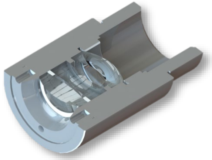
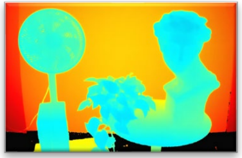








Computational Imaging

Lecture 04： Cameras I

Qilin Sun（孙启霖）

School of Data Science

The Chinese University of Hong Kong, Shenzhen

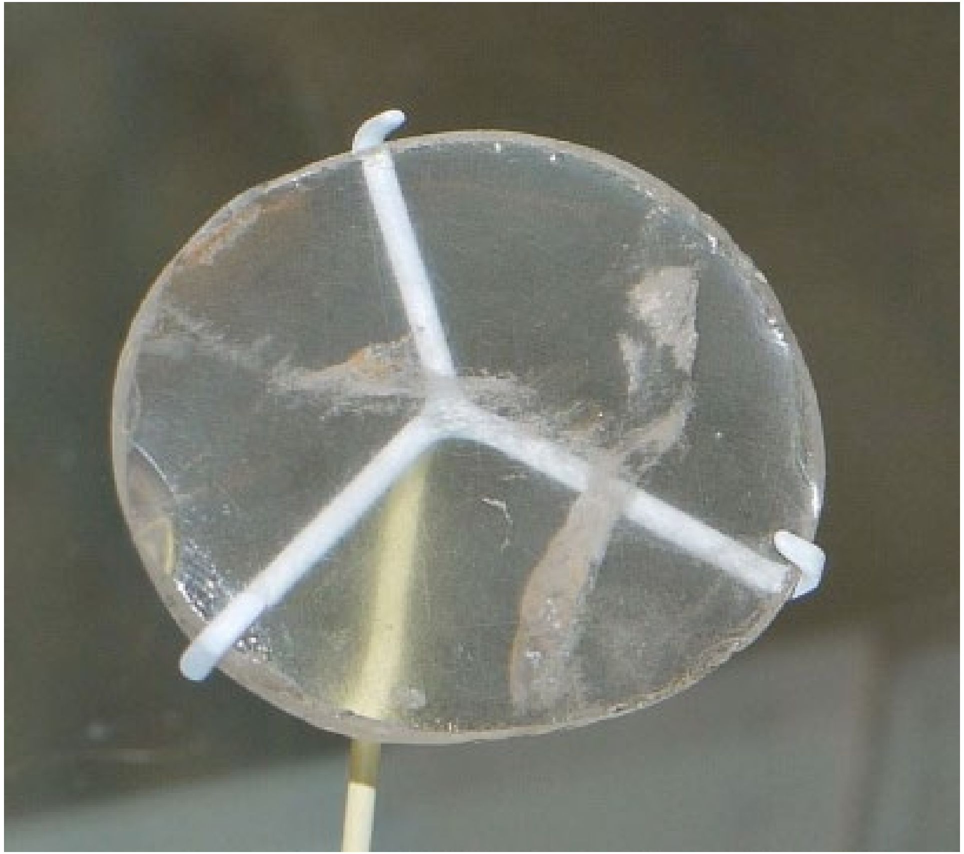
Today's Topic

- Lens
  - Aperture
  - Depth of Field
  - Field of View
  - Diffraction Limit
- Tips for Photography
- Sensors
  - Pixels and CFA
  - Exposure and ISO
  - Dynamic Range

Lens

Camera Optics: Lens

- Focus light
- Magnify objects

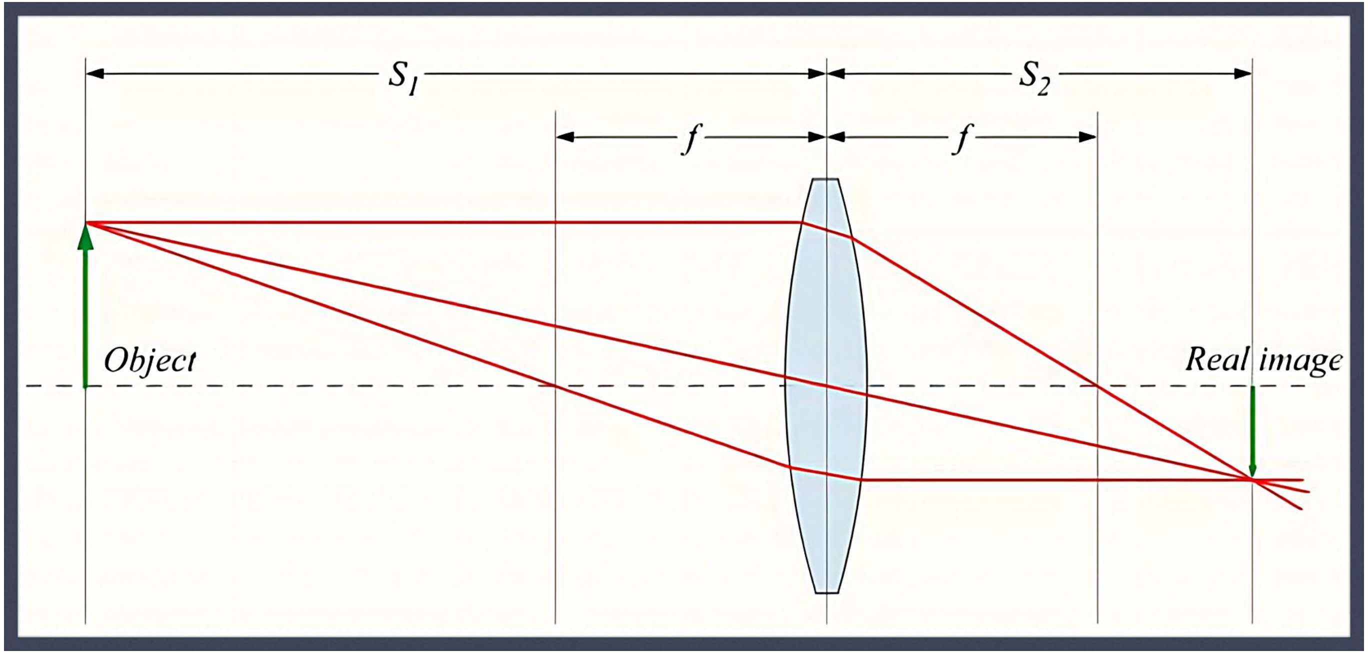


Nimrud lens - 2700 years old

Camera Optics: Lens

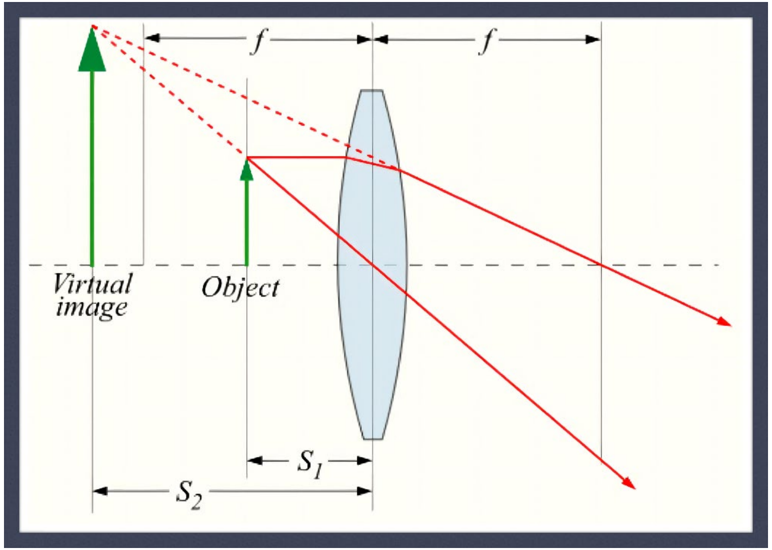
lensmaker's equation: $$\frac{1}{f}=\frac{1}{S_1}+\frac{1}{S_2}$$

magnification: $$M=-\frac{S_2}{S_1}=\frac{f}{f-S_1}$$

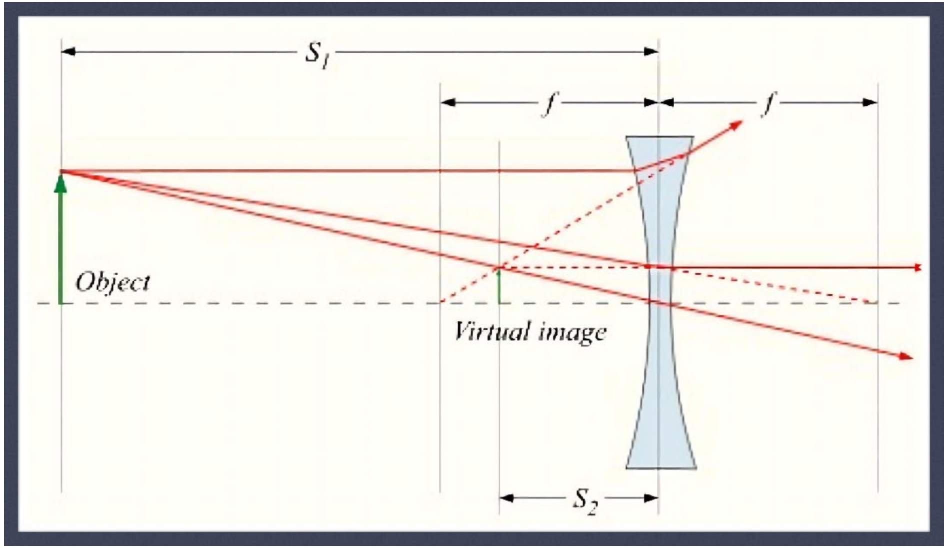


Camera Optics: Lens

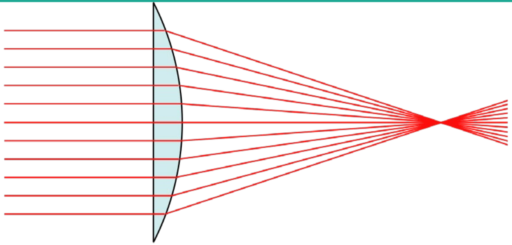
S1<f: magnifying glass



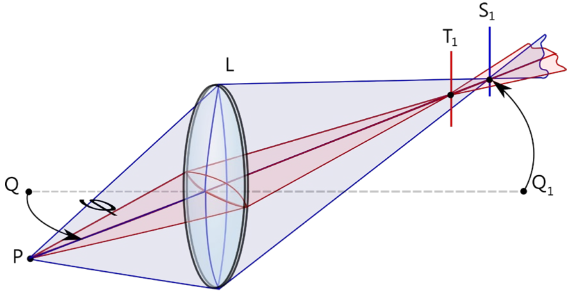
magnification



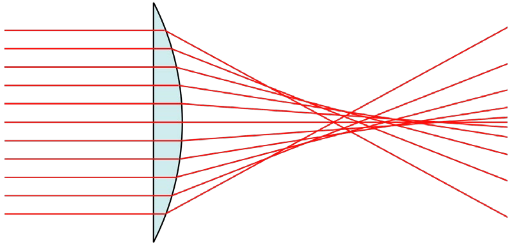
Camera Optics: Lens Aberrations



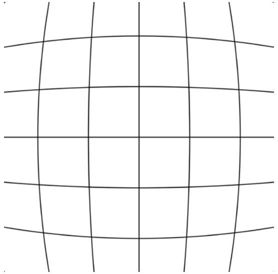
Ideal



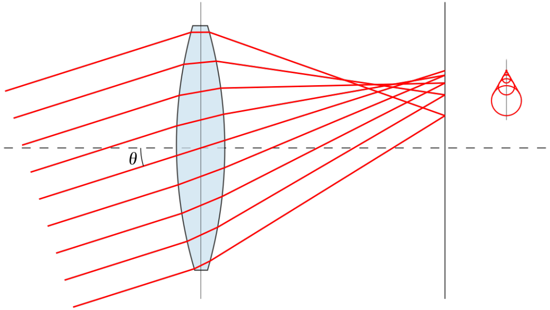
Astigmatism



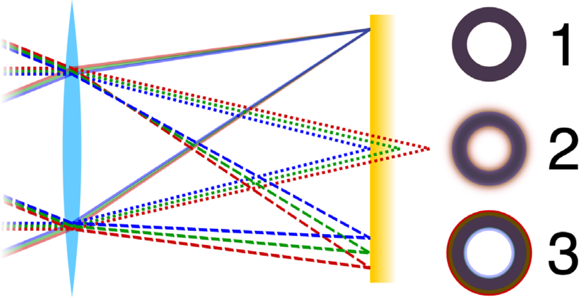
Seperical Abberation



Distortion



Coma



Chromatic Abberation

Camera Optics: Lens Aberrations

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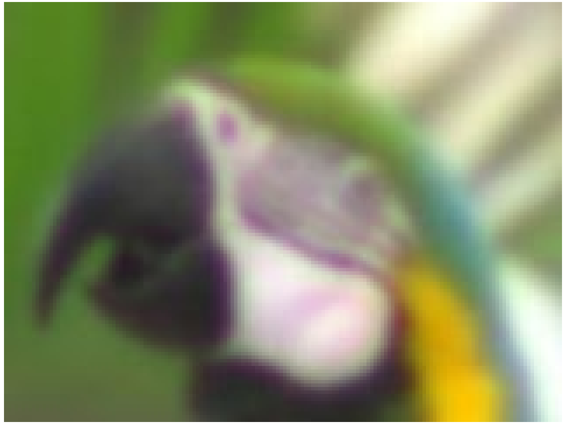
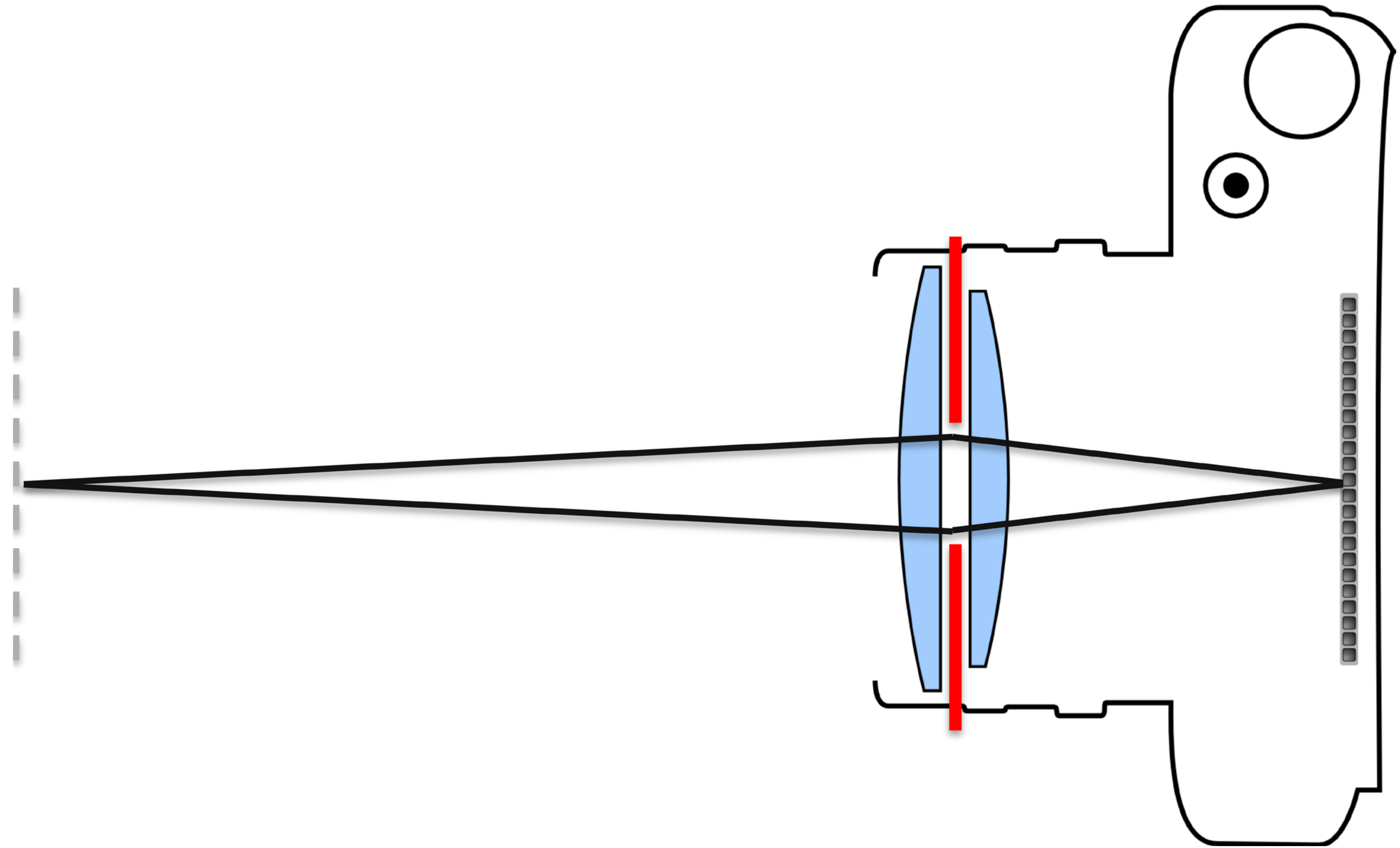
Sharp Image

