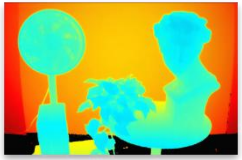


GAMES 204

Computational Imaging

Lecture 04： Cameras

Qilin Sun（孙启霖）

香港中文大学（深圳）

点昀技术（Point Spread Technology）

Todays Topic

- Introduction
- Imaging Optics
- Aperture
- Depth of Field
- Field of View
- Tips for Photography
- Diffraction Limit
- Sensors
- Noise Introduction
- Exposure
- Dynamic Range

Slide credits

Many of these slides were adapted from:

Wolfgang Heidrich(KAUST)

Ren Ng(Uc Bakery)

Kris Kitani, Ioannis Gkioulekas (15-463, 15-663, 15-862).

Fredo Durand (MIT).

Marc Leovy, Gordon Wetzstein (Stanford).

CS559-Computer Graphics

Introduction

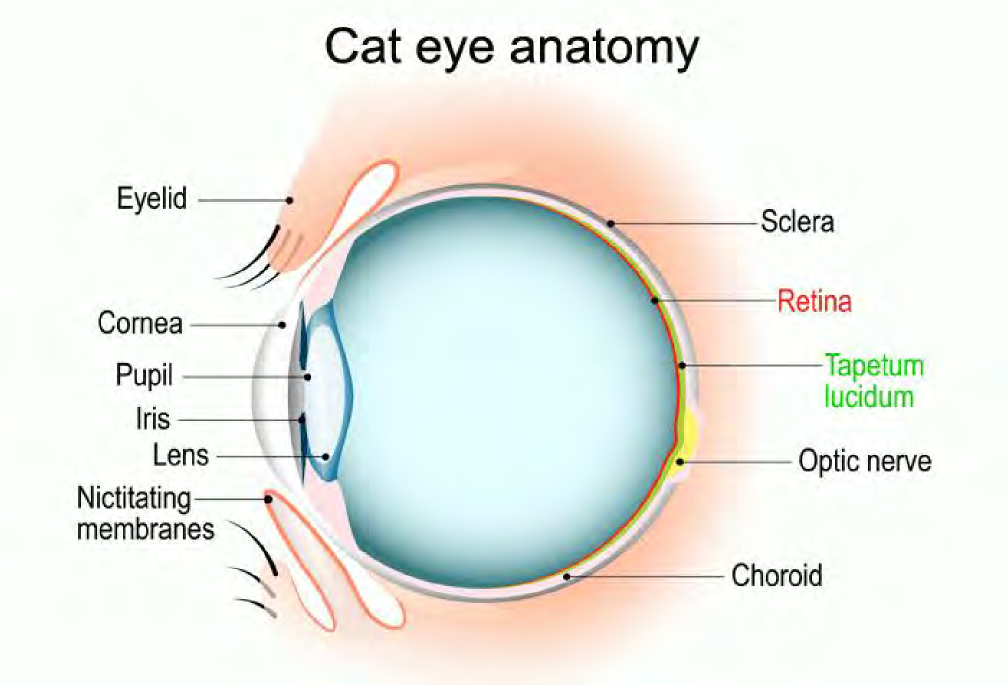
Introduction

nautilus eye
wikipedia

Introduction

https://www.dailypaws.com/cats-kittens/behavior/common-cat-behaviors/why-do-cats-eyes-glow-in-the-dark

Why Do Cats' Eyes Glow in the Dark?



The dark blue, teal, and gold tapetum lucidum from the eye of a cow

https://encyclopaediafelidae.com/through-cat-eyes/

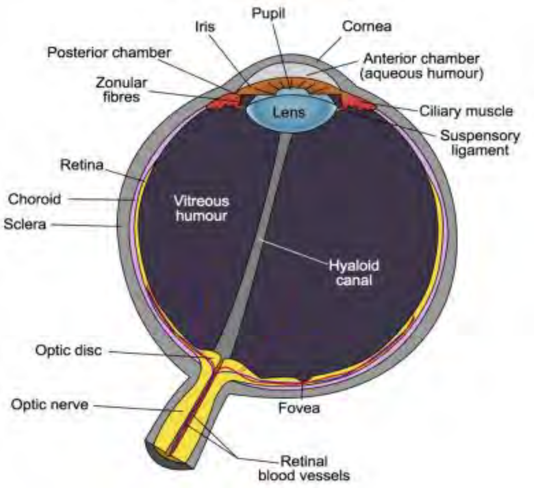
Compound Eye

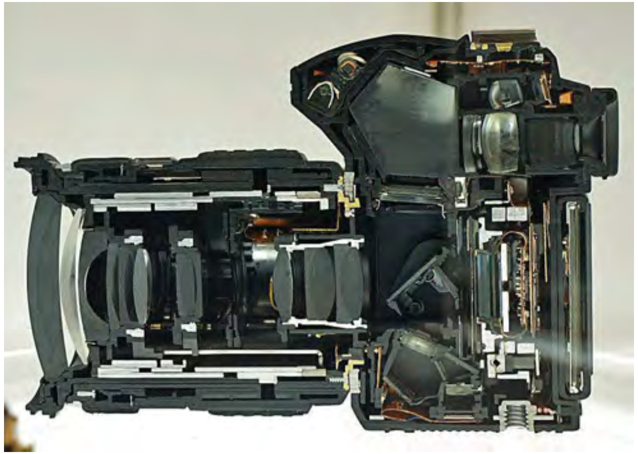
National Geographic

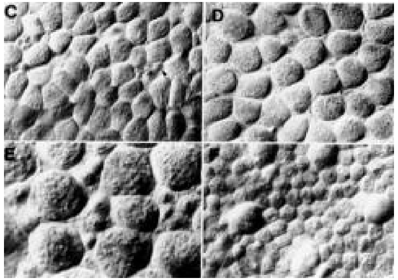
Human Visual System

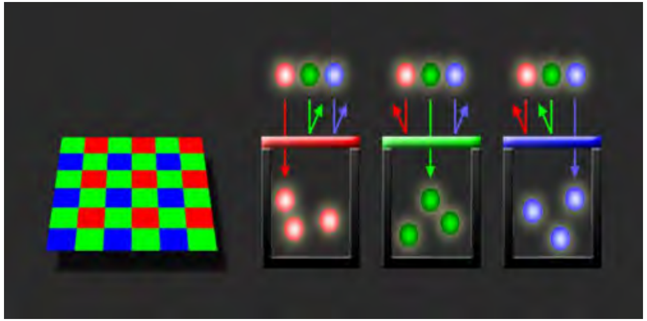
- Visual acuity: 20/20 is ~1 arc min
- Field of view: ~190° monocular, ~120° binocular, ~135° vertical
- Temporal resolution: ~60 Hz (depends on contrast, luminance)
- Dynamic range: instantaneous 6.5 f-stops, adapt to 46.5 f-stops
- Color: everything in the CIE xy diagram; distances are linear in CIE Lab
- Depth cues in 3D displays: vergence, focus, conflicts, (dis)comfort
- Accommodation range: ~8cm to ∞, degrades with age

