier.

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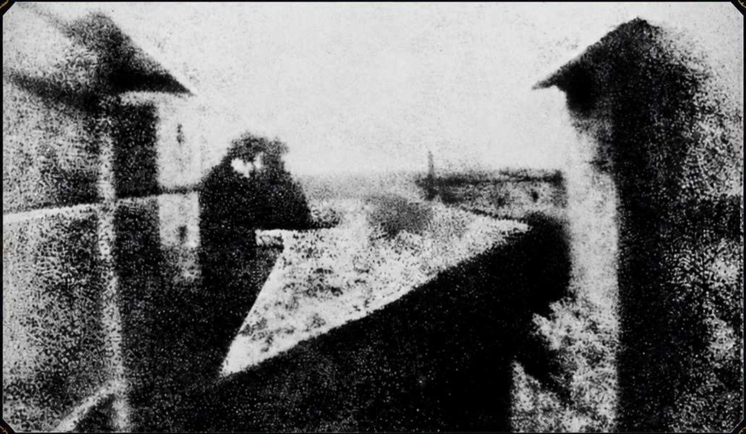
Niépce — View from the Window at Le Gras

1826

~8 h exposure



Very long exposure

Recorded illumination from different times of day

Often considered the first surviving permanent photograph.

Niépce • Le Gras, France | Heliograph on pewter plate

Modern Pinhole Lens Example

The Lensbaby Obscura Duo

The Lensbaby Obscura duo

A modern accessory that recreates the pinhole look on a digital camera.

Pinhole Photography

Dreamlike rendering in an old rural scene

- soft focus
- edge falloff
- timeless mood

Pinhole Landscape

Wide-angle scene with ethereal depth

- wide field of view
- soft rendering
- glowing sky

Low-Angle Pinhole Perspective

Perspective exaggeration with soft edges

strong perspective ◆ corner falloff ◆ *vintage* character

long exposure

motion streaks

expressive blur

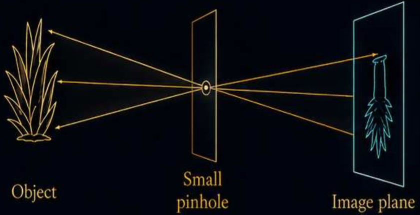
Motion in Pinhole Imaging

Long exposure transforms motion into texture

Replacing the Pinhole with a Lens

Photograph made with small pinhole

- Sharper geometry
- Lower light



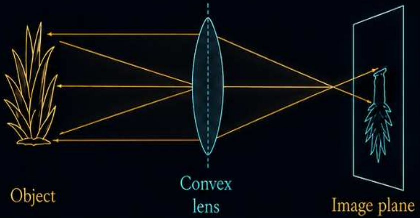
Inverted image on image plane

Sharper image

Less light reaches the image plane

Photograph made with lens

- Brighter image
- Same projection geometry



Inverted image on image plane

Brighter image

More light reaches the image plane

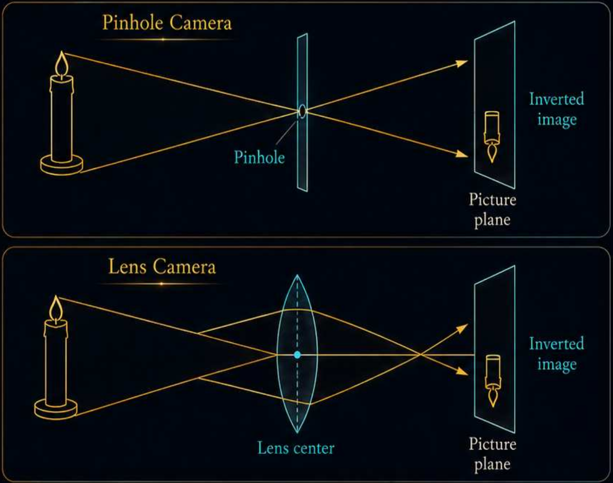
A lens gathers more light while preserving the same basic planar projection geometry.

Replacing the Pinhole with a Lens

Same projection idea, improved light collection

A photographic camera produces the same 2D planar geometric projection as a camera obscura.

- A lens replaces the pinhole, and film or a digital sensor becomes the picture plane.
- Rotating the camera (and lens) around the lens center adds or removes vanishing points.



Daguerreotype

- Invented in 1836 by Louis Daguerre
- Lenses focus light, enabling shorter exposures and better chemistry-driven image formation.

The daguerreotype marked the transition from camera obscura to practical photography.