Blurred Image due to optical aberrations

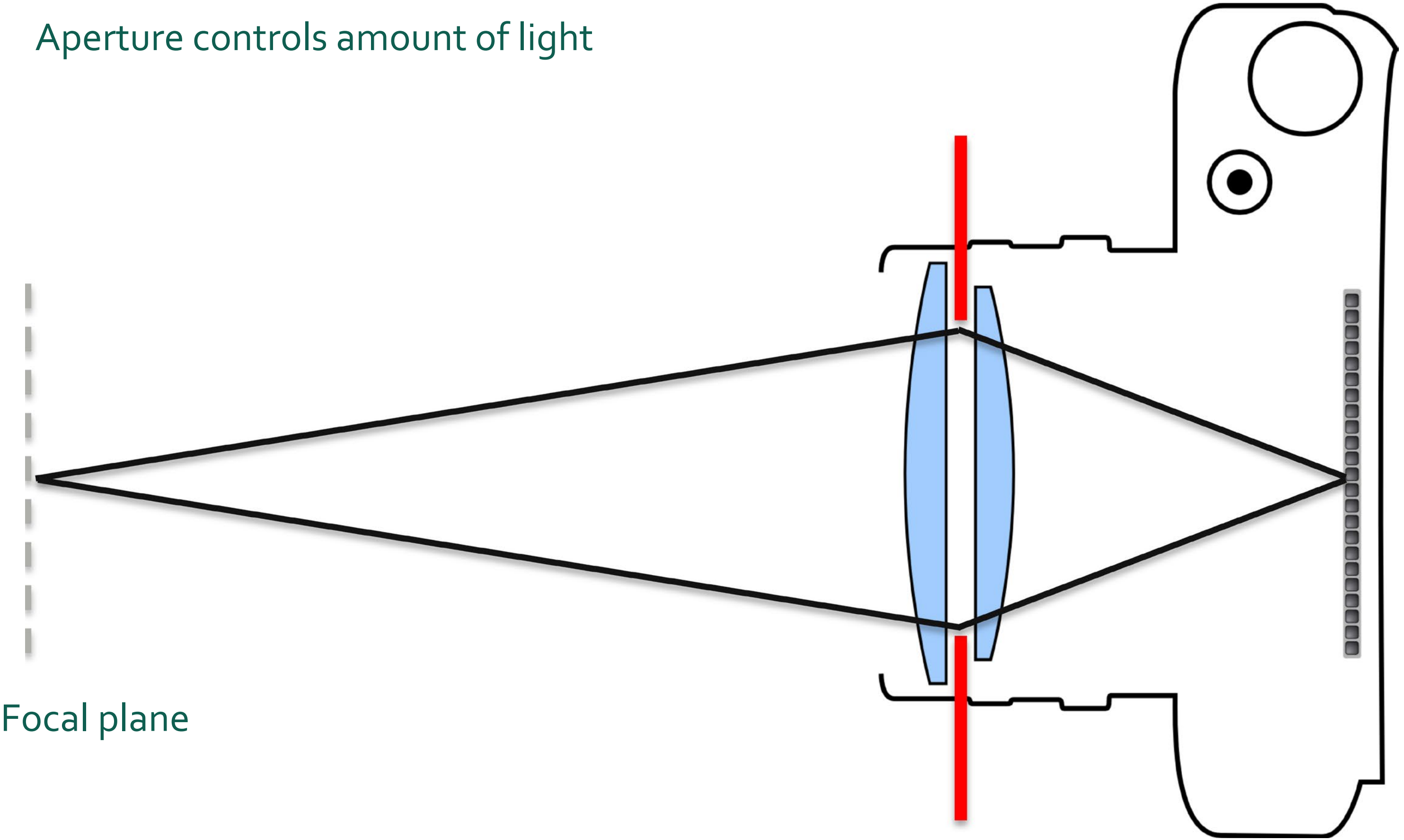


Camera Aperture



Camera Aperture

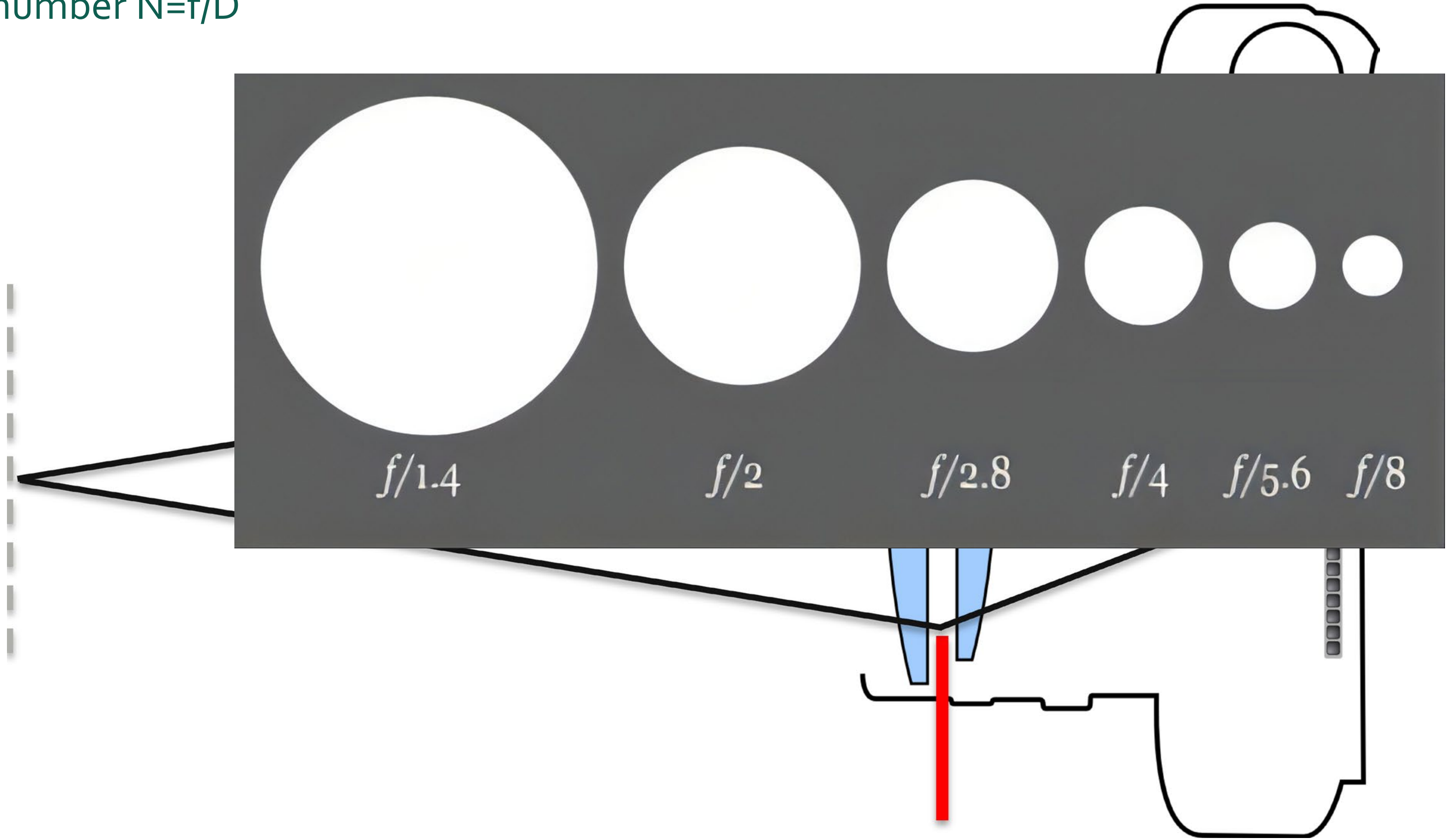
Aperture controls amount of light



Focal plane

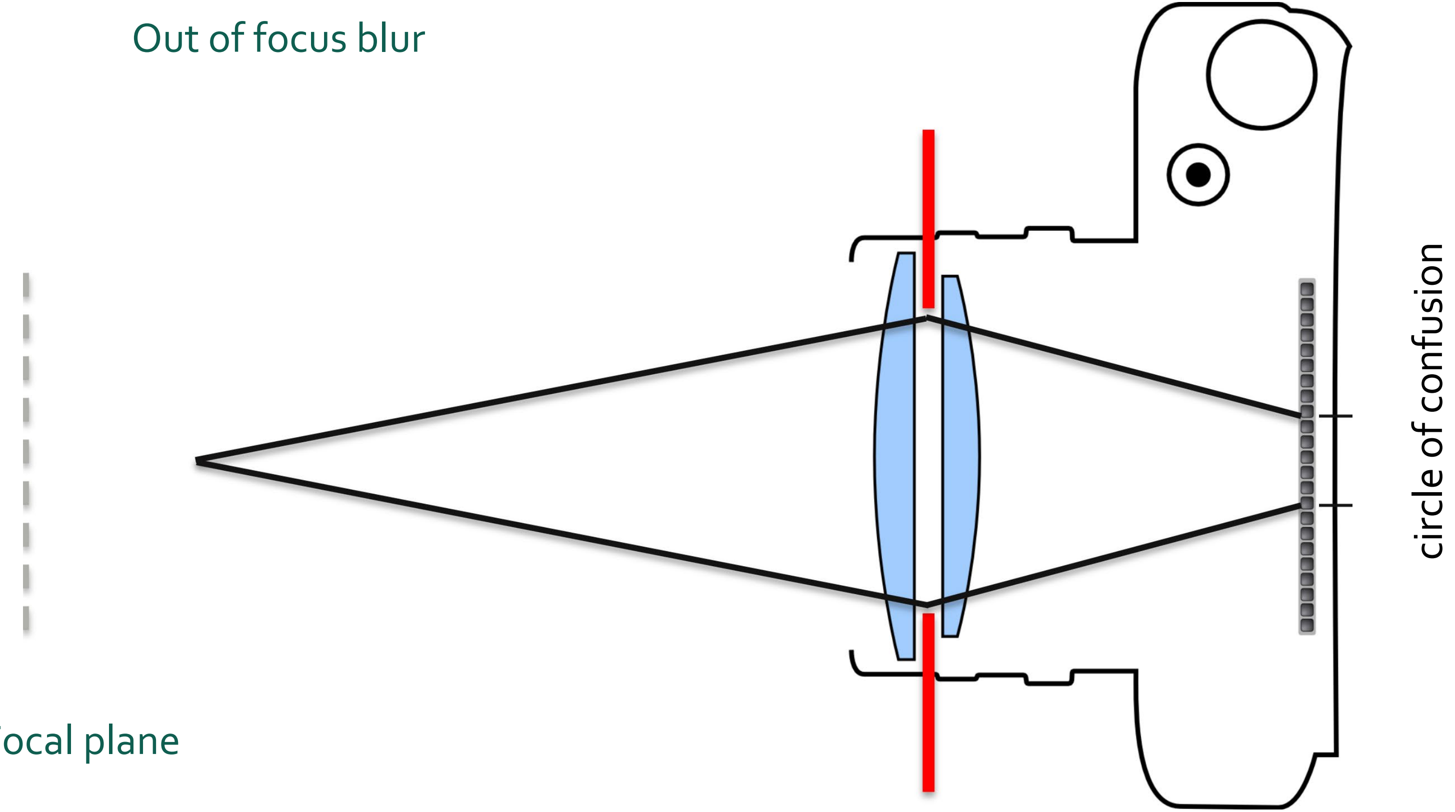
Camera Aperture

Unit: f-number N=f/D



Camera Aperture

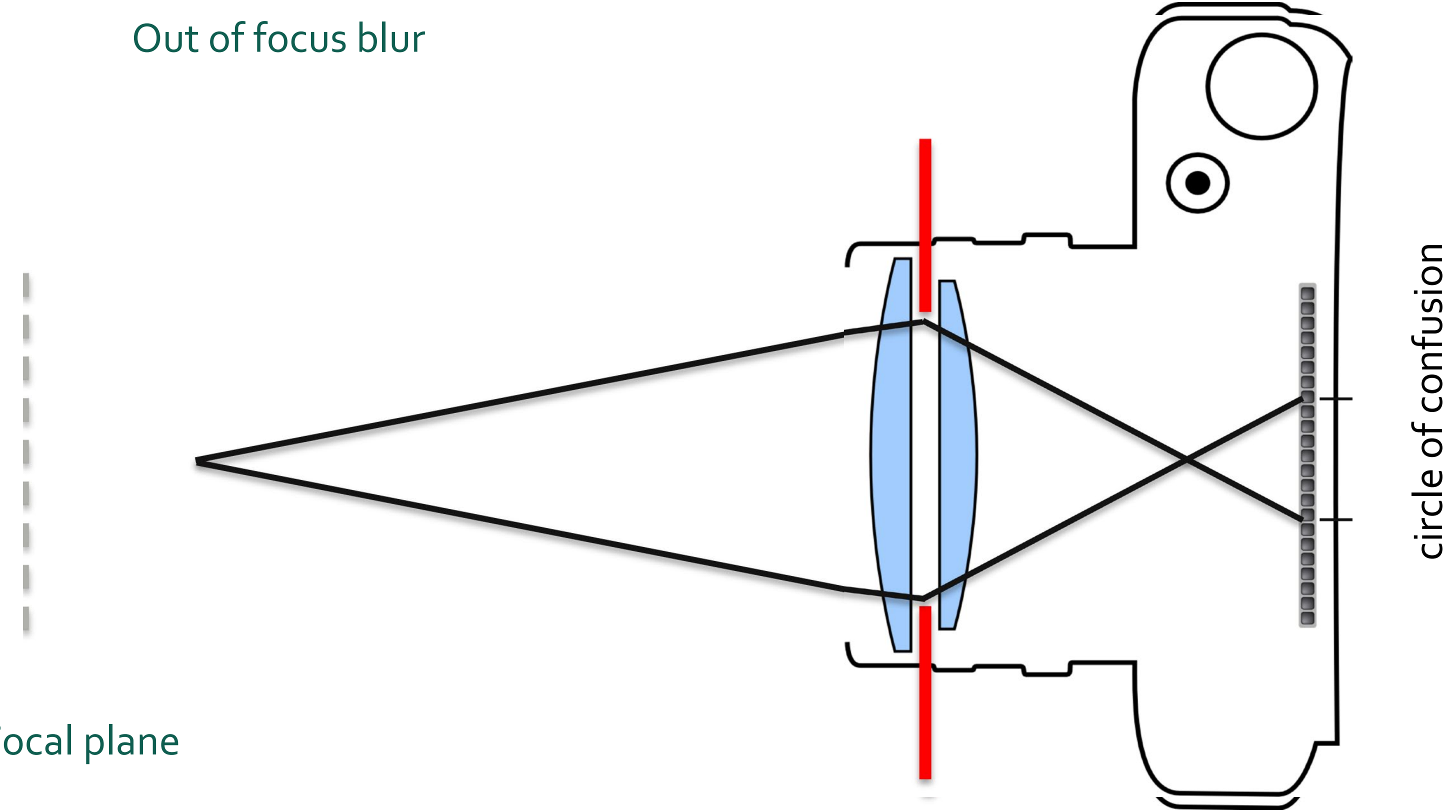
Out of focus blur



Focal plane

Camera Aperture

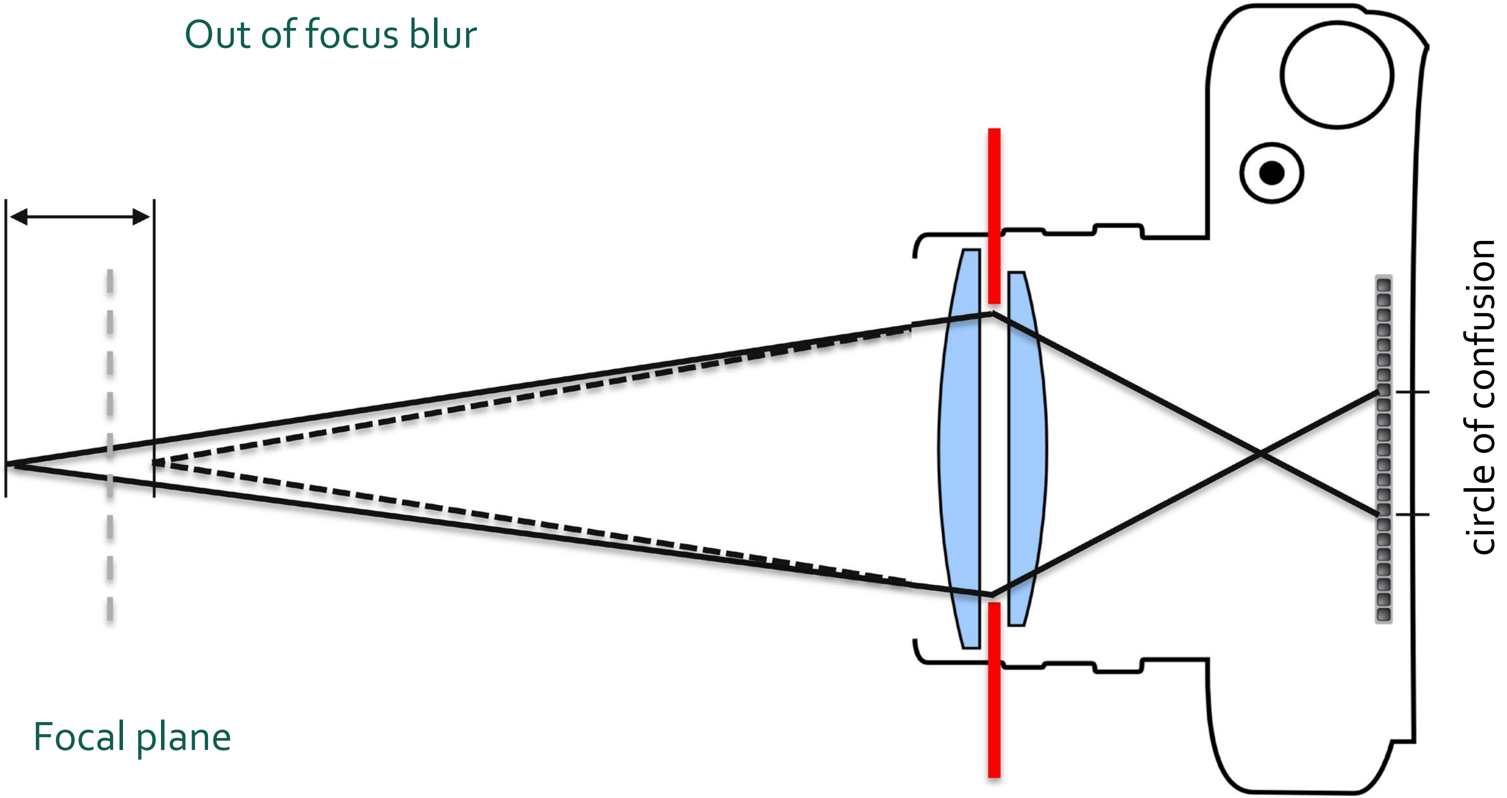
Out of focus blur



Focal plane