Eye vs Camera









[Williams 91]

RocketStock

Imaging Optics

Camera Optics: Lens

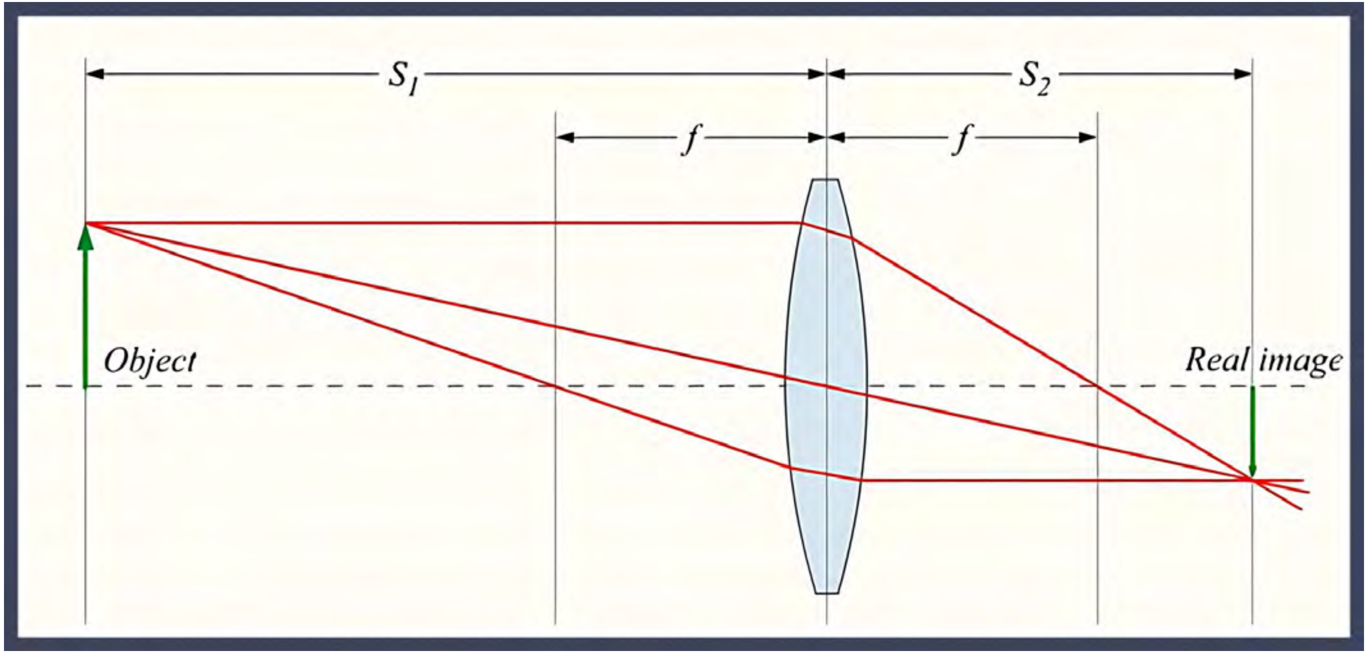
- Focus light
- Magnify objects

Nimrud lens - 2700 years old

Camera Optics: Lens

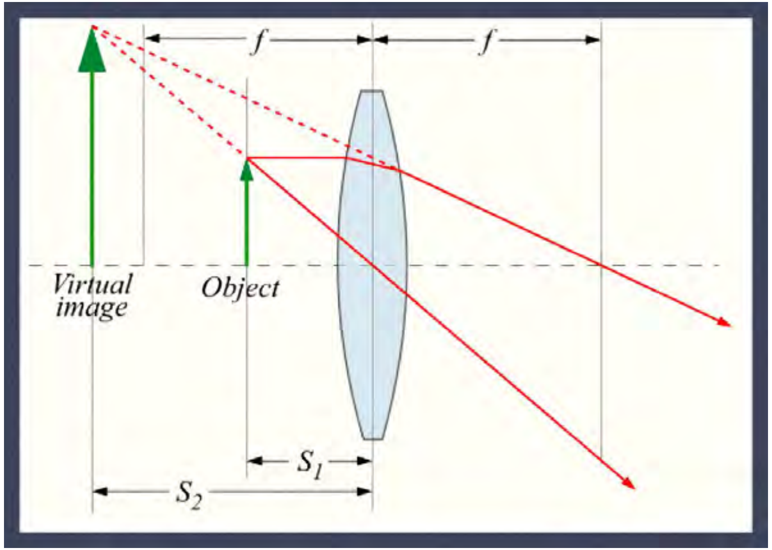
lensmaker's equation: $$\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2}$$