Daguerre – Boulevard du Temple

1838

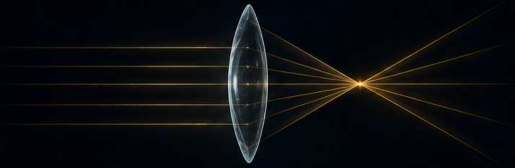
Exposure: 10–12 minutes

One of the earliest photographs to capture a human figure.

Long exposure erased most moving traffic, leaving only the nearly motionless subjects visible.

Lenses

- focus light
- magnify objects

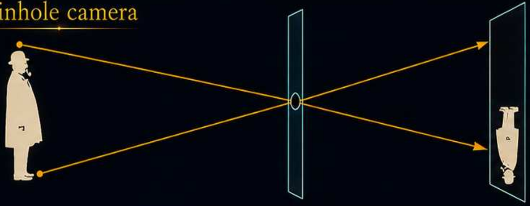


Nimrud lens —
approximately 2700 years old

Replacing the Pinhole with a Lens

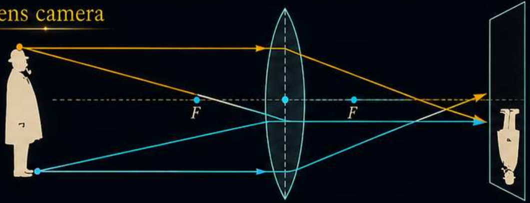
Same projection idea, improved light collection

Pinhole camera



- Sharper geometry
- Less light
- Inverted image on image plane

Lens camera

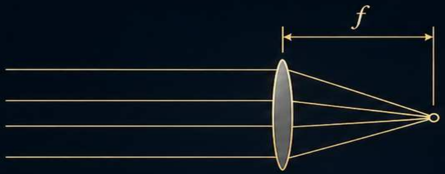


- Brighter image
- Same planar projection
- More light reaches the image plane

A lens gathers more light while preserving the same basic projection geometry.

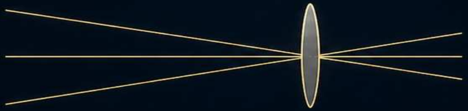
Geometrical Optics

- parallel rays converge to a point
  located at focal length f from lens

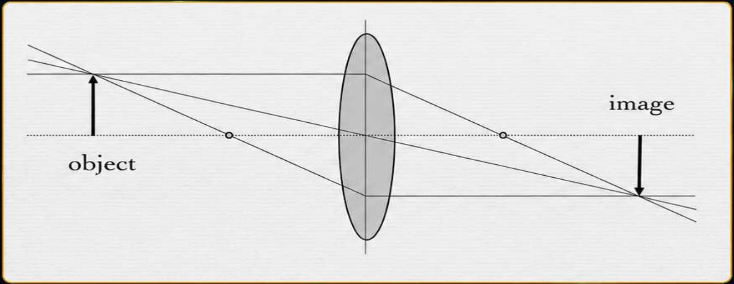


- rays through the center of the lens
  are not deviated

- rays going through center of lens are not deviated
  - hence same perspective as pinhole



Gauss's Ray Tracing Construction

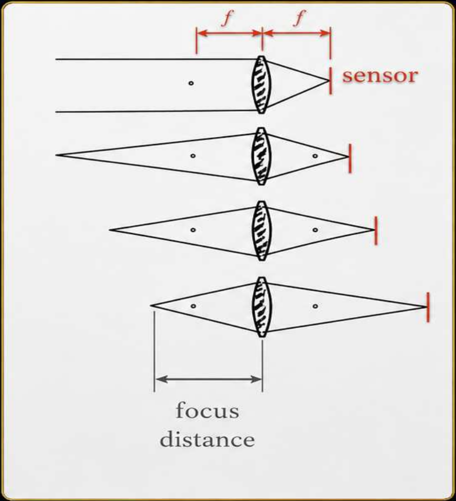


✦ Rays coming from points on a plane parallel to the lens are focused to points on another plane parallel to the lens.

Changing the Focus Distance

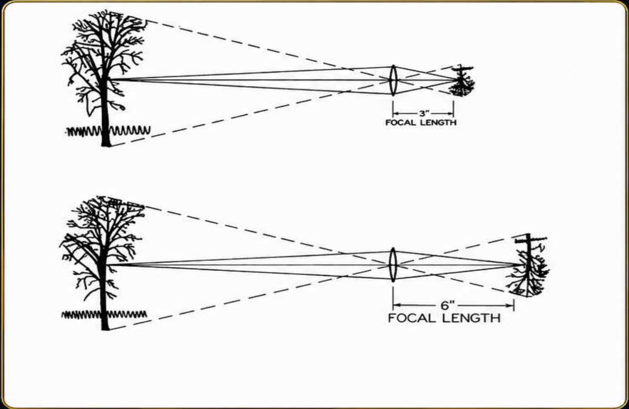
- to focus on objects at different distances,
  move the sensor relative to the lens
- in a handheld camera,
  one actually moves the lens, not the sensor
- by convention, focus distance
  is on the object side of the lens

The original focus-distance geometry is preserved exactly.