Camera Depth of Field

Out of focus blur



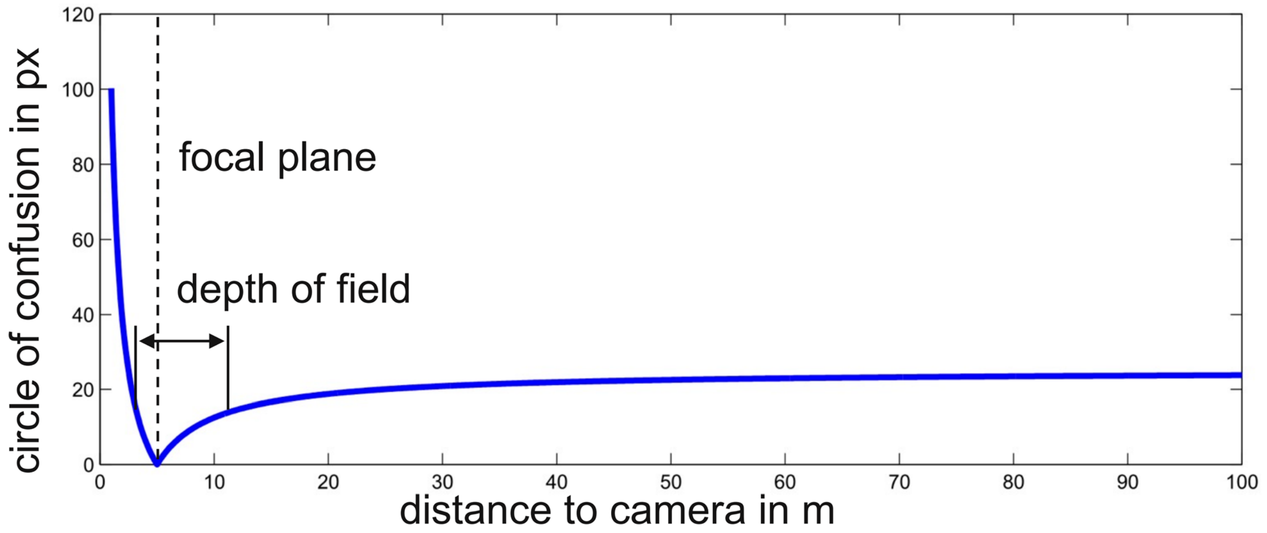
Focal plane

Camera Depth of Field

$$c = MD\frac{|S - S_1|}{S}$$

Canon 5D Mark III: f=50mm, f/2.8 (N=2.8),

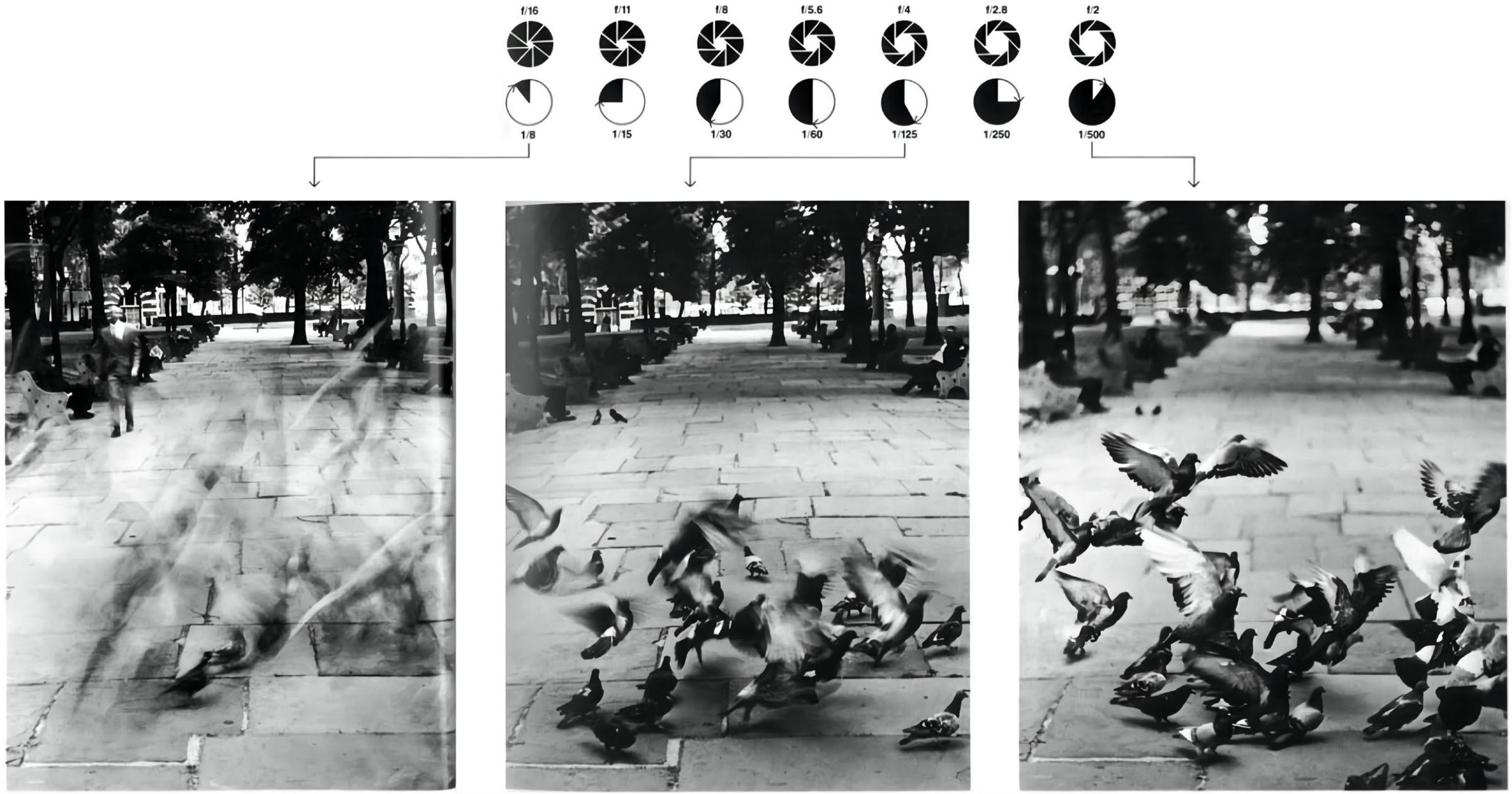
focused at 5m, pixel size=7.5um



Camera Depth of Field

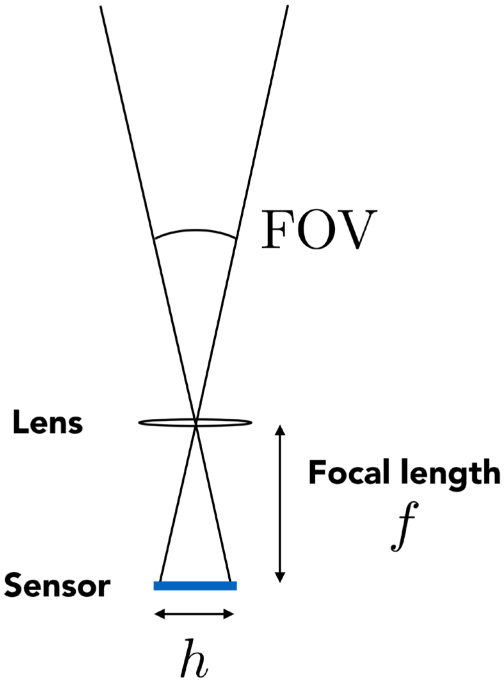
http://photographywisdom.com/

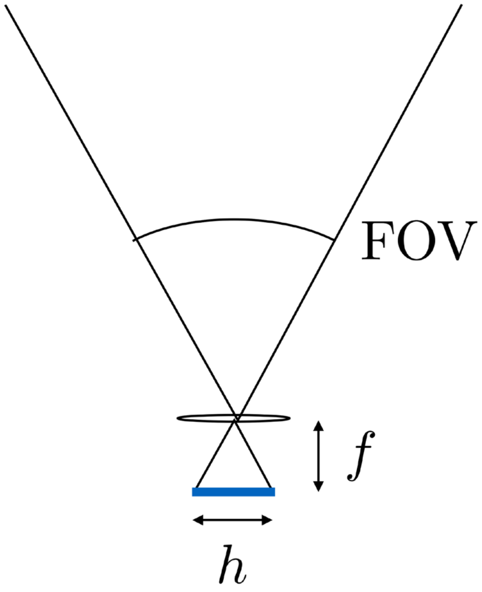
Camera Depth of Field



London, Photography

Camera Field of View (FOV)