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

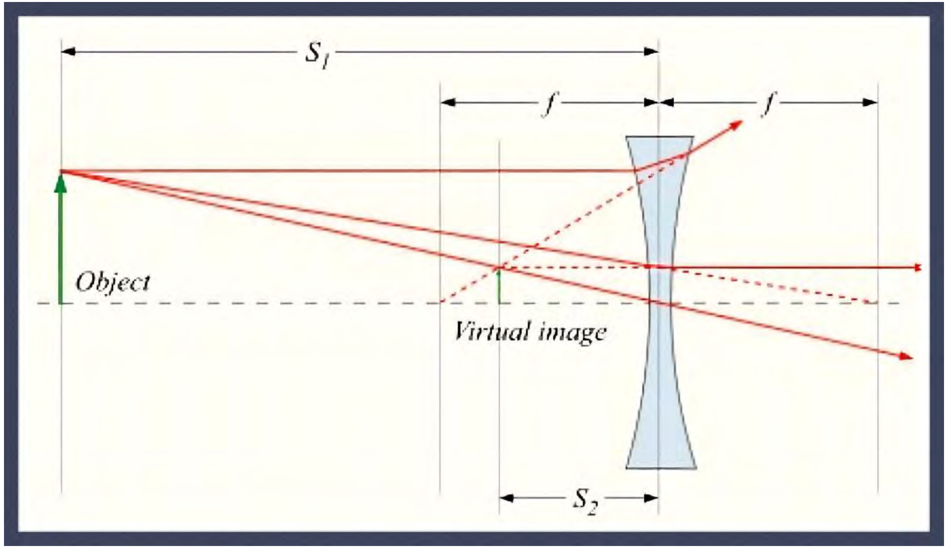


Camera Optics: Lens

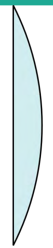
S1<f: magnifying glass



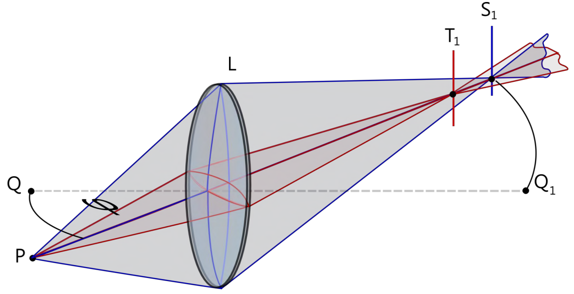
magnification



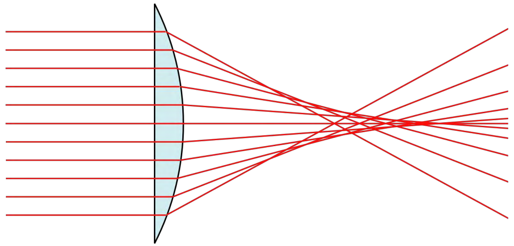
Camera Optics: Lens Aberrations