Changing the Focal Length

- weaker lenses have longer focal lengths
- to keep the same object in focus, move the sensor farther back
- focused image of a finite-distance tree is slightly beyond the focal length

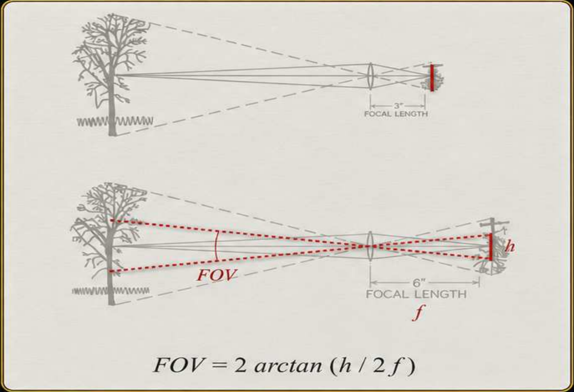


The tree would be in focus at the lens focal length only if it were infinitely far away.

Changing the Focal Length

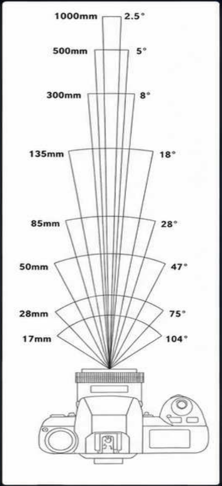
- if the sensor size is constant, the field of view becomes smaller

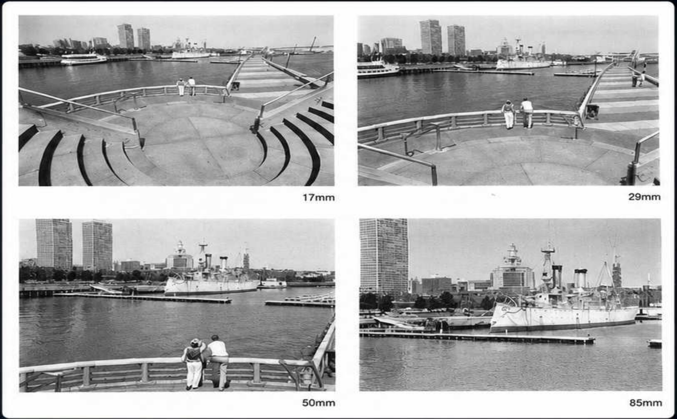
$$FOV = 2\ \arctan(h / 2f)$$



Longer focal length narrows the angular field of view while preserving the same sensor height h.

Focal Length and Field of View

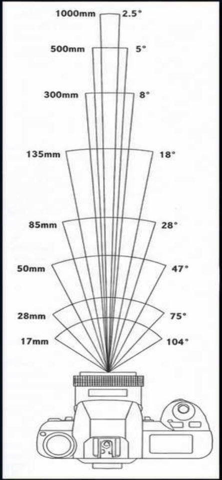


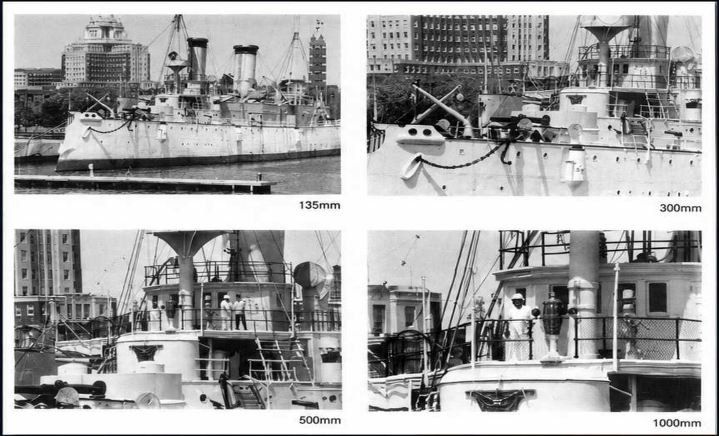


(London)

FOV measured diagonally on a 35mm full-frame camera (24 × 36 mm)

Focal Length and Field of View

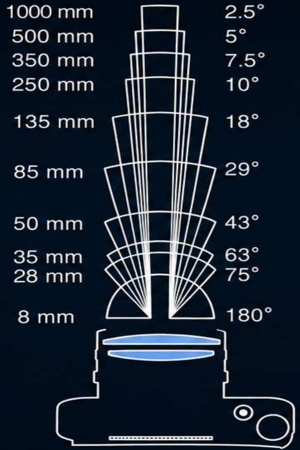




(London)