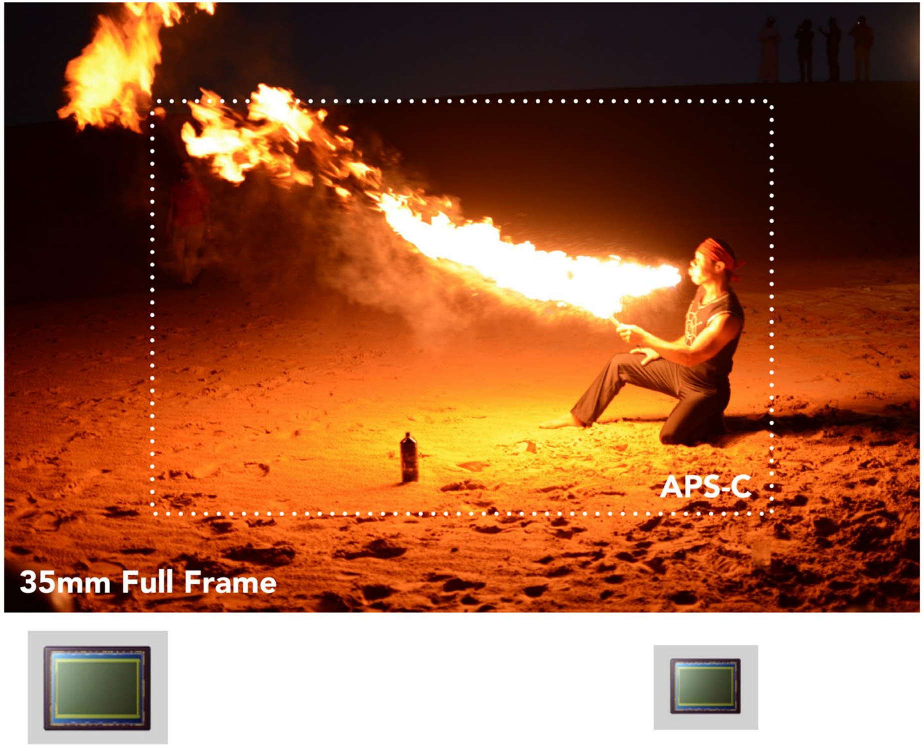


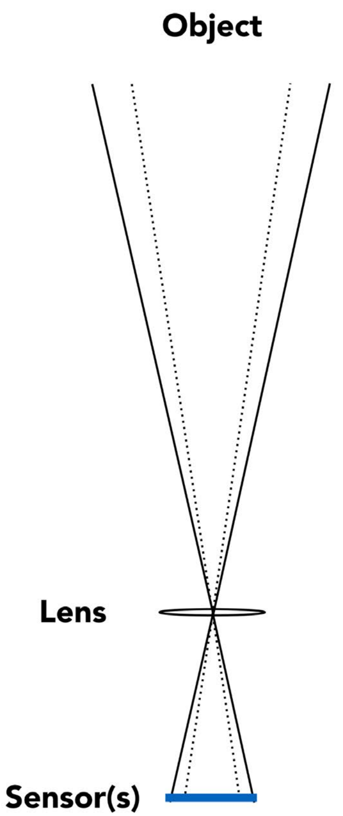


$$\mathrm{FOV} = 2\ \arctan\left(\frac{h}{2f}\right)$$

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

Camera Field of View (FOV)





Camera Field of View (FOV)

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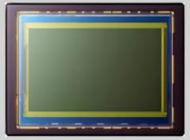
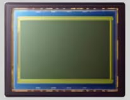
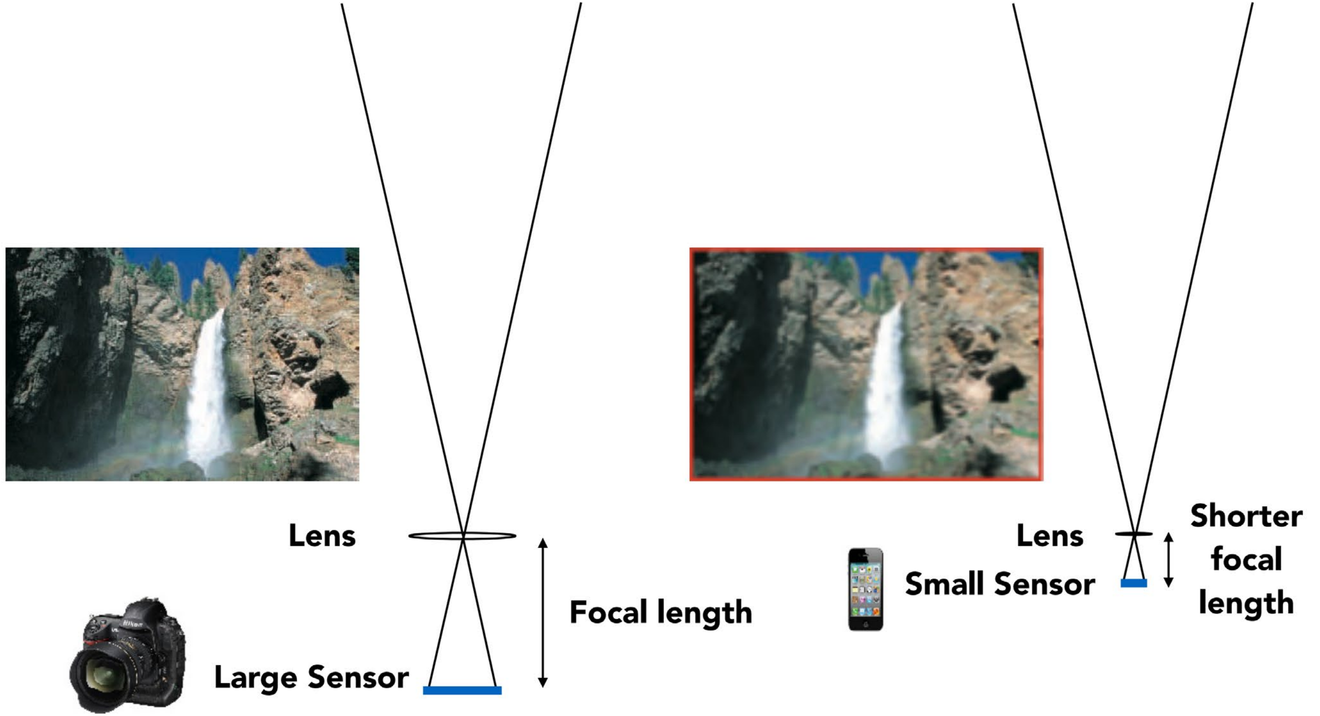
Sensor Name	Medium Format	Full Frame	APS-H	APS-C	4/3	1"	1/1.63"	1/2.3"	1/3.2"
Sensor Size	53.7 x 40.2mm	36 x 23.9mm	27.9x18.6mm	23.6x15.8mm	17.3x13mm	13.2x8.8mm	8.38x5.59mm	6.16x4.62mm	4.54x3.42mm
Sensor Area	21.59 cm²	8.6 cm²	5.19 cm²	3.73 cm²	2.25 cm²	1.16 cm²	0.47 cm²	0.28 cm²	0.15 cm²
Crop Factor	0.64	1.0	1.29	1.52	2.0	2.7	4.3	5.62	7.61
Image									
Example									

lensvid.com

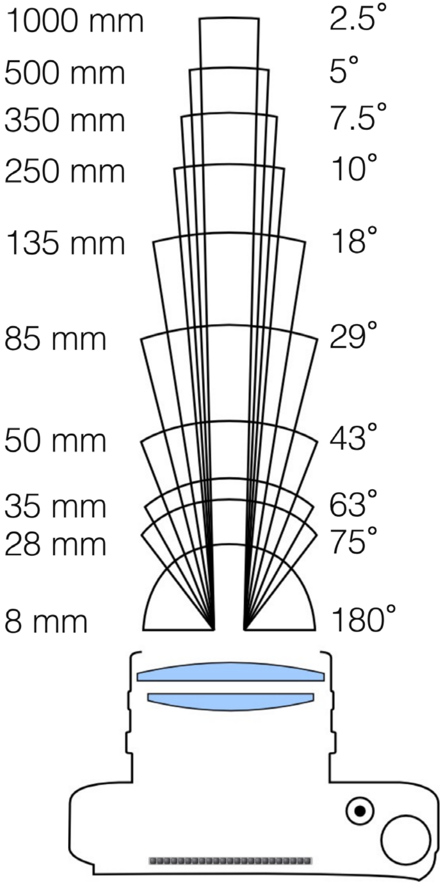
Camera Field of View (FOV)

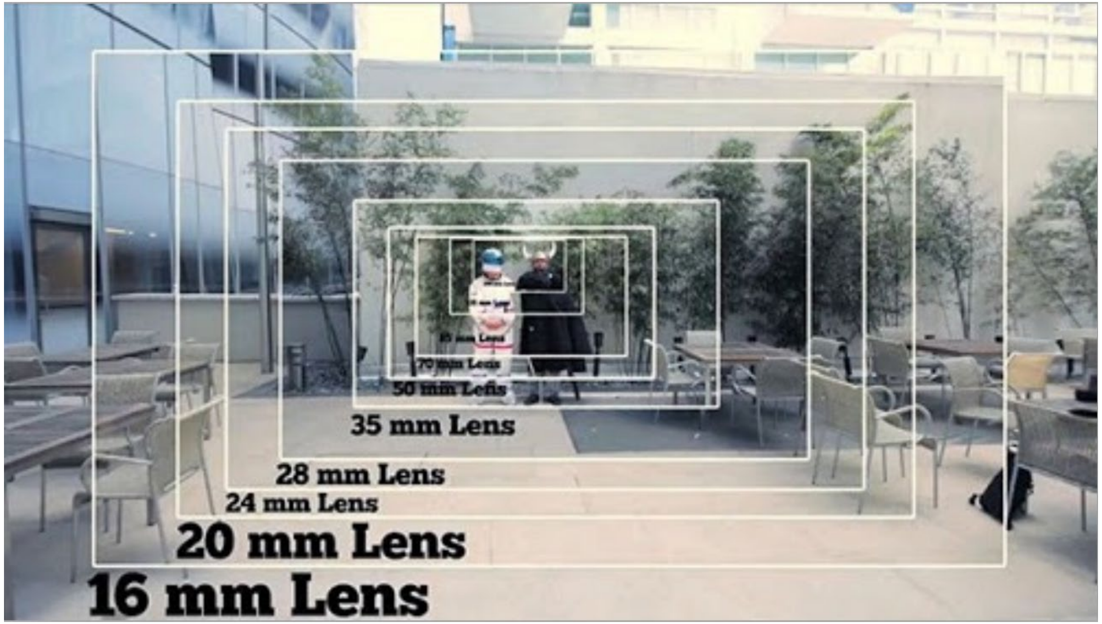
Mobile Phone: Maintain FOV on Smaller Sensor?



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

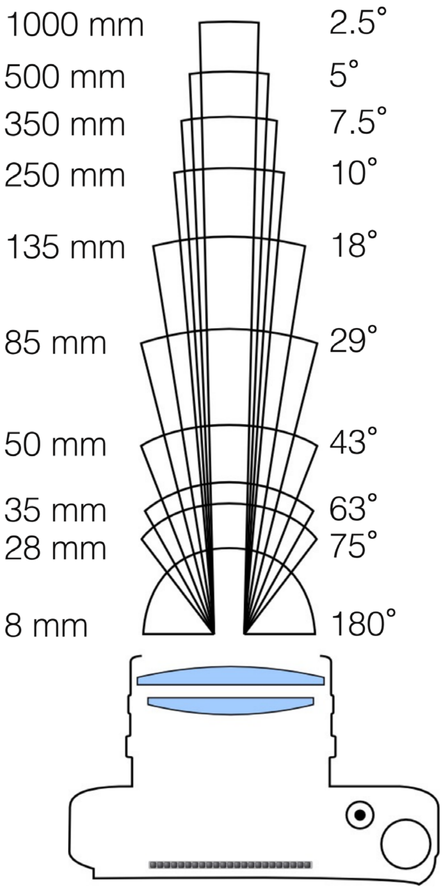
Camera Field of View (FOV)

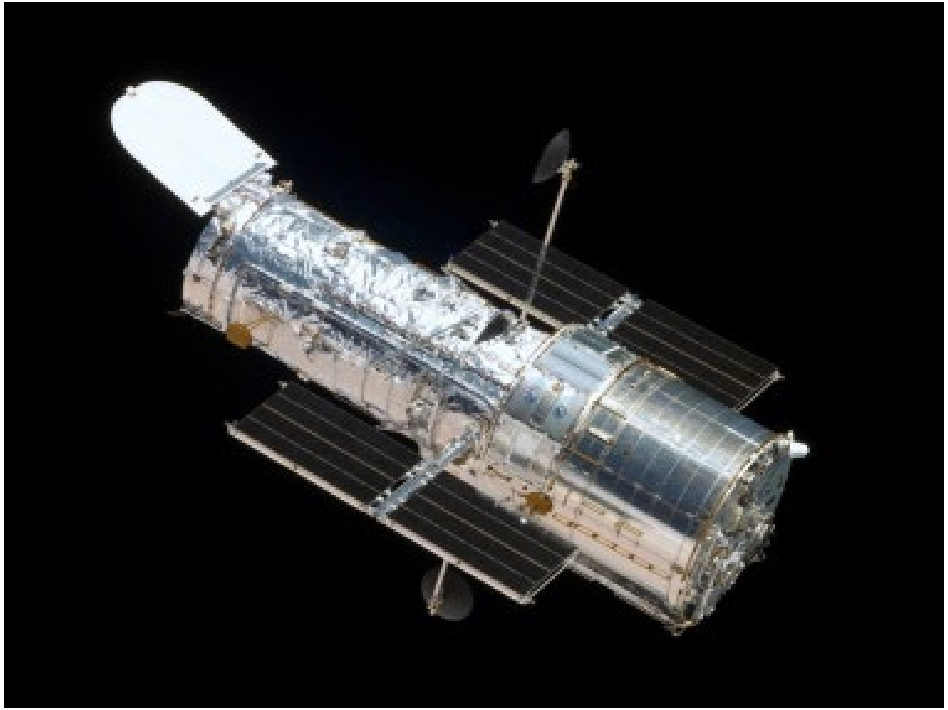




Andrew McWilliams

Camera Field of View (FOV)

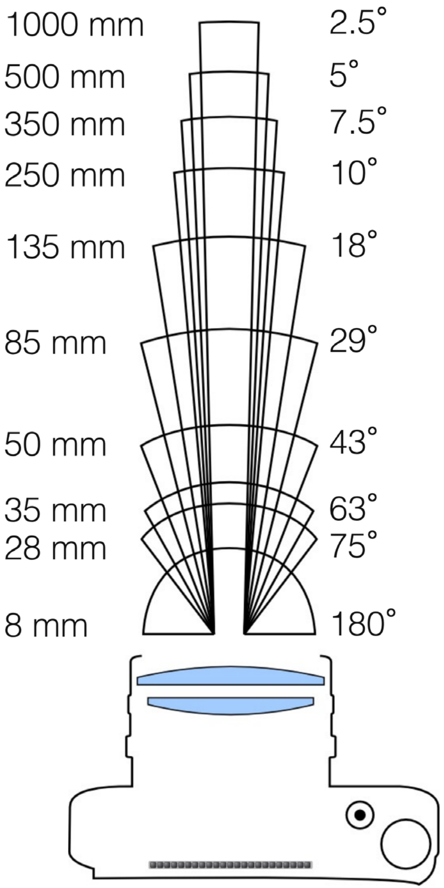




Hubble – What's the focal length?