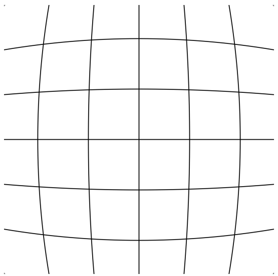
Ideal



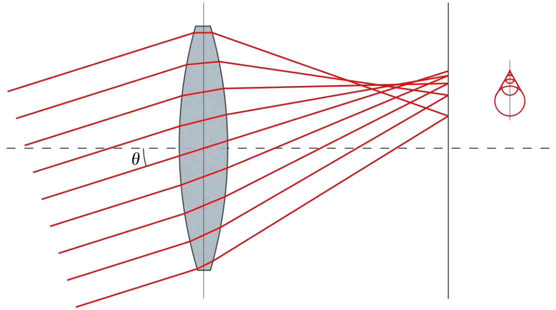
Astigmatism



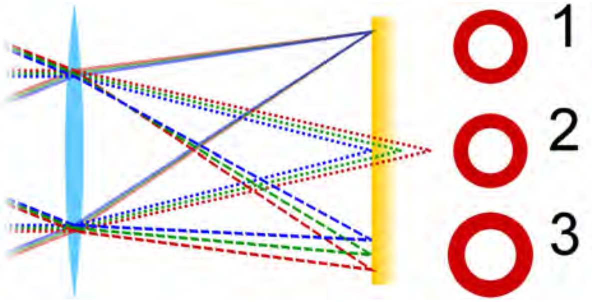
Seperical Abberation



Distortion



Coma



Chromatic Abberation

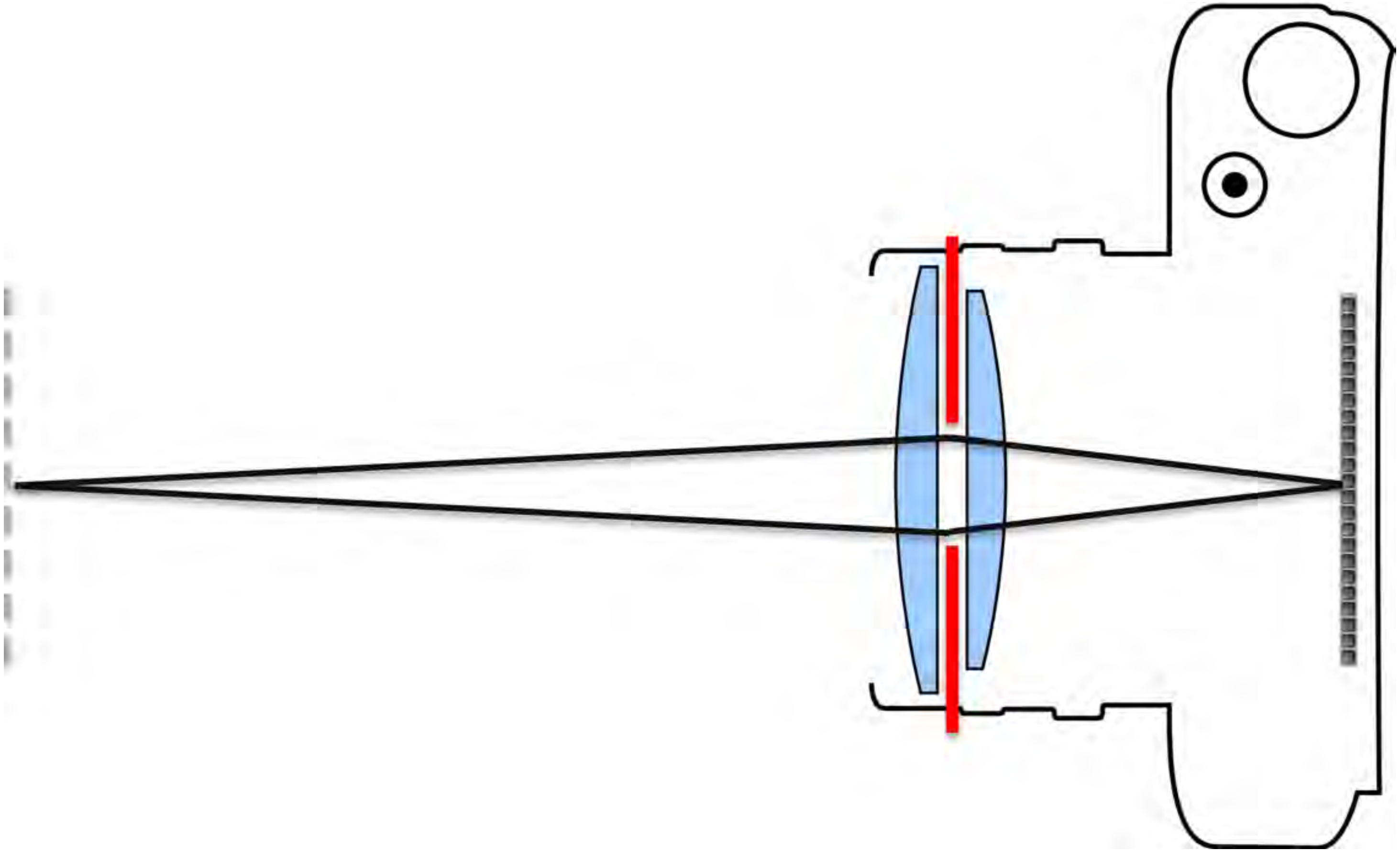
Camera Optics: Lens Aberrations

Sharp Image