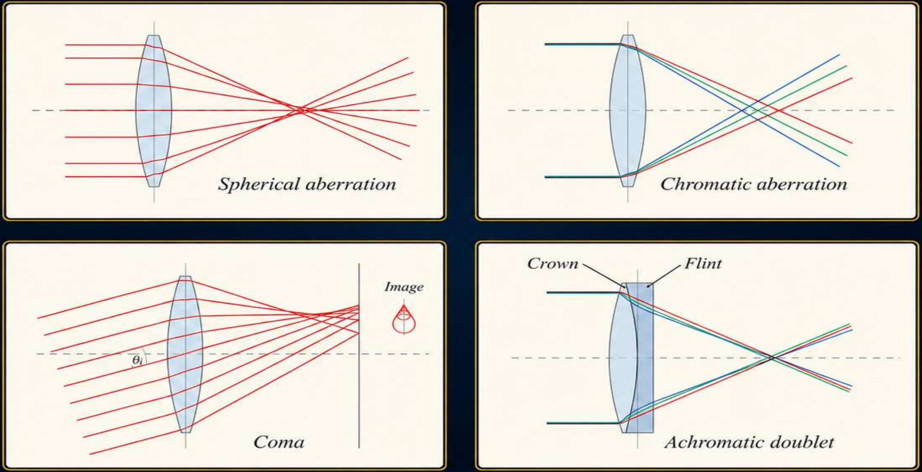
FOV measured diagonally on a 35mm full-frame camera (24 × 36 mm)

Field of View



Hubble – what's the focal length?

Lenses - Aberrations



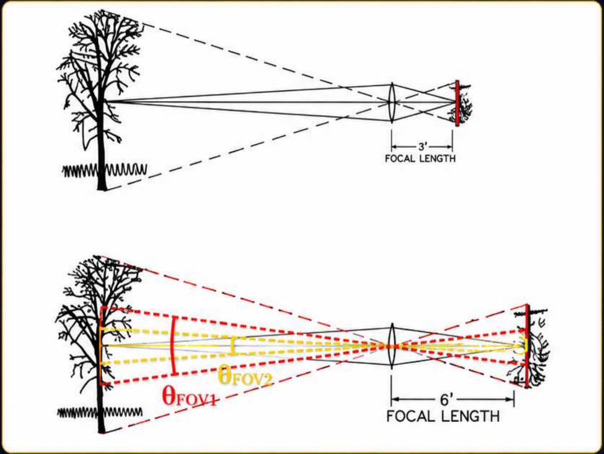
Lenses - Aberrations

Sharp Image

Blurred Image due to optical aberrations

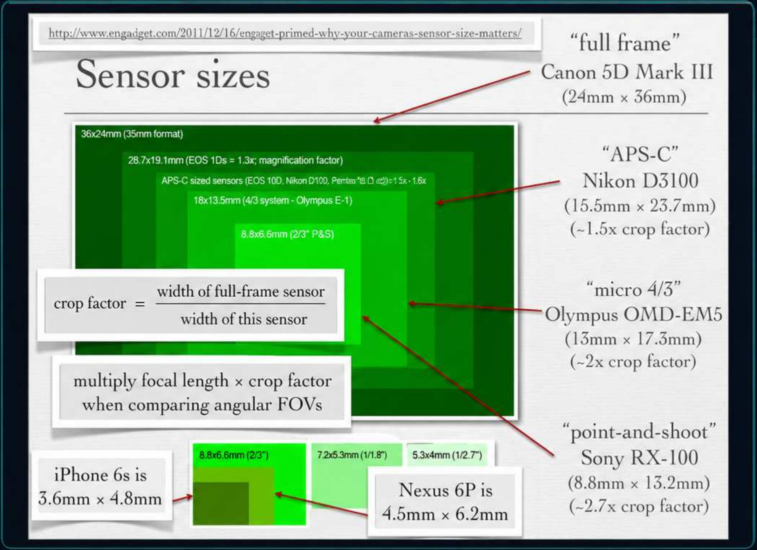
Changing the Sensor Size

- if the sensor size is smaller, the field of view is smaller too
- smaller sensors either have fewer pixels, or smaller pixels, which are noisier



(Kingslake)