57.6 m

Camera Field of View (FOV)



- 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

Diffraction Limit

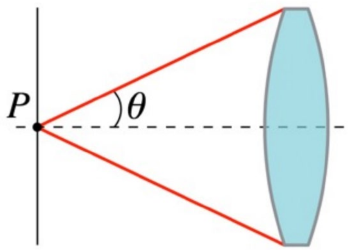
Ernst Abbe 1873:

$$d = \frac{\lambda}{2n\sin\theta} = \frac{\lambda}{2NA} \approx \lambda N$$

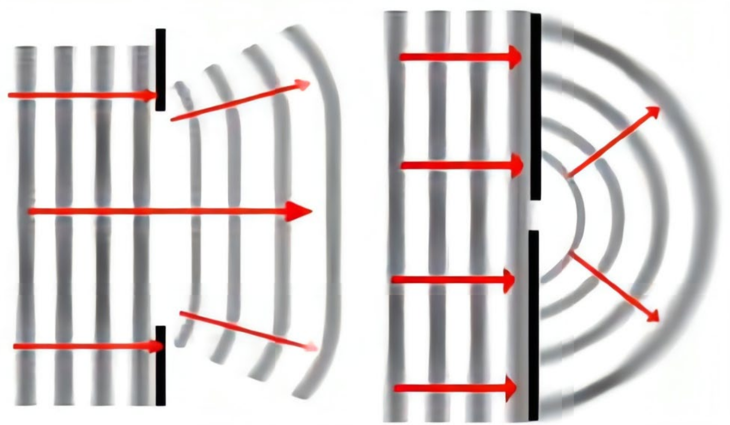
f-number

numerical aperture

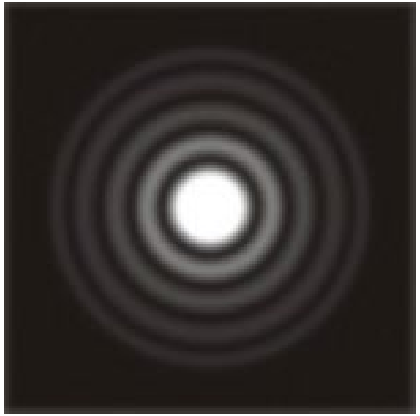
spot radius (image space)



Diffraction



Airy pattern



Diffraction Limit

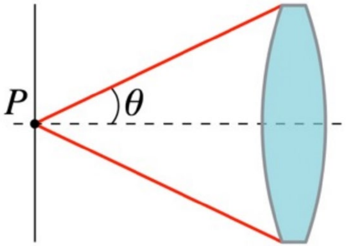
Ernst Abbe 1873:

f-number

$$d = \frac{\lambda}{2n\sin\theta} = \frac{\lambda}{2NA} \approx \lambda N$$

numerical aperture

spot radius (image space)



- Microscope objectives today: NA 1.4-1.6 à d=λ/2.8
- Small f-number (large NA) = high resolution but shallow depth of field
  - inherent tradeoff between “3D” information and 2D resolution
  - space-bandwidth product (uncertainty principle)

Tips for Photography

Tips: Photographer's Mindset

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From Canon EF Lens Work III

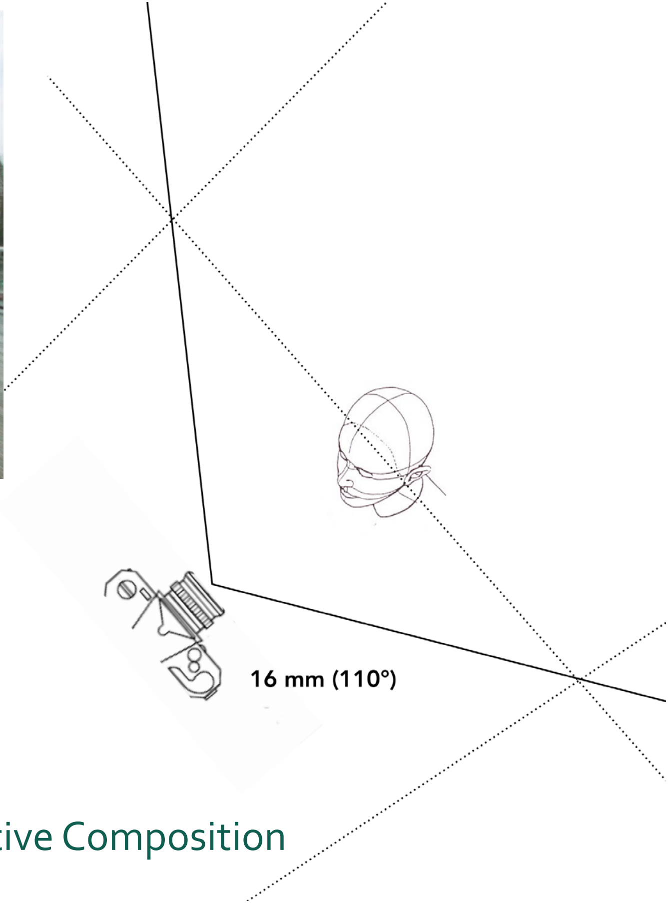
In this sequence,
distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

Perspective Composition – Camera Position / Focal Length

Tips: Photographer's Mindset

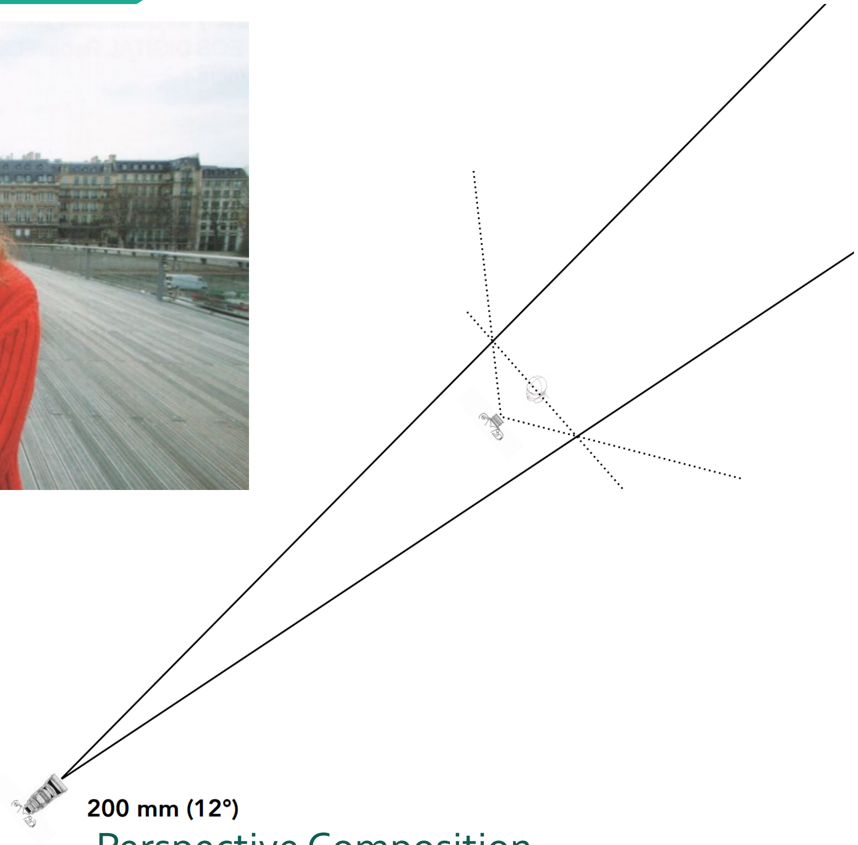
Up close and zoomed wide
with short focal length



Perspective Composition

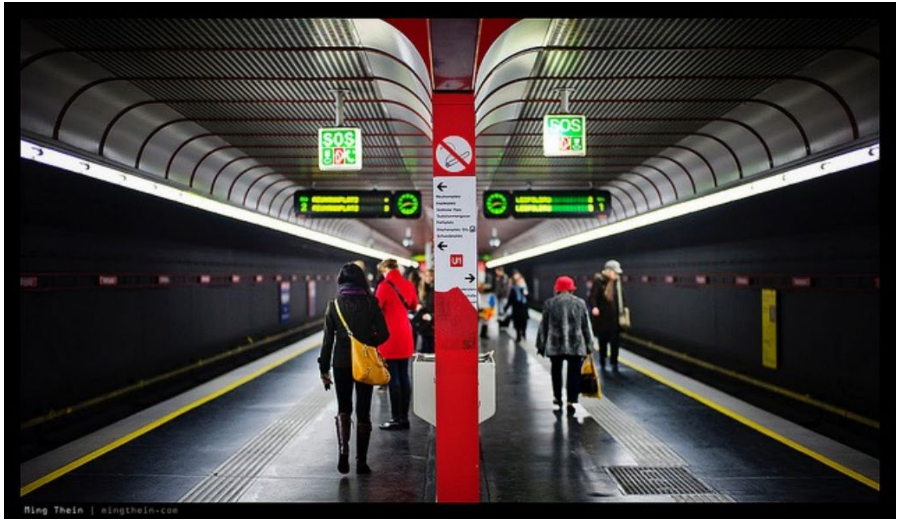
Tips: Photographer's Mindset

Walk back and zoom in
with long focal length



Perspective Composition

Tips: Photographer's Mindset



"Choose your perspective before you choose your lens."

— Ming Thein, mingthein.com

Perspective Composition

Tips: 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

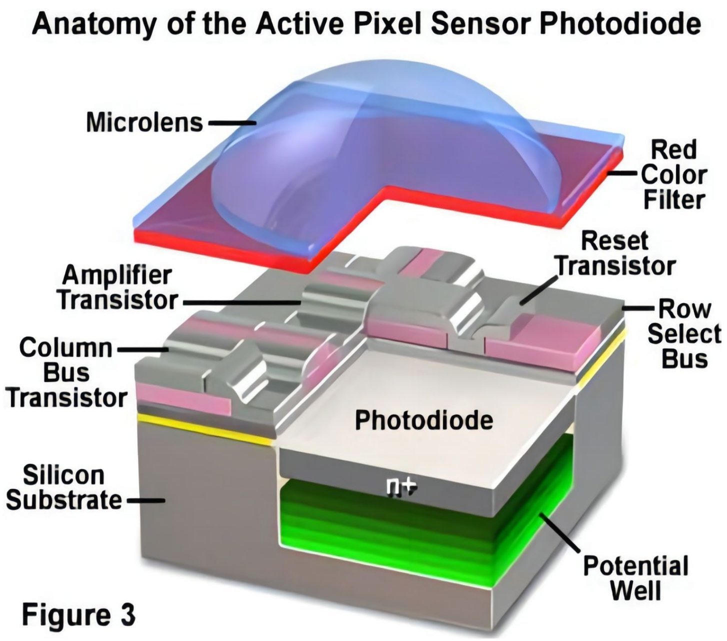
Tip 3: Change the zoom and camera distance to your subject

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

Tips: Dolly Zoom

Sensors

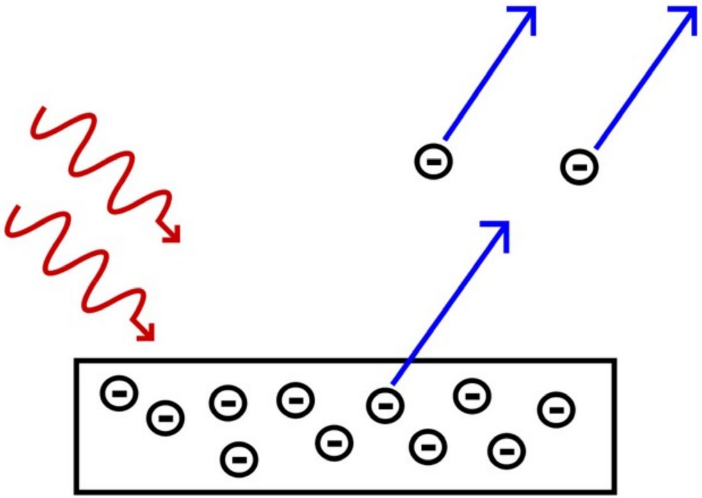
Sensors: What's a Pixel?



www.olympus-lifescience.com

photon to electron converter

photoelectric effect!



wikipedia

Sensors: What's a Pixel?

Anatomy of the Active Pixel Sensor Photodiode

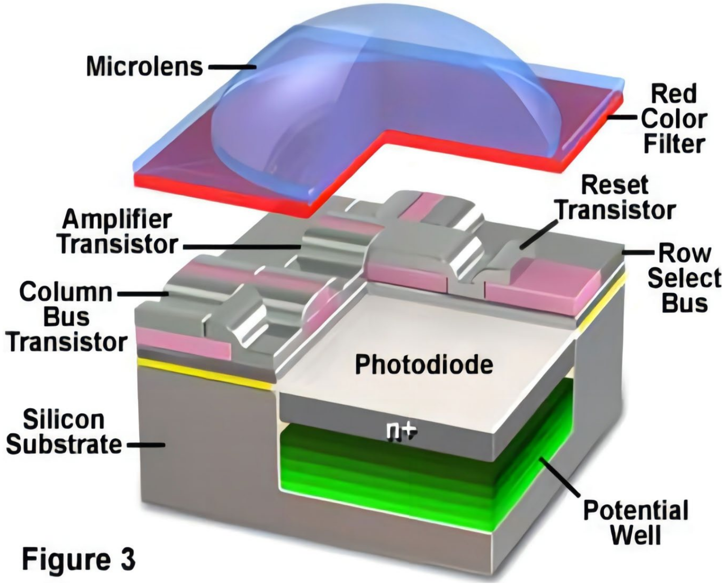


Figure 3

www.olympus-lifescience.com

- Microlens: focus light on photodiode
- Color filter: select color channel
- Quantum efficiency: ~50%
- Fill factor: fraction of surface area used for light gathering

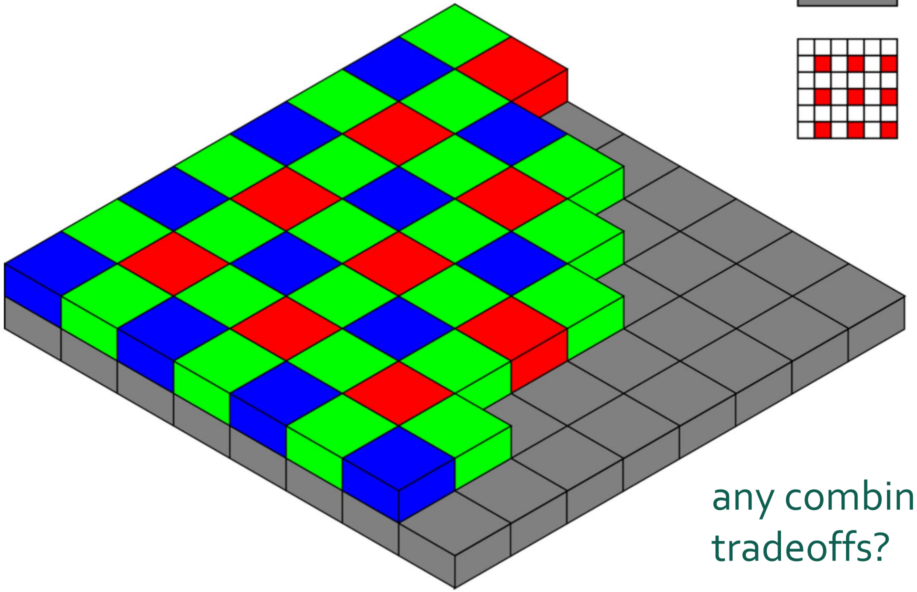
Sensors: What's a Pixel?