Blurred Image due to optical aberrations

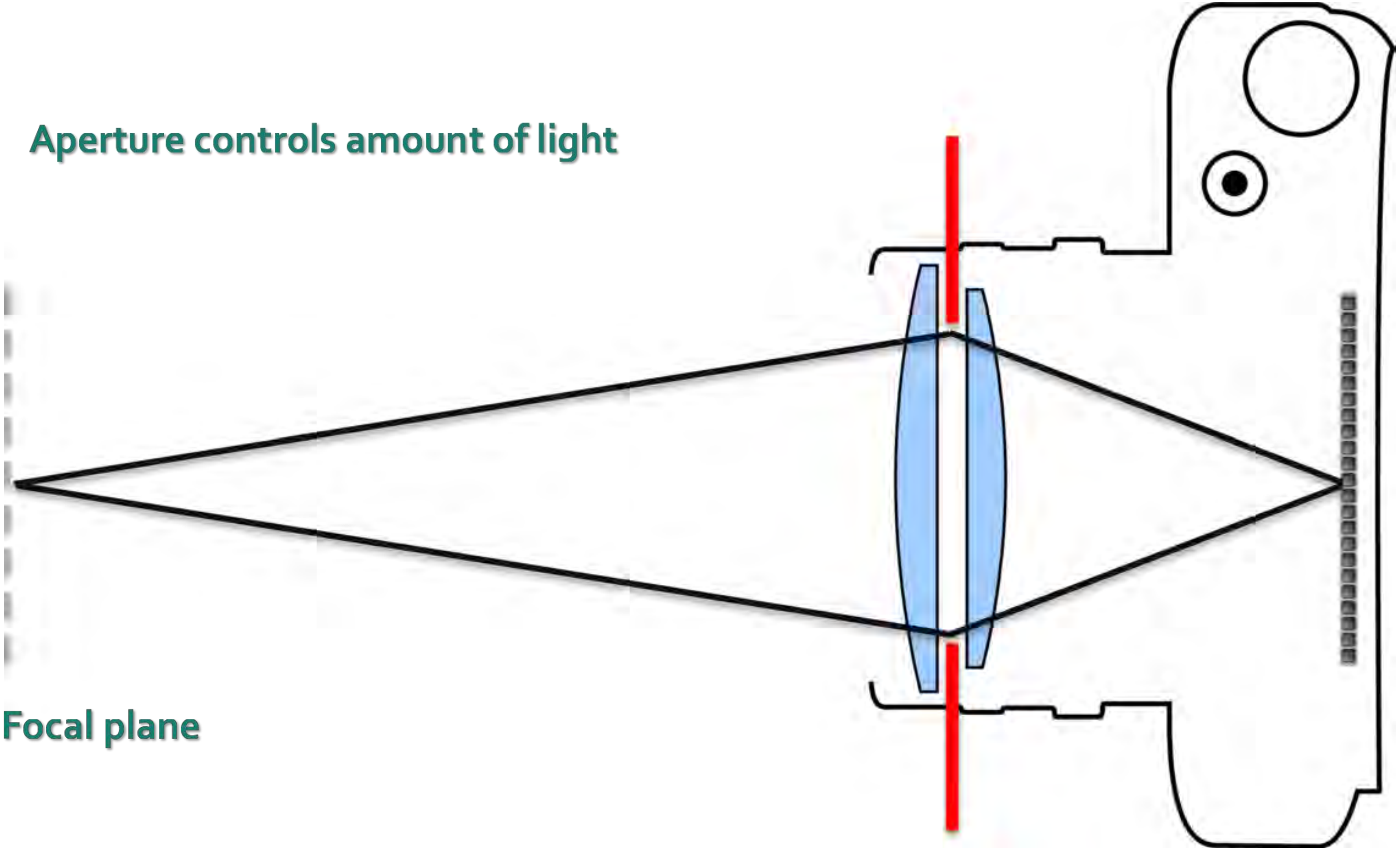
Aperture

Camera Aperture



Camera Aperture

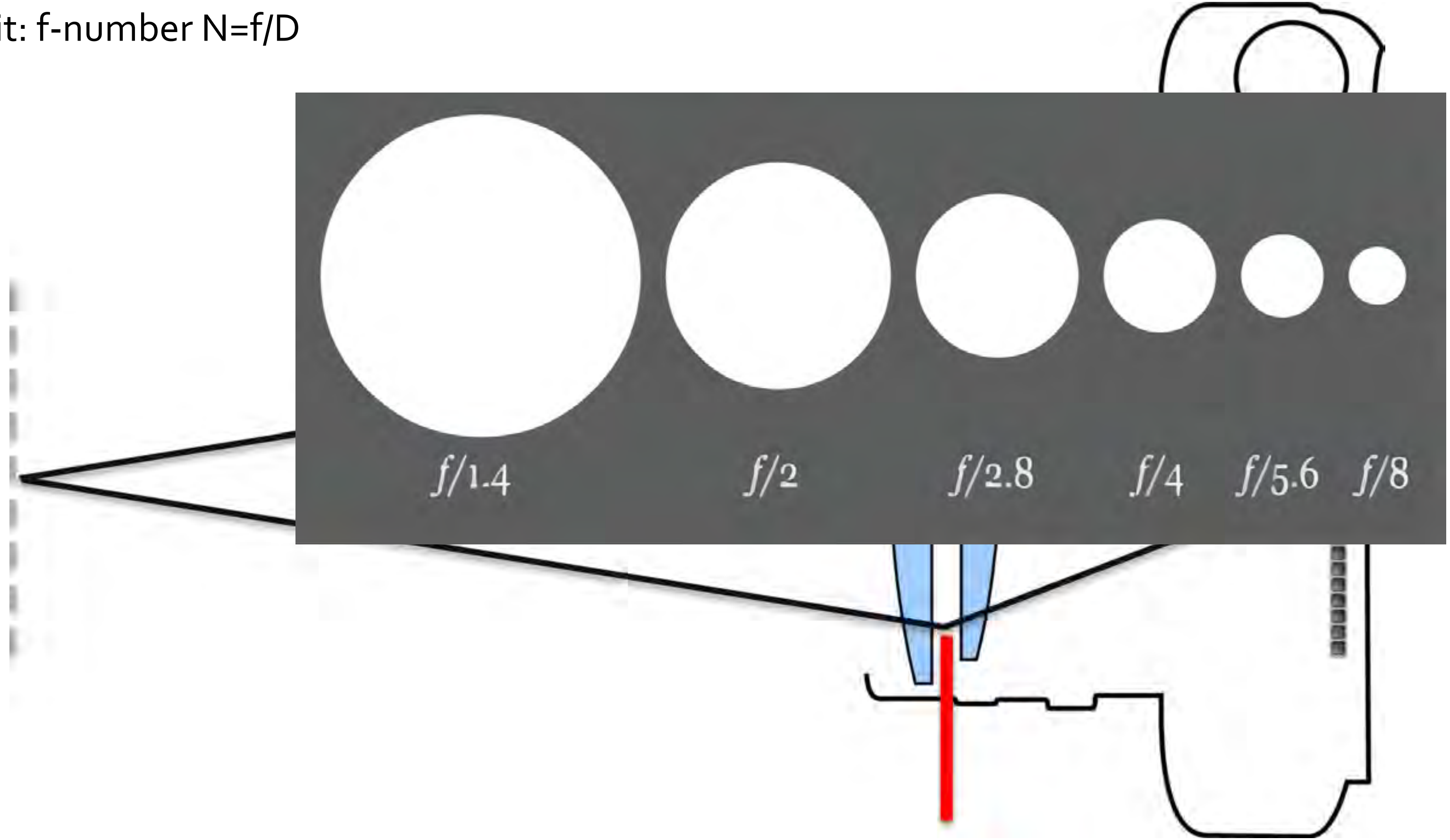
Aperture controls amount of light



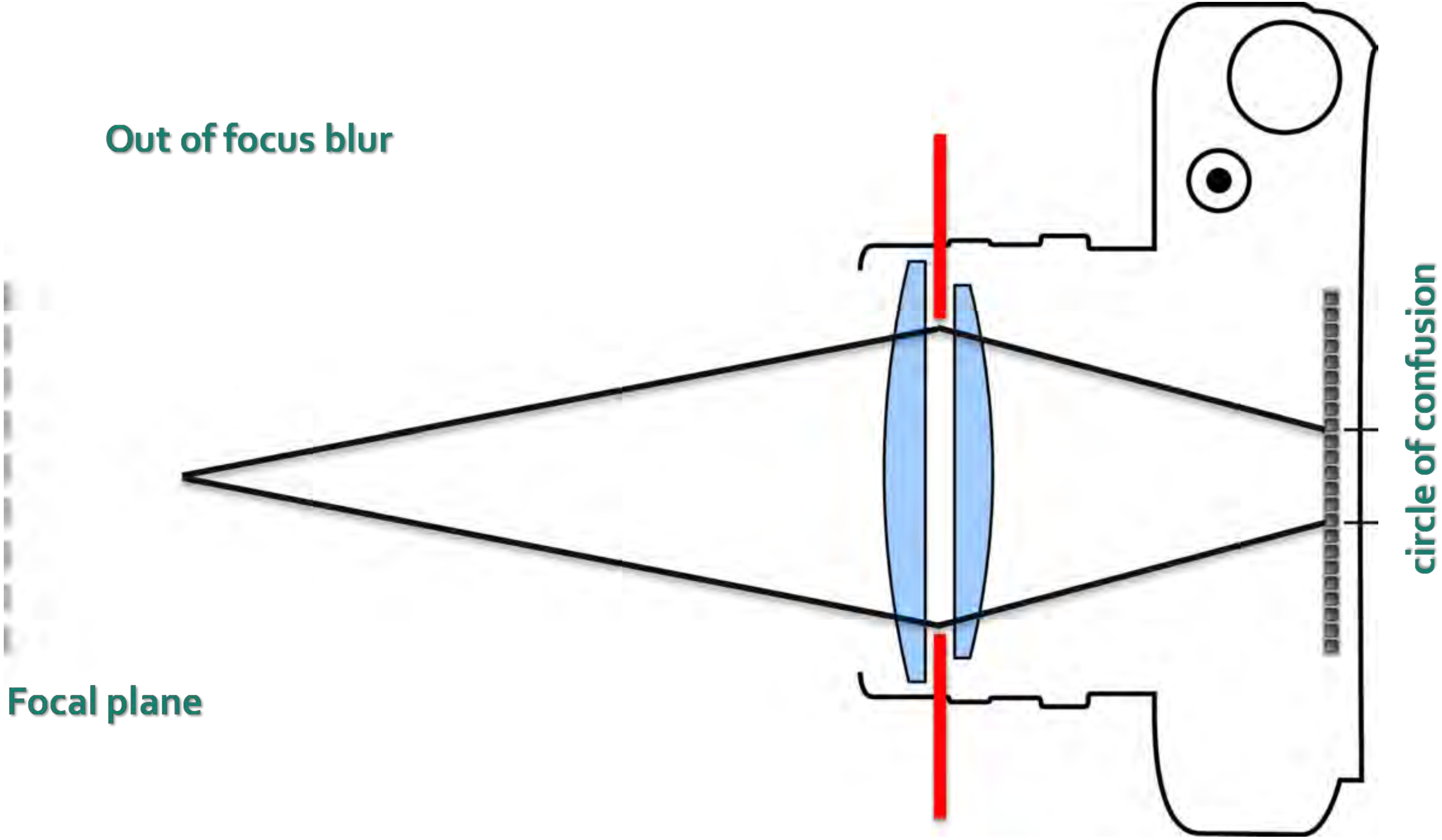
Focal plane

Camera Aperture

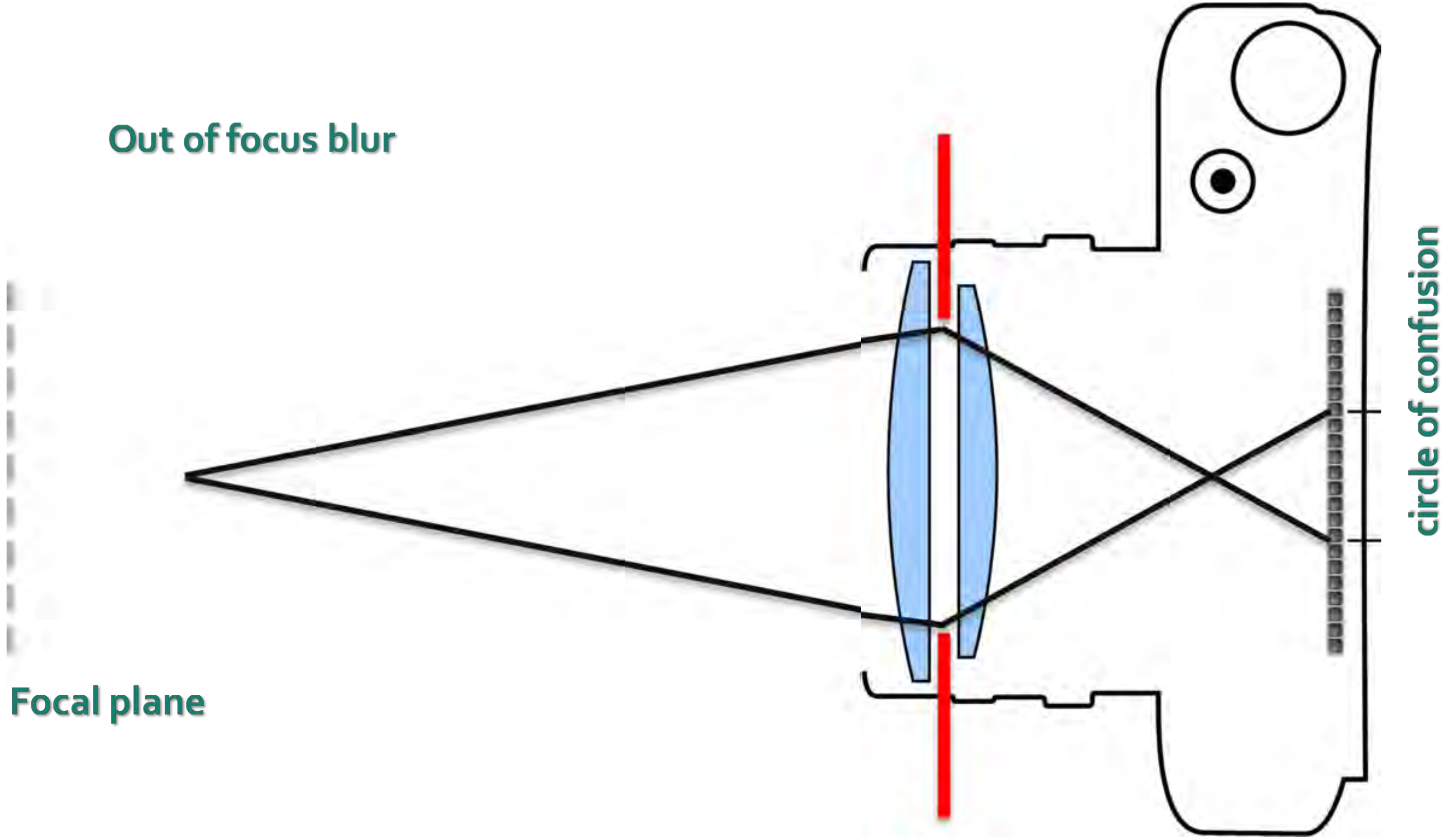
Unit: f-number N=f/D