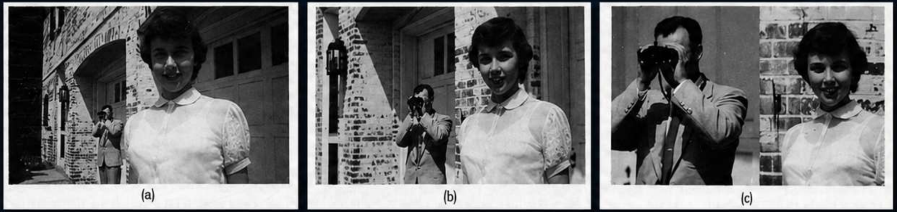
Sensor sizes



Micro Four Thirds Example

Changing the Focal Length Versus Changing the Viewpoint

(Kingslake)



wide-angle

telephoto and moved back

- changing the focal length lets us move back from a subject, while maintaining its size on the image
- but moving back changes perspective relationships

Effect of Focal Length on Portraits

- standard "portrait lens" is 85mm

wide angle

standard

telephoto

Exposure

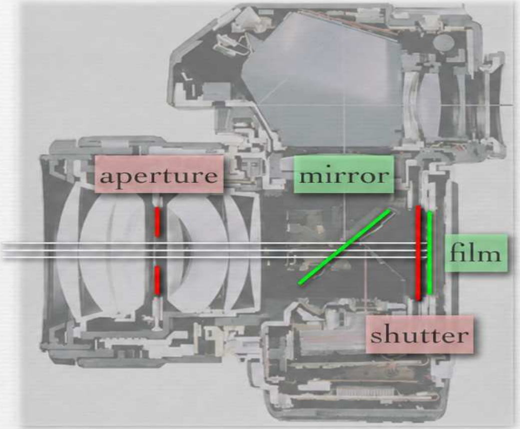
$$H = E \times T$$

- exposure = irradiance × time

- irradiance (E)
  - amount of light falling on a unit area of sensor per second
  - controlled by aperture

- exposure time (T)
  - in seconds
  - controlled by shutter

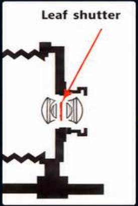
Single Lens Reflex Camera



Nikon F4
(film camera)

Shutters

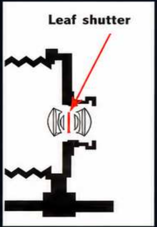
- quiet
- slow (max 1/500s)
- out of focus
- need one per lens



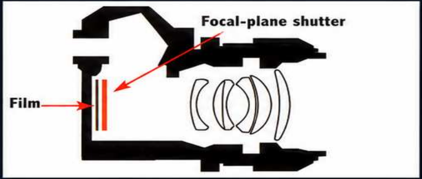
Shutters

(London)

Someone asked why SLRs can't use electronic shutters like cell phones. My answer could have been clearer. They can and do for the live electronic (non-optical) viewfinder, as I showed in lecture, but these images have low resolution. For snapshots, which utilize the full resolution of the sensor, it's impossible to read off this many pixels fast enough to accomplish short shutter speeds; the focal plane distortion would be severe.



- quiet
- slow (max 1/500s)
- out of focus
- need one per lens



- loud
- fast (max 1/4000)
- in focus
- distorts motion

Jacques-Henri Lartigue, Grand Prix (1912)

Exposure

$$H = E \times T$$

- exposure = irradiance × time

- **irradiance (E)**
  - amount of light falling on a unit area of sensor per second
  - controlled by aperture

- **exposure time (T)**
  - in seconds
  - controlled by shutter

EXPOSURE (Aperture constant)

Underexposed Too little light | **Proper Exposure** Balanced light | **Overexposed** Too much light

EXPOSURE TIME (Aperture constant)

Short Exposure Time 1/1000 s — Freezes motion, less light | **Long Exposure Time** 2.0 s — Motion blur, more light

Shutter Speed

- controls how long the sensor is exposed to light
- linear effect on exposure until sensor saturates
- denoted in fractions of a second:
  - 1/2000, 1/1000,…,1/250, 1/125, 1/60,...,15, 30, B(ulb)
- normal humans can hand-hold down to 1/60 second
  - *rule of thumb*: longest exposure = 1 / f
  - e.g. 1/180 second for a 180mm lens

using 35mm equivalent focal length

GF1 (2× crop) with Leica 90mm

Main Side-Effect of Shutter Speed

- motion blur
- doubling exposure time doubles motion blur

Slow shutter speed

Fast shutter speed

(London)

Useful Shutter Speeds

1/25 sec (lucky!)

- Slower shutter speeds let in more light—ideal for low-light or static subjects.

1/40 sec

- Moderate shutter speeds help capture scenes with more depth and detail.

Adjust shutter speed to balance light, motion, and creative intent.

Useful Shutter Speeds

1/125 sec

1/250 sec

Faster shutter speeds freeze more action and detail.

Useful Shutter Speeds

1/800 sec

How Fast is a Volleyball Spike?