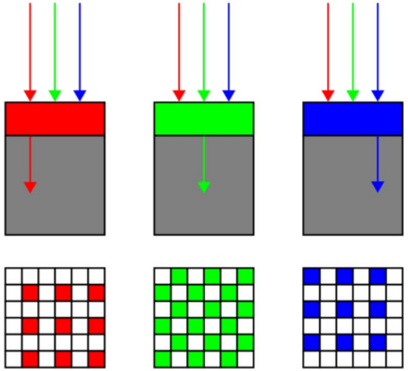
Sensors: What's a Pixel?

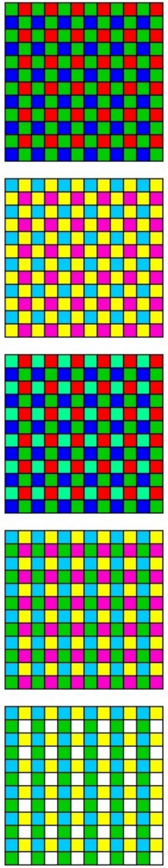
Sensors: What's a Pixel?

Sensors: Color Filter Arrays

Bayer pattern







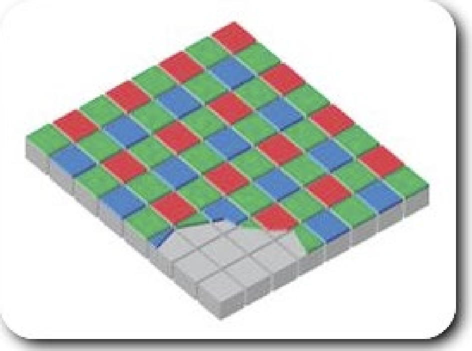
any combination possible
tradeoffs?

wikipedia

Sensors: Color Filter Arrays

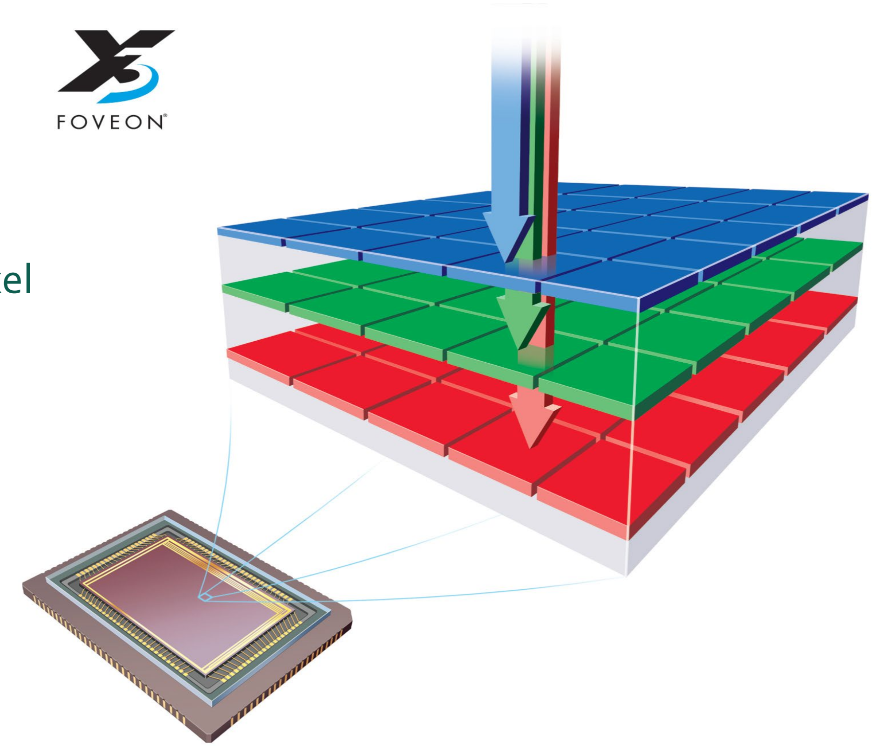
Approach

- Pixels are covered by color filters
- Twice as many green pixels as red or blue ones
  - Interpreted as "intensity"
- Missing color values are interpolated for every pixel
  - More in later lecture
- Note: camera specs report the total number of pixels in a sensor
  - I.e a image recorded by a 1-chip camera only consists of 1/3 measured values, 2/3 are interpolated



Sensors: “Direct Imaging Sensor”

FOVEON



Approach

- Layered RGB sensors
- All channels actually measure for every pixel

But

- Currently lower resolution
- Reportedly problems with color quality

Sensors

Common Semiconductor sensors used in cameras:

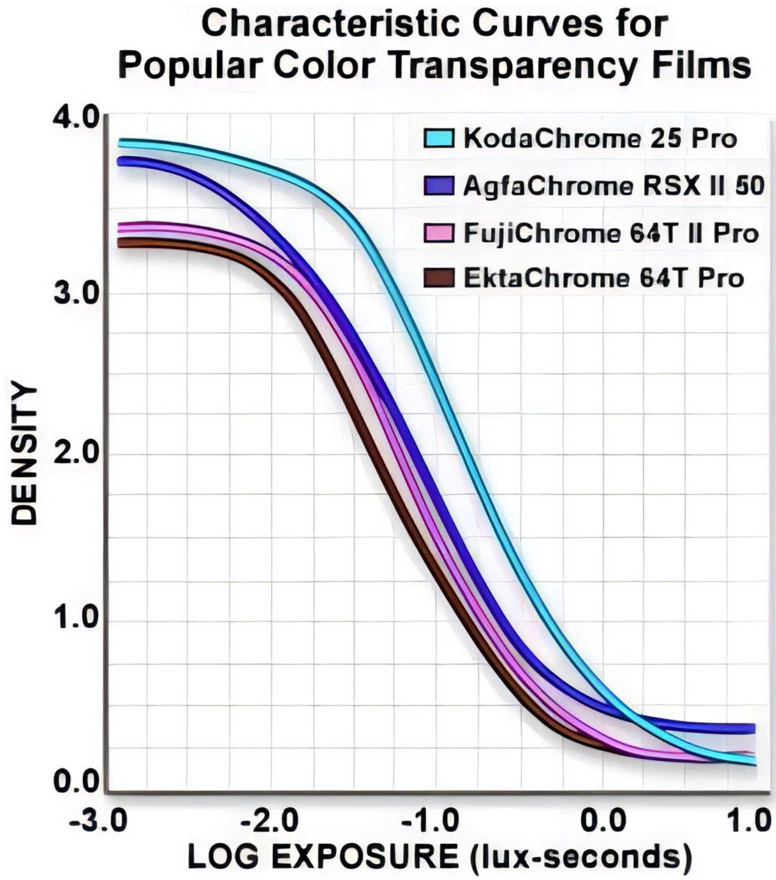
- Charge Coupled Devices (CCD)
- Complementary Metal-Oxide-Semiconductor (CMOS)
- Foveon

Others

- Charge Injection Devices (CID)
- Photomultipliers
- Cathode Ray Tubes (CRT)
- Single Photon Avalance Diode Array(SPAD)
- Quanta Image Sensor (QIS)
- Two-bucket Sensor
- Photonic Mixer Device (PMD)
- ...

Analog Film

- Highly non-linear response:
  - Here shown for slide film
- Terminology:
  - Transmittance T: portion of light transmitted (0…1)
  - Density: log(1/T)
  - Contrast: ratio between max. and min. discernible intensity
- Example:
  - Transmittance 0.001
  - Density: 3
- Contrast of film:
  - 1,000:1 or more



Semiconductor Light Sensors -Photoconductivity

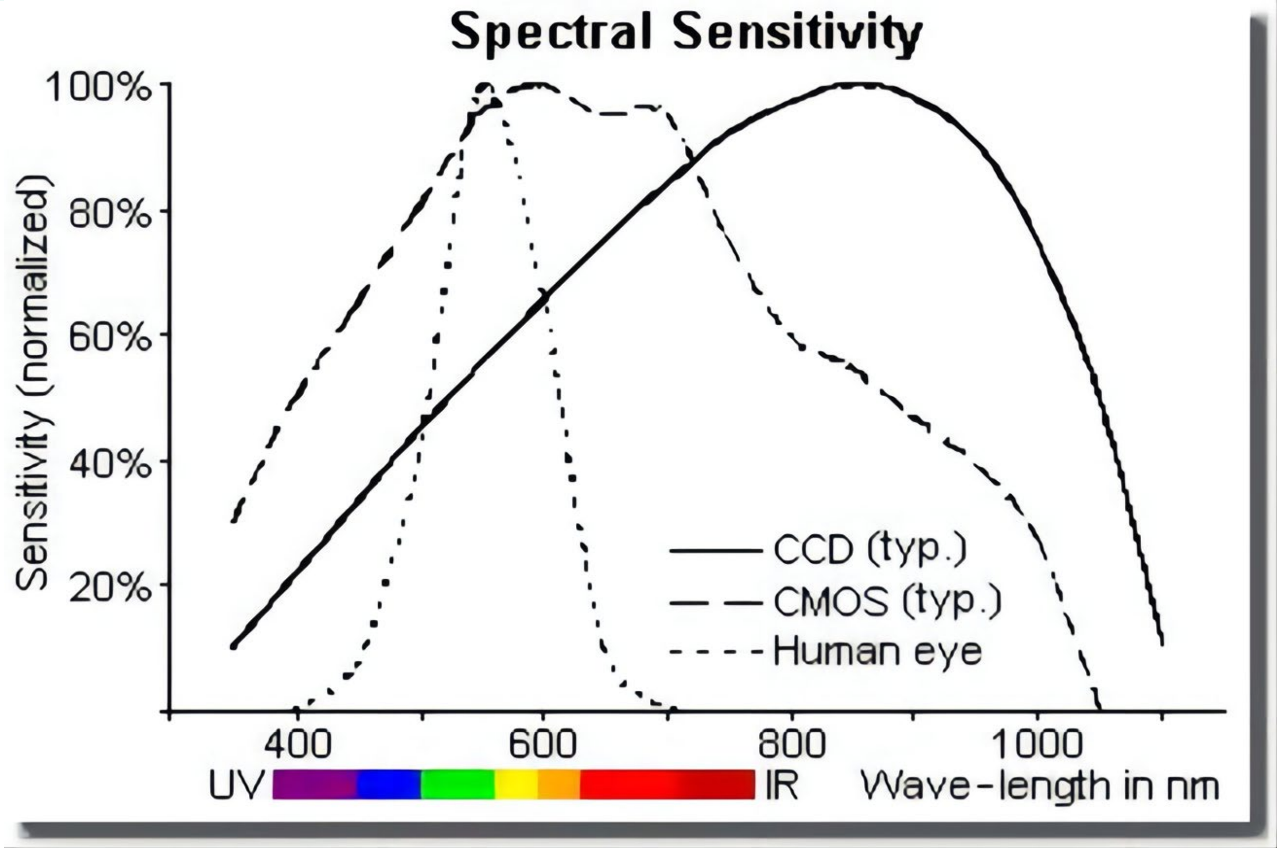
Principle:

- A photon entering a semiconductor material collides with an atom
- Through the collision, an electron is moved from the valence band to the conductance band
    - The electron leaves behind a positively charged "hole"
    - Electrons in the conductance band can move freely about the material, and can hence be measured as a charge

Basic Properties:

- Response is linear
    - Every photon interacting with an atom generates a single electron
- Quantum efficiency is high
    - Percentage of photons generating electrons is about 85% for blue and green in consumer products

Spectral Sensitivity

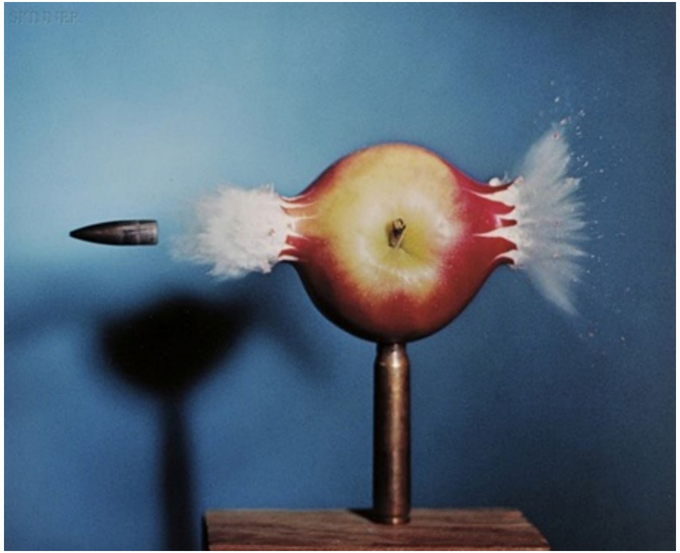


CCD: High Sensivity for infrared

Exposure

High-Speed Photography

- Short exposure
- Bright strobe illumination
- Gun synced to camera

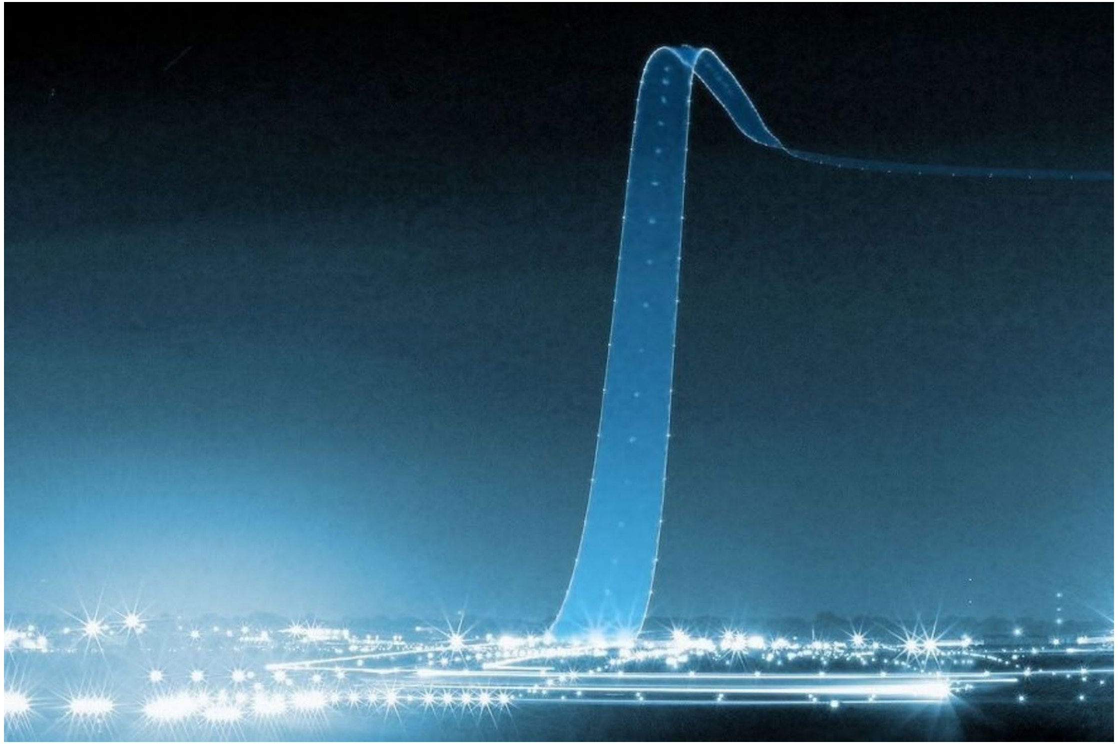


Harold Edgerton

Mark Watson

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

Long-Exposure Photography



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

Exposure (shutter speed)