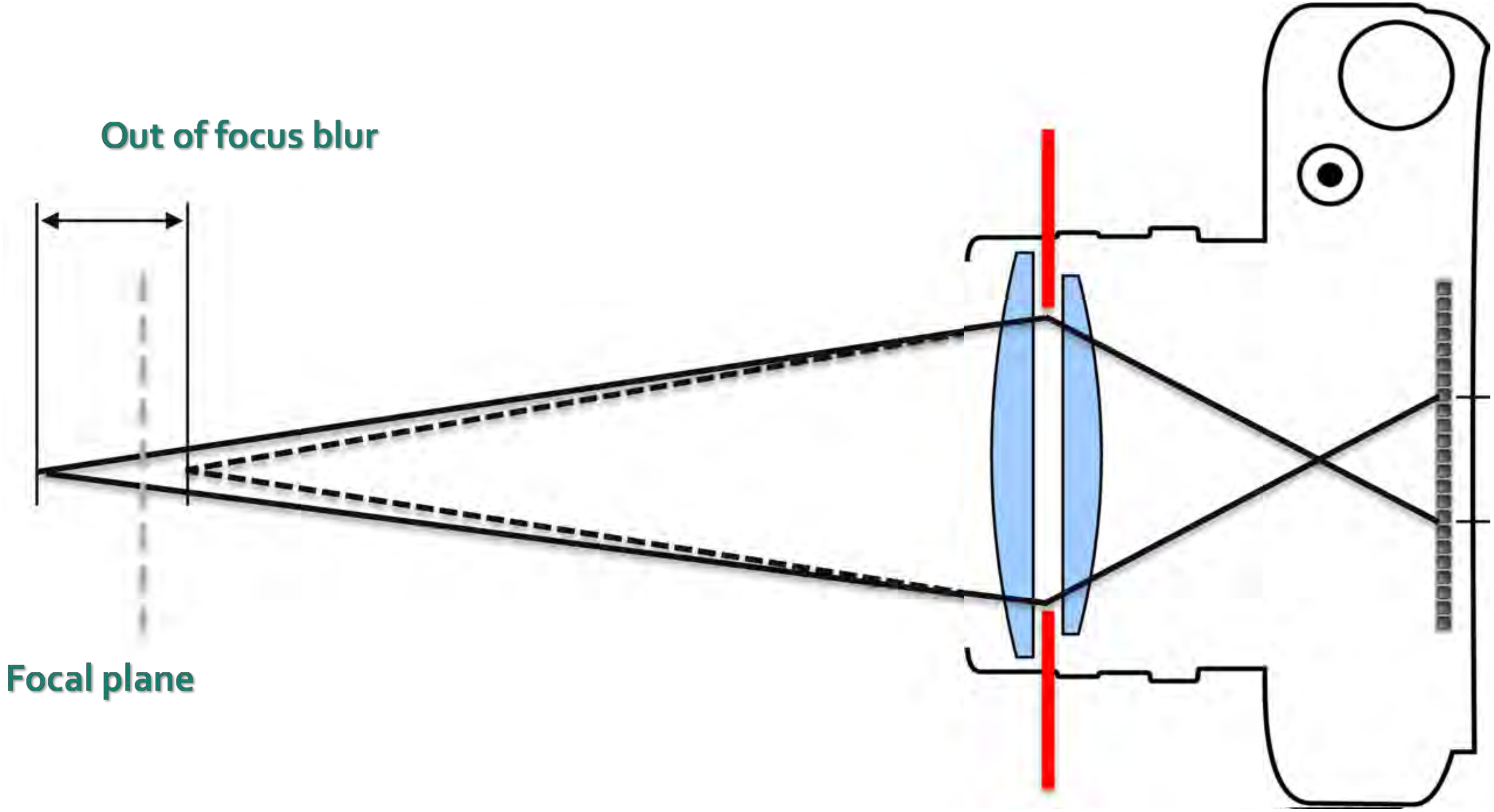
Camera Aperture



Camera Aperture



Camera Depth of Field



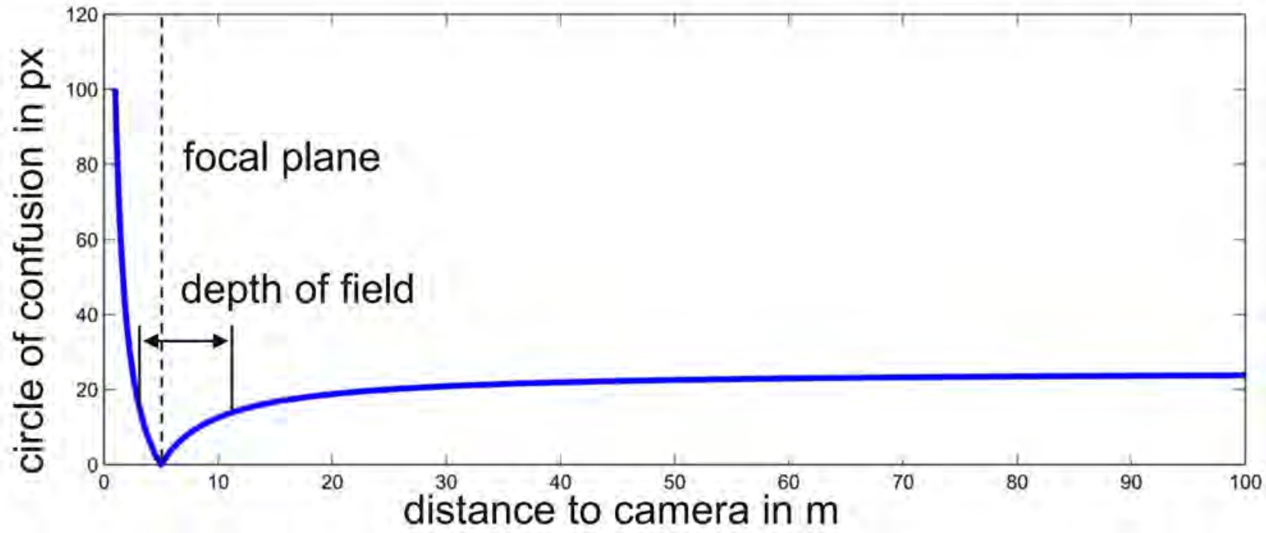
Depth of Field

Camera Depth of Field

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

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