Women's volleyball

✦

(Canon 1DII, 1/800 second)

- derive required shutter speed from length of motion blur
- 5 pixels in 1/800 sec $\Rightarrow$ 1 pixel in 1/4000 sec !

Focal-Plane Shutter Distortion

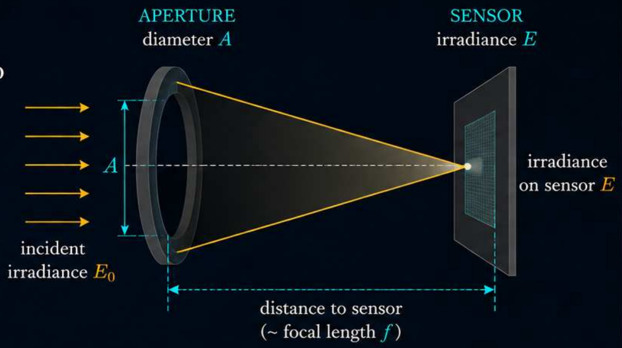
Women's volleyball

(Canon 1DIII, 1/800 second)

- A focal-plane (rolling) shutter exposes the image row by row.
- During fast motion, different rows are captured at slightly different times, causing geometric distortion (e.g., a curved arm or ball trajectory).

Aperture

- irradiance on sensor is proportional to
  - square of aperture diameter A
  - inverse square of distance to sensor (~ focal length f)

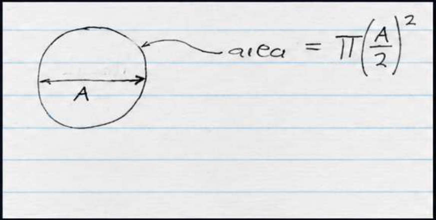


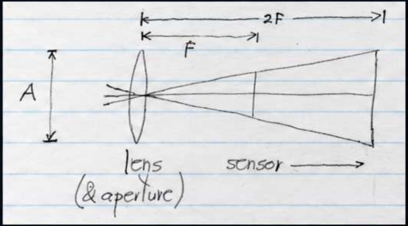
$$E \propto \frac{A^2}{f^2}$$

E = irradiance on sensor
A = aperture diameter
f = distance to sensor (~ focal length)

Irradiance on Sensor

(contents of whiteboard)



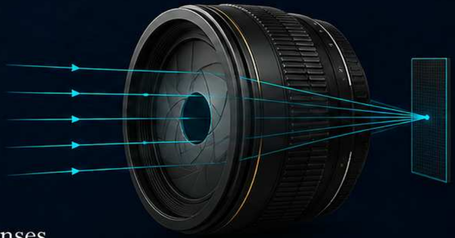


- As the diameter A of the aperture doubles, its area (hence the light that can get through it) increases by 4× (first drawing).
- Think of the lens as a collection of pinholes, each having a fixed angular field of view (cone in 2nd drawing) determined by the lens design.
- A certain amount of light gets through each pinhole. By conservation of energy, that light will fall on whatever sensor is placed in its path.
- If the distance to the sensor is doubled, the area intersecting the cone increases by 4×, so the light falling per unit area decreases by 4×.

Aperture

- irradiance on sensor is proportional to
  - square of aperture diameter A
  - inverse square of distance to sensor (~ focal length f)
- so that aperture values give irradiance regardless of focal length, *aperture number* N is defined relative to focal length

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



- f/2.0 on a 50mm lens means the aperture is 25mm
- f/2.0 on a 100mm lens means the aperture is 50mm

∴ low F-number (N) on long telephotos require fat lenses

How Fast is a Volleyball Spike?

Women's volleyball

(Canon 1DII, 1/800 second)

- derive required shutter speed from length of motion blur
- 5 pixels in 1/800 sec $\Rightarrow$ 1 pixel in 1/4000 sec !

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Aperture

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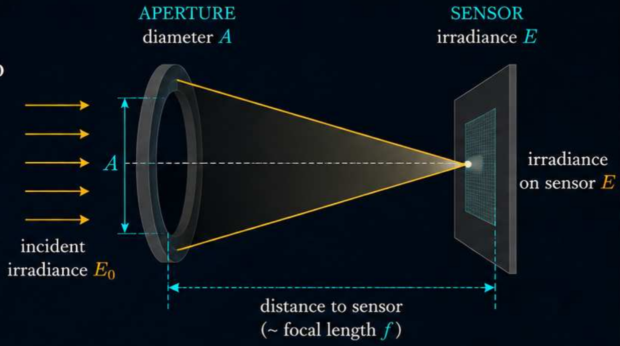
  - square of aperture diameter A
  - inverse square of distance to sensor (~ focal length f)