- Q = T x E
- Exposure = time x irradiance (e.g. 1/250, 1/60, 1, 15, bulb)
- 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

¼ sec, f/3.3

2 sec, f/6.3,

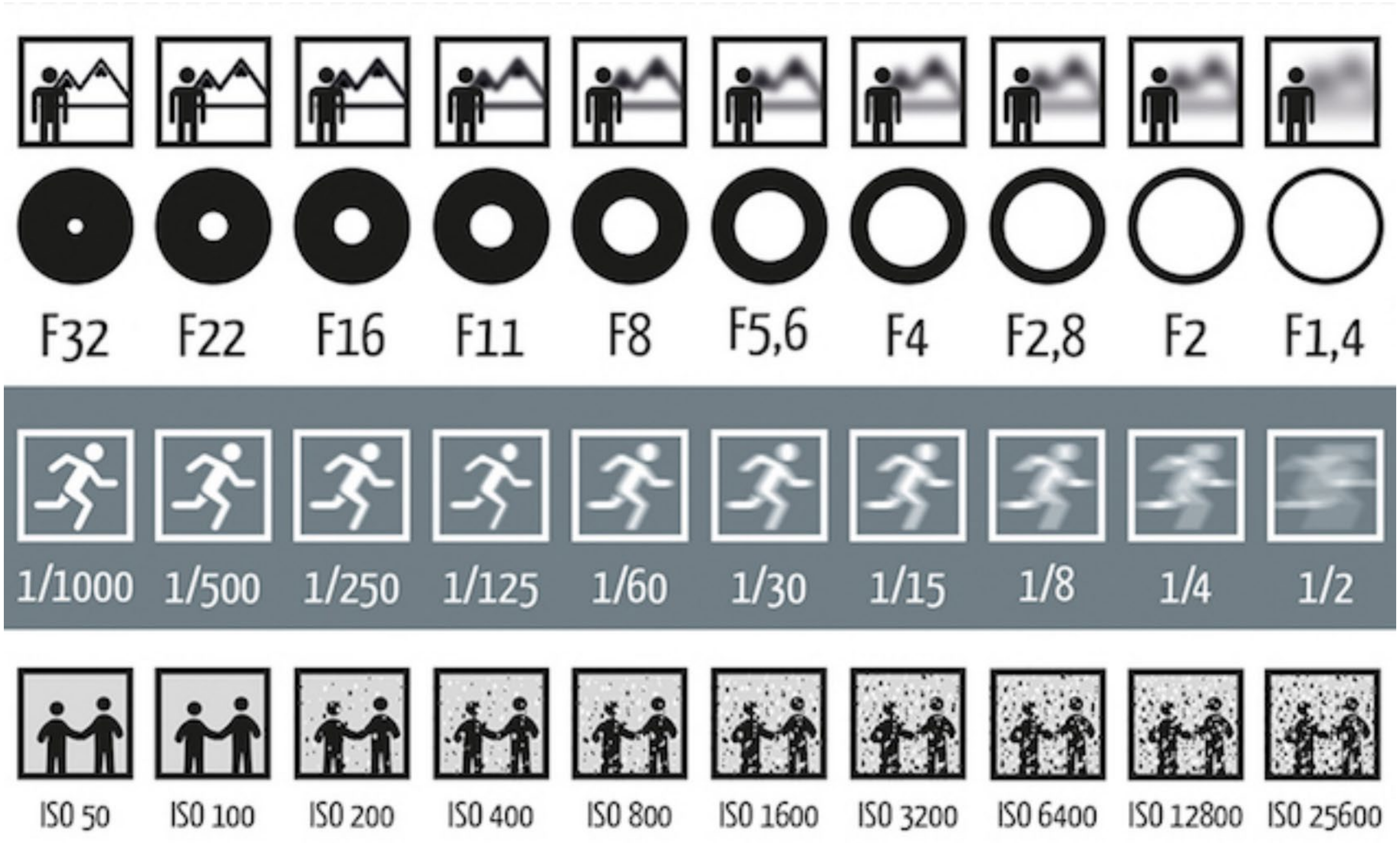
wikipedia

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, “film speed”))

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

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The Chinese University of Hong Kong, Shenzhen

sensor

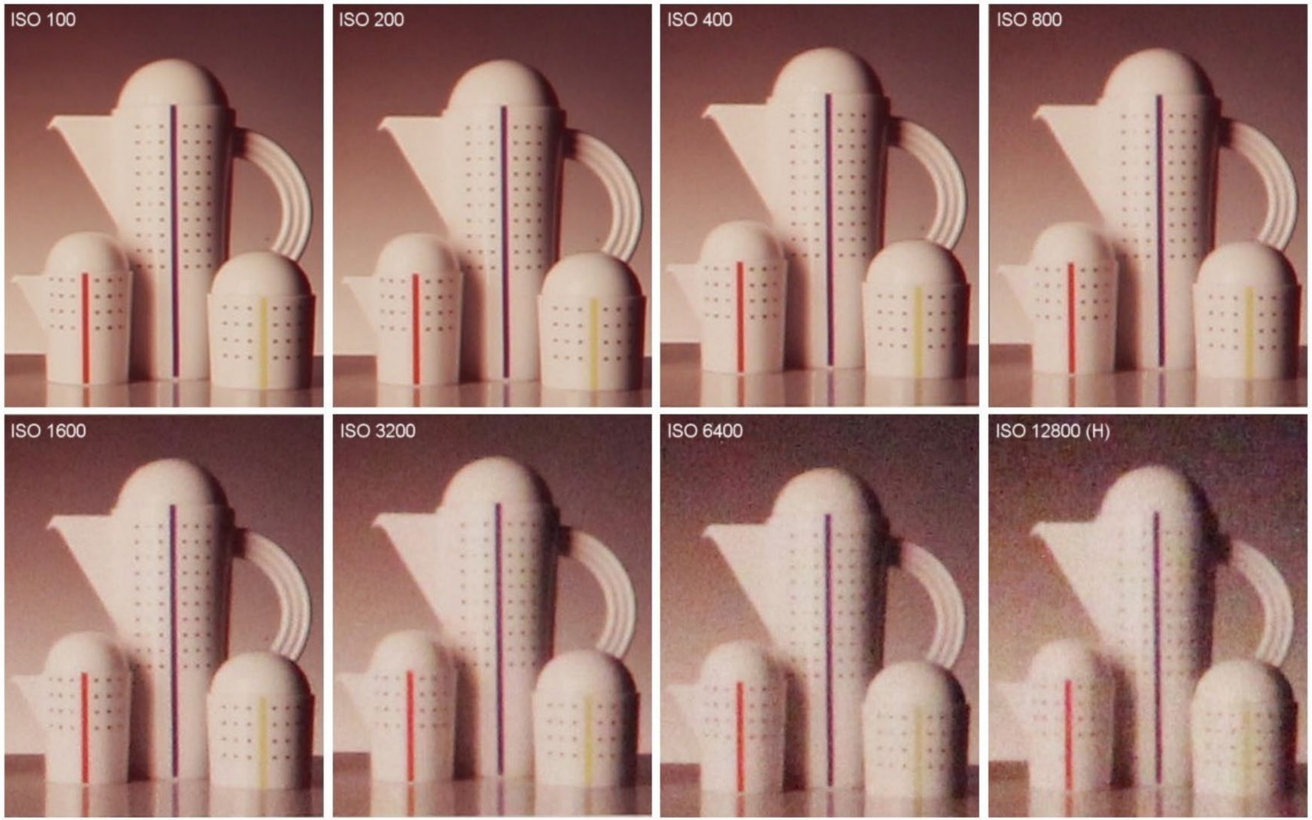
sensitivity

–

analog gain

applied before

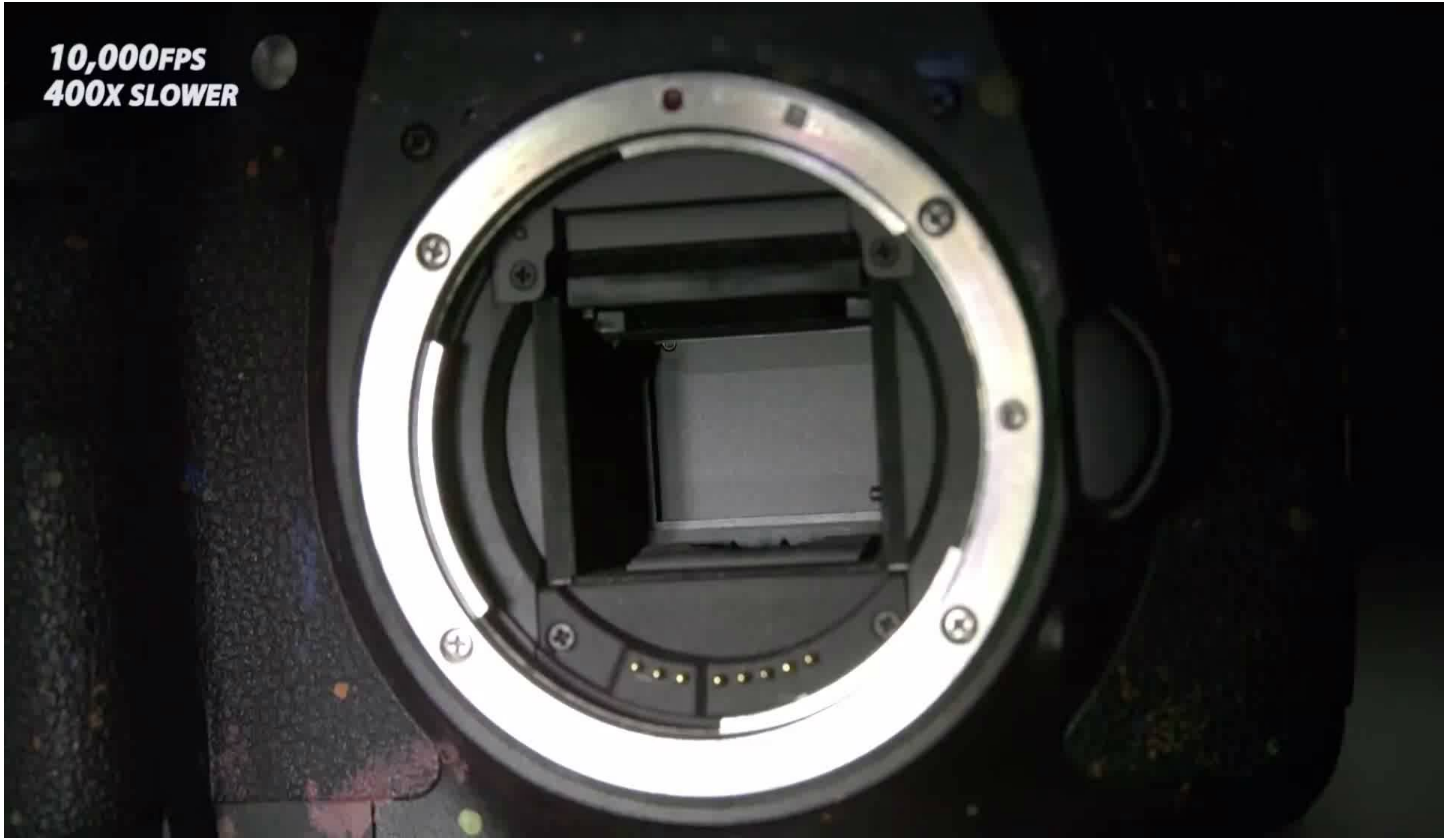
ADC!



bobatkins.com

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

Shutters: Physical



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

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

Main Side Effect of Shutter Speed

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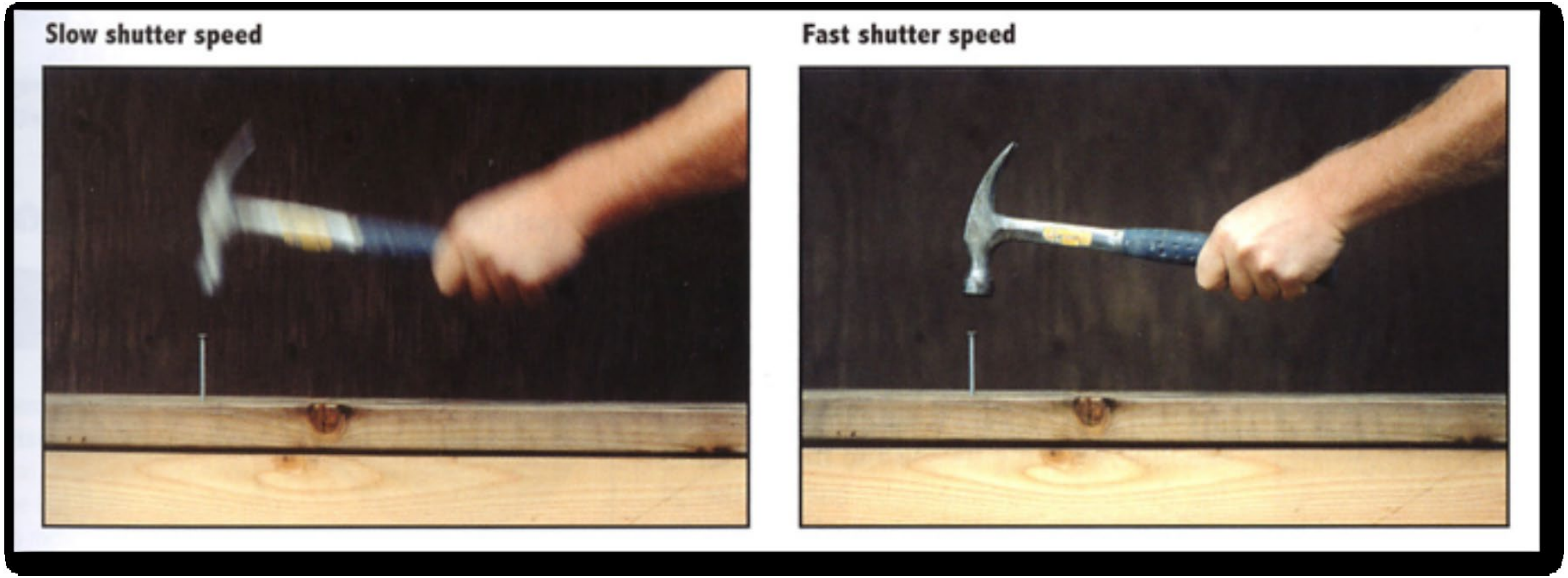
Doubling shutter time doubles motion blur