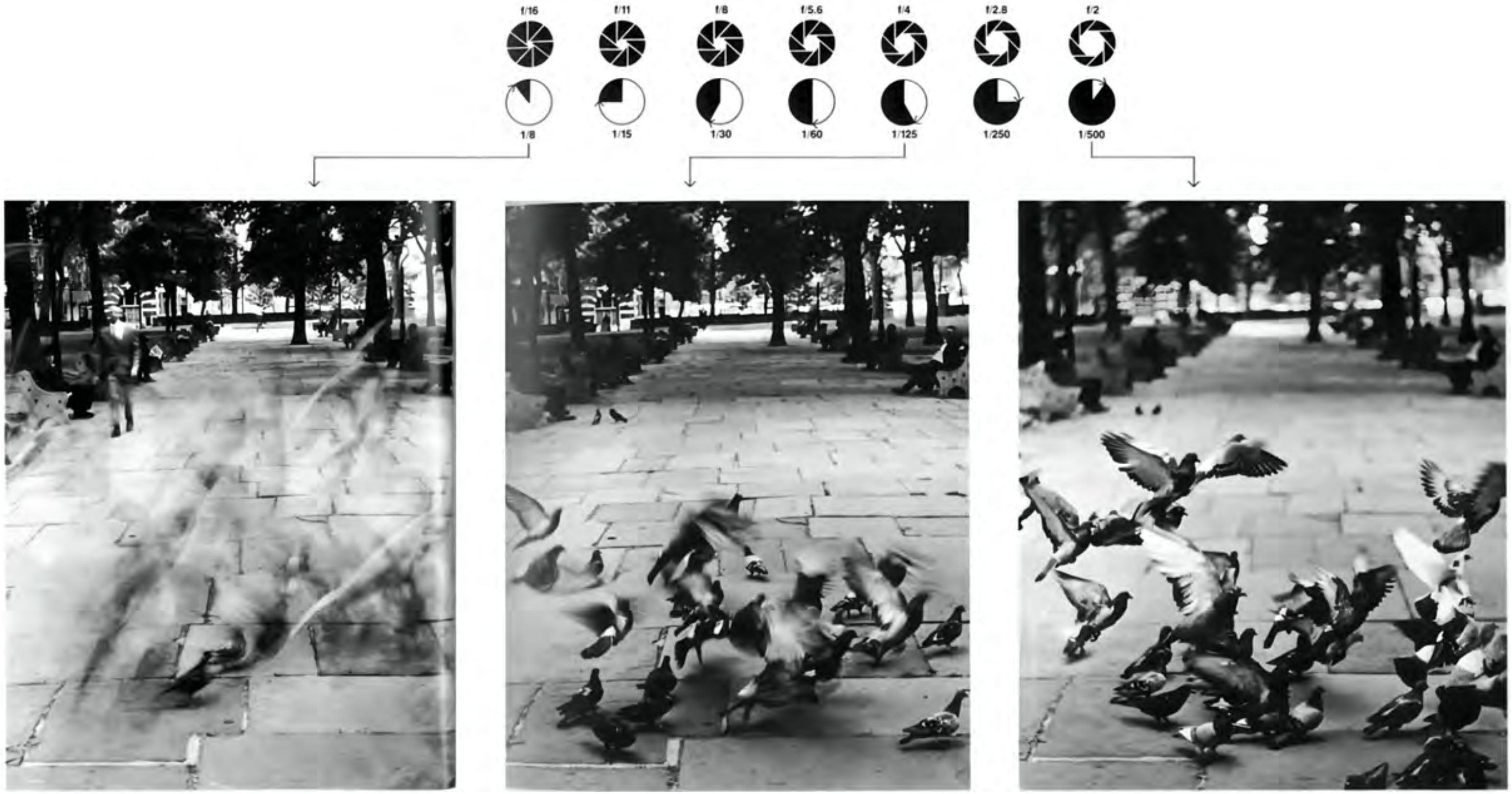
focused at 5m, pixel size=7.5um



Camera Depth of Field

http://photographywisdom.com/

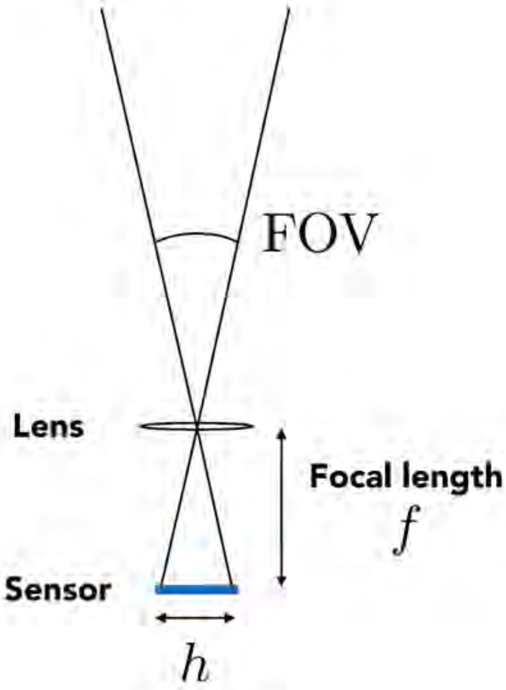
Camera Depth of Field

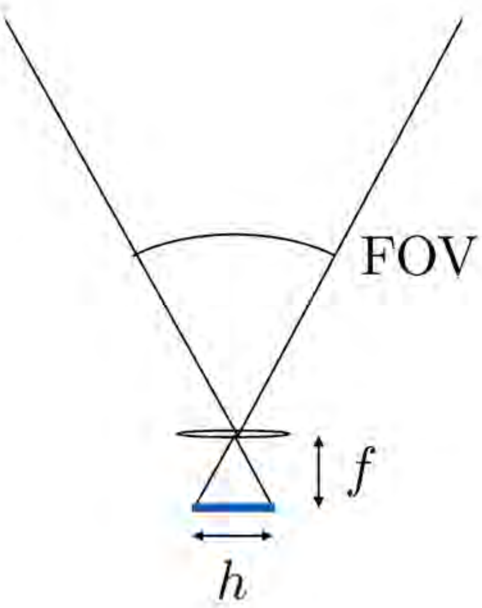


London, Photography

Field of View

Camera Field of View (FOV)

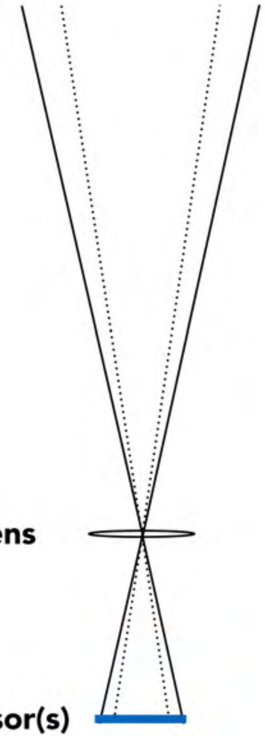