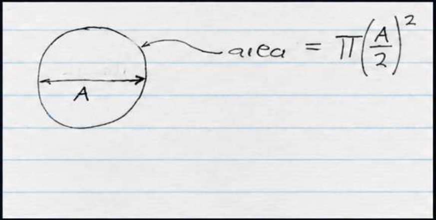


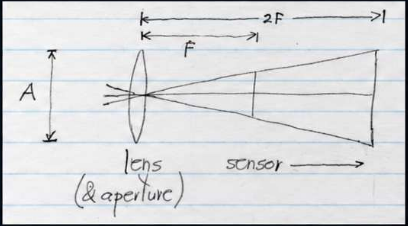
$$E \propto \frac{A^2}{f^2}$$

E = irradiance on sensor
A = aperture diameter
f = distance to sensor (~ focal length)

Irradiance on Sensor

(contents of whiteboard)



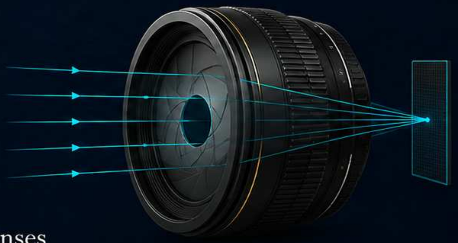


- As the diameter A of the aperture doubles, its area (hence the light that can get through it) increases by $4\times$ (first drawing).
- Think of the lens as a collection of pinholes, each having a fixed angular field of view (cone in 2nd drawing) determined by the lens design.
- A certain amount of light gets through each pinhole. By conservation of energy, that light will fall on whatever sensor is placed in its path.
- If the distance to the sensor is doubled, the area intersecting the cone increases by $4\times$, so the light falling per unit area decreases by $4\times$.

Aperture

- irradiance on sensor is proportional to
  - square of aperture diameter A
  - inverse square of distance to sensor (~ focal length f)
- so that aperture values give irradiance regardless of focal length, *aperture number* N is defined relative to focal length

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

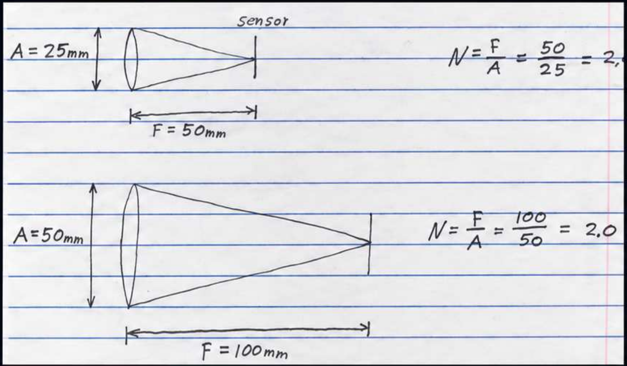


- f/2.0 on a 50mm lens means the aperture is 25mm
- f/2.0 on a 100mm lens means the aperture is 50mm

$\therefore$ low F-number (N) on long telephotos require fat lenses

Example F-number Calculations

Contents of Whiteboard



- The f-number is the relative aperture $N = \dfrac{f}{A}$.
- Doubling both aperture diameter A and focal length f leaves N unchanged.
- In these examples, both lenses are $f/2$.

Aperture

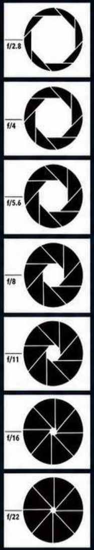
> As Florian Kainz pointed out during lecture (and Peter Sherman explained in the dory), F-stops are used by videographers in place of F-stops (or N) because they include light loss due to transmission through the lens. F-stops let you compute exposure more accurately, but you need F-stops to compute depth of field.

- irradiance on sensor is proportional to
  - square of aperture diameter A
  - inverse square of distance to sensor ($\sim$ focal length f)
- so that aperture values give irradiance regardless of lens, *aperture number* N is defined relative to focal length

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

  - $f/2.0$ on a 50mm lens means the aperture is 25mm
  - $f/2.0$ on a 100mm lens means the aperture is 50mm
  - low F-number (N) on long zooms require fat lenses
- doubling N reduces A by 2x, hence light by 4x
  - going from $f/2.0$ to $f/4.0$ cuts light by 4x
  - to cut light by 2x, increase N by $\sqrt{2}$

f/2.8
f/4
f/5.6
f/8
f/11
f/16
f/22



(London)

Q. Does an $f/2$ cell phone lens gather as much light from each patch of the scene as an $f/2$ SLR lens?

- a smaller lens is accompanied by a smaller focal length, in order to keep the angular field of view constant
- thus, N $(= f/A)$ stays constant
- for each scene patch, a smaller lens gathers less light
- but due to the smaller focal length, it concentrates this light into a smaller area on the sensor
- thus, the amount of light per unit area stays constant
- a smaller focal length is accompanied by smaller pixels, in order to keep the pixel count constant
- so the scene patch covers the same number of pixels, but they are smaller, hence fewer photons, hence noisier