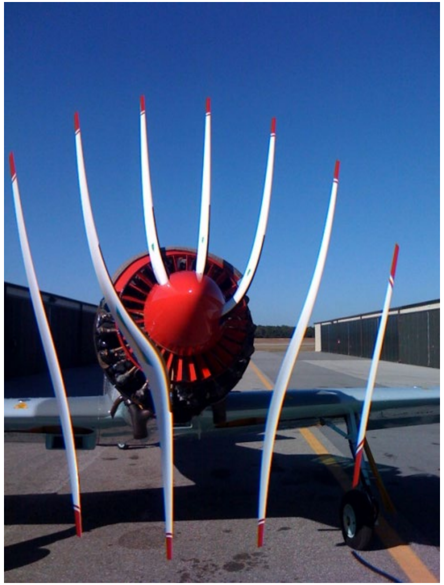
London

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

Credit: David Adler, B&H Photo Video
https://www.bhphotovideo.com/explora/video/tips-and-solutions/rolling-shutter-versus-global-shutter



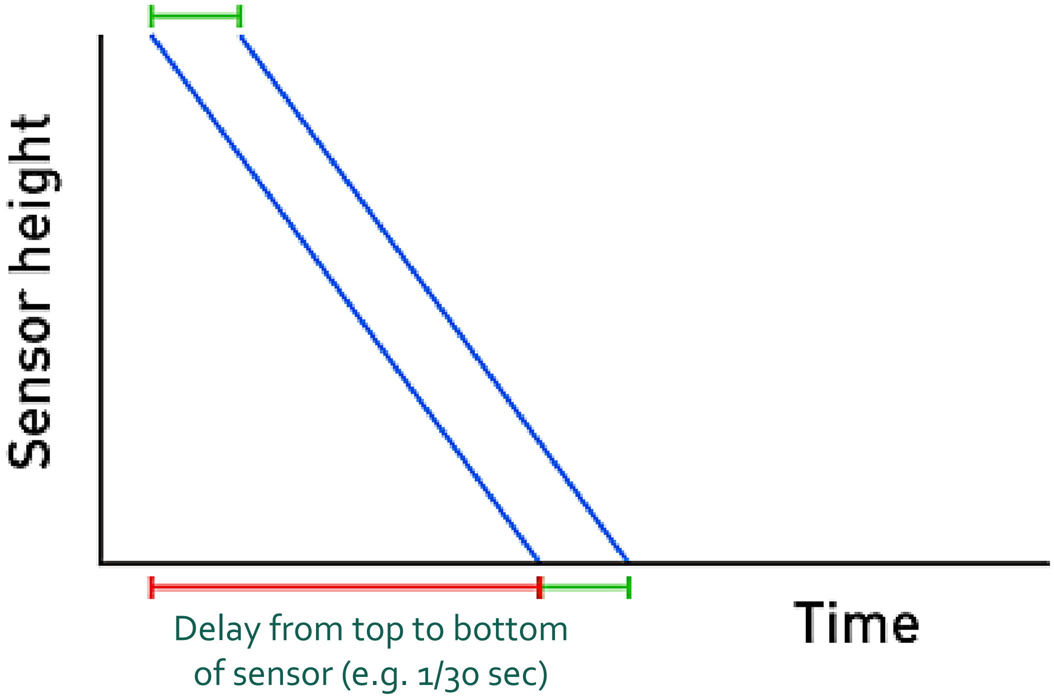
Credit: Soren Ragsdale
https://flic.kr/p/5S6rKw

Electronic Rolling Shutter

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

Electronic Rolling Shutter

香港中文大學（深圳）
The Chinese University of Hong Kong, Shenzhen



dpreview.com

Global Shutter vs. Rolling Shutter

All sensor pixels exposed at same time

Row-by-row readout of image

- shorter exposure times per pixel
- motion artifacts

http://lfa.mobivap.uva.es/~fradelg/phd/notes/global-shutter.html

Exposure Tradeoffs: Depth of Field vs Motion Blur

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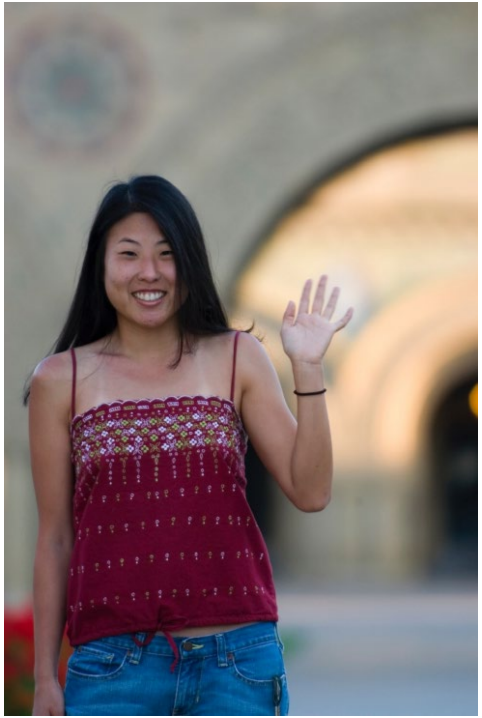


f / 4
1/125 sec

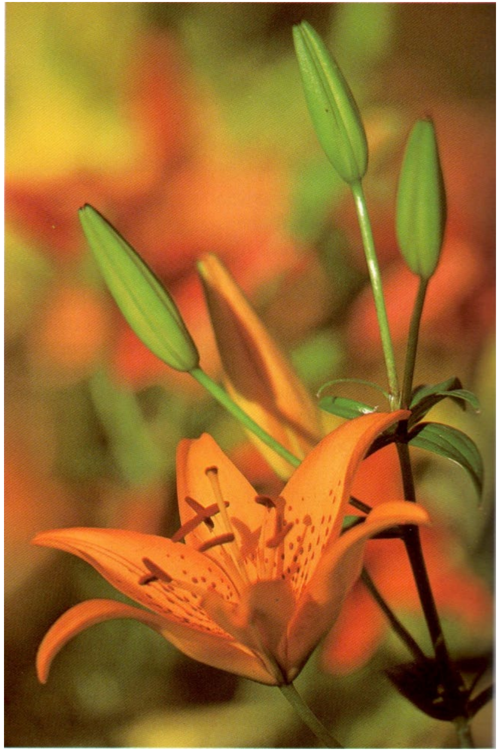
f / 11
1/15 sec

f / 32
1/2 sec

Photographers must trade off depth of field and motion blur for moving subjects

Exposure Tradeoffs: Depth of Field vs Motion Blur

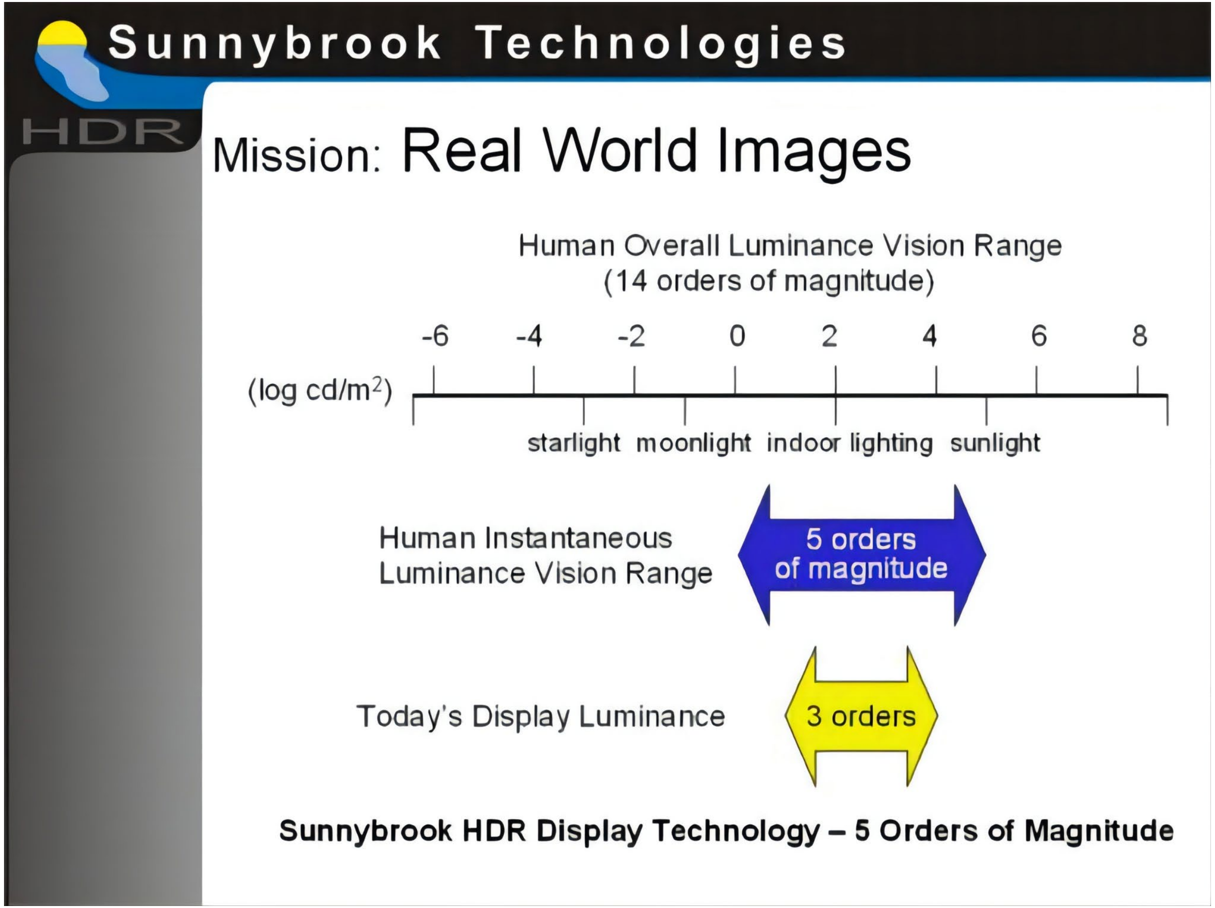
Shallow Depth of Field Can Create a Stronger Image



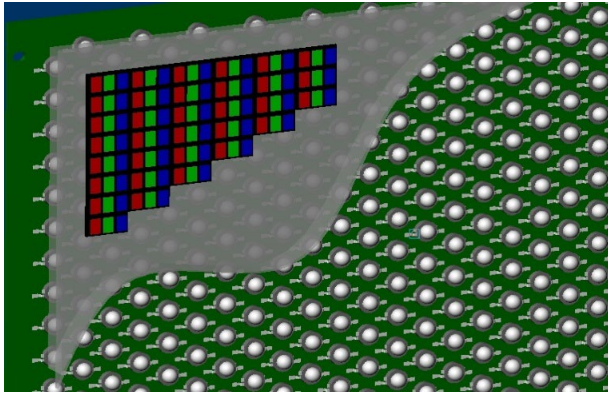
From Peterson, Understanding Exposure

200mm, f/4, 1/1000 (left) and f/11, 1/125 (right)

Dynamic Range



High Dynamic Range Displays



Low Resolution LED Array

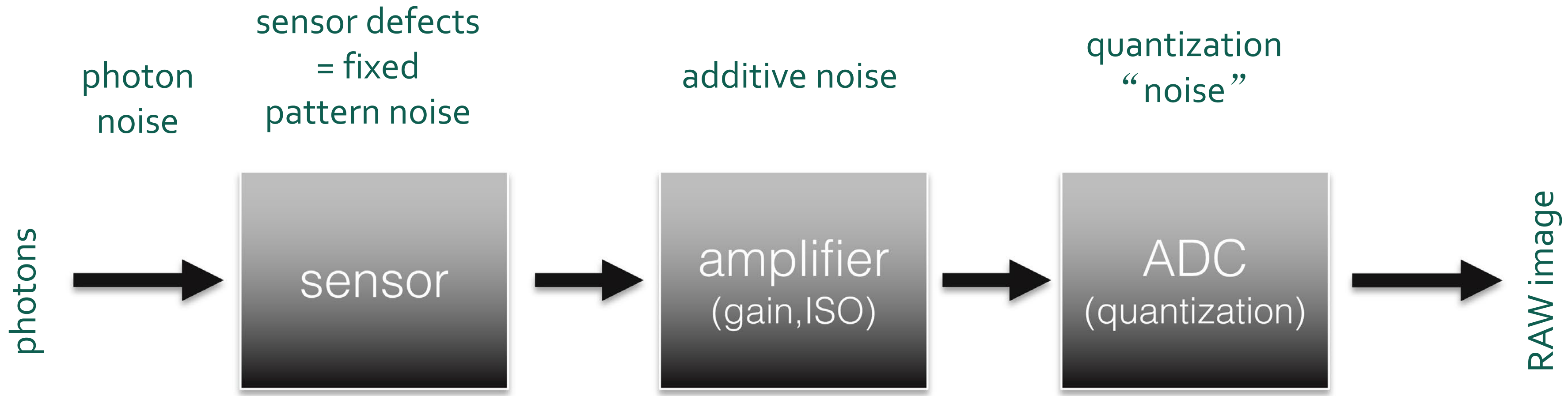
- About 1000-2000 LEDs

- Conventional LCD

- Diffusion aOptics

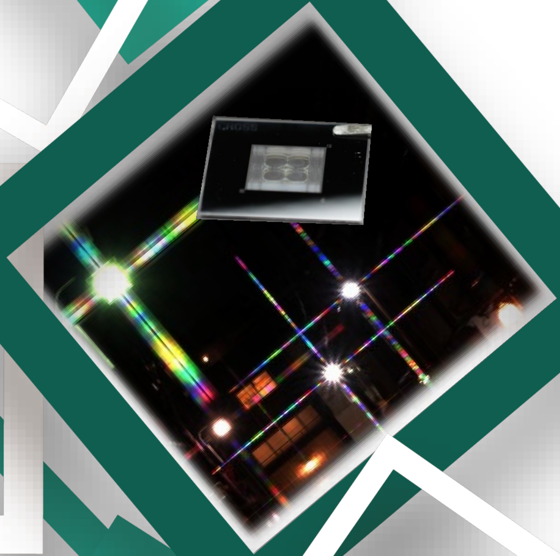
Wolfgang Heidrich [BrightSite Technology]

Photons to RAW Image



Today's Topic

- Lens
  - Aperture
  - Depth of Field
  - Field of View
  - Diffraction Limit
- Tips for Photography
- Sensors
  - Pixels and CFA
  - Exposure and ISO
  - Dynamic Range



Thank You!

Qilin Sun（孙启霖）

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