Main Side-Effect of Aperture

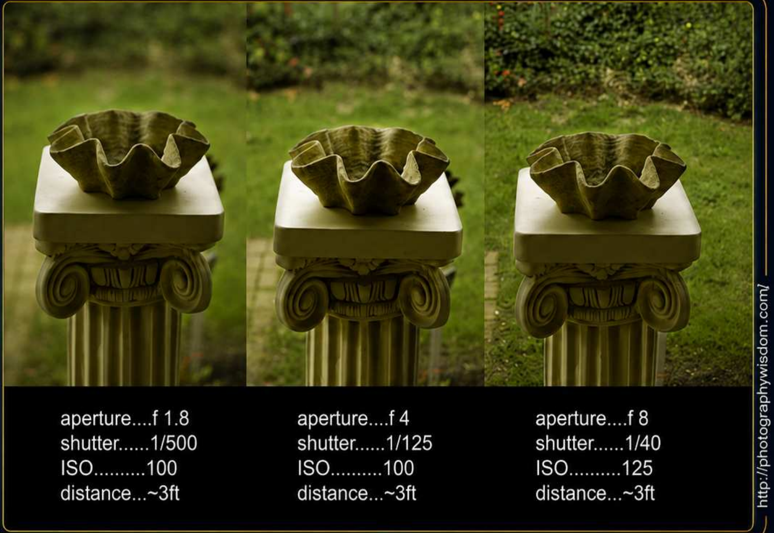
- depth of field
- doubling N (two f/stops) doubles depth of field

Large aperture opening

Small aperture opening

Aperture controls the range of distances that appear acceptably sharp.

Depth of Field



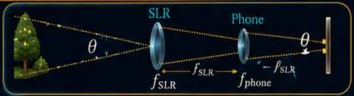
Depth of field is the range of distances that appear acceptably sharp.

Larger aperture → shallower depth of field.

Smaller aperture → greater depth of field.

Q. Does an $f/2$ cell phone lens gather as much light from each patch of the scene as an $f/2$ SLR lens?

a smaller lens is accompanied by a smaller focal length,
in order to keep the angular field of view constant



thus, N $(= f / A)$ stays constant

for each scene patch, a smaller lens gathers less light

but due to the smaller focal length,
it concentrates this light into a smaller area on the sensor

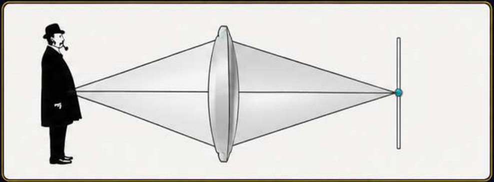
thus, the amount of light per unit area stays constant

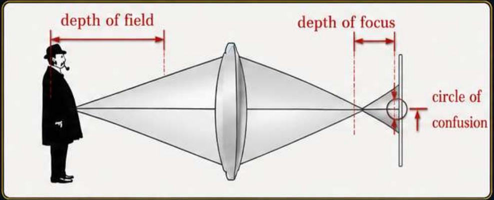
a smaller focal length is accompanied by smaller pixels,
in order to keep the pixel count constant

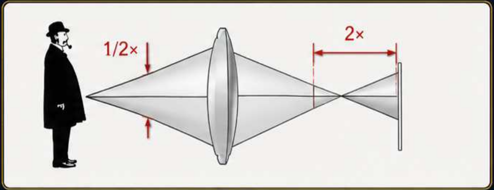
so the scene patch covers the same number of pixels,
but they are smaller, hence fewer photons, hence noisier

Depth of Field (Briefly)

- A point in the scene is focused to a point on the sensor.
- If the sensor moves in depth, that point becomes *blurred*.
- When the blur exceeds the allowable *circle of confusion*, it is no longer acceptably sharp.
- The zone in sensor space that remains sharp enough is the *depth of focus*.
- The corresponding zone in the scene is the *depth of field*.
- Halving the aperture diameter doubles the *depth of field*.







Depth of Field & Motion Blur

APERTURE (*f*-number) Smaller *f*-number = larger aperture	f/16	f/11	f/8	f/5.6	f/4	f/2.8	f/2
SHUTTER SPEED (seconds) Faster speed = shorter exposure	1	1/15	1/30	1/60	1/125	1/250	1/500

London, Photography

Smaller apertures (higher *f-numbers*) and *faster shutter speeds* increase *depth of field* and *reduce motion blur*.