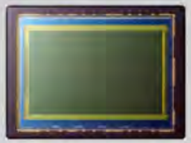
$$\mathrm{FOV} = 2\ \arctan\left(\frac{h}{2f}\right)$$

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

Camera Field of View (FOV)



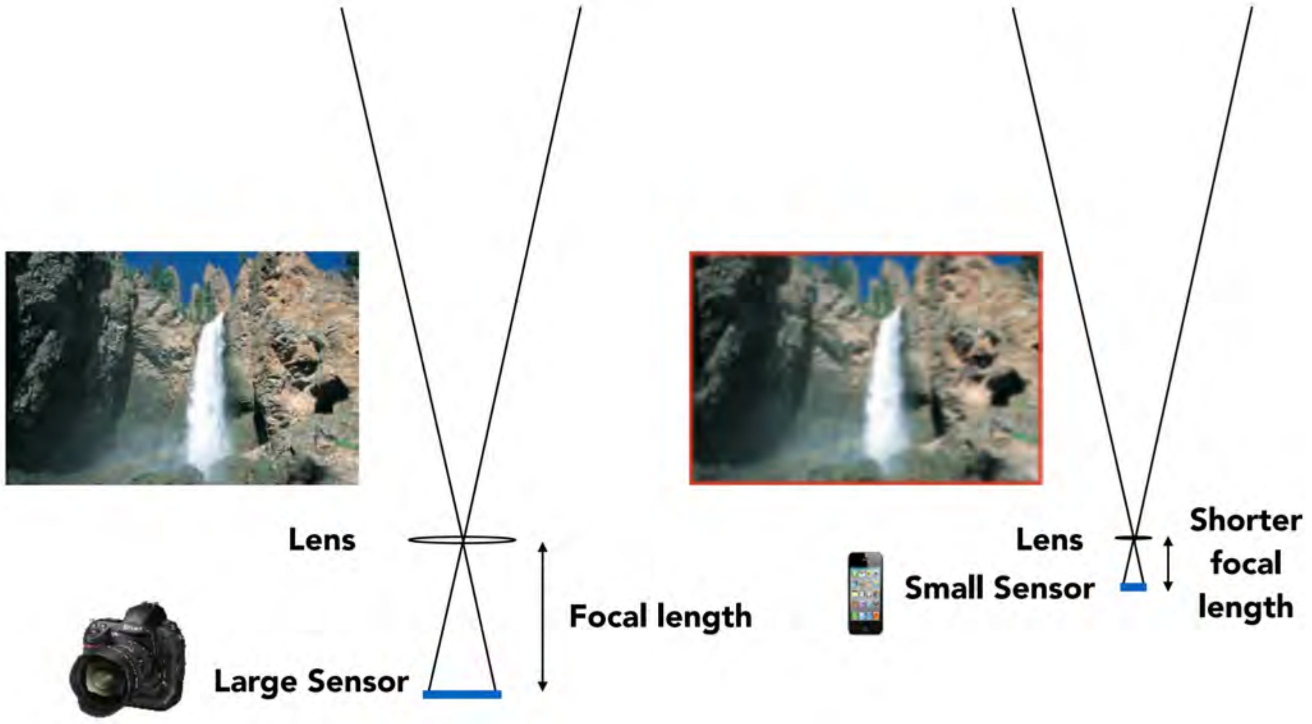
Camera Field of View (FOV)

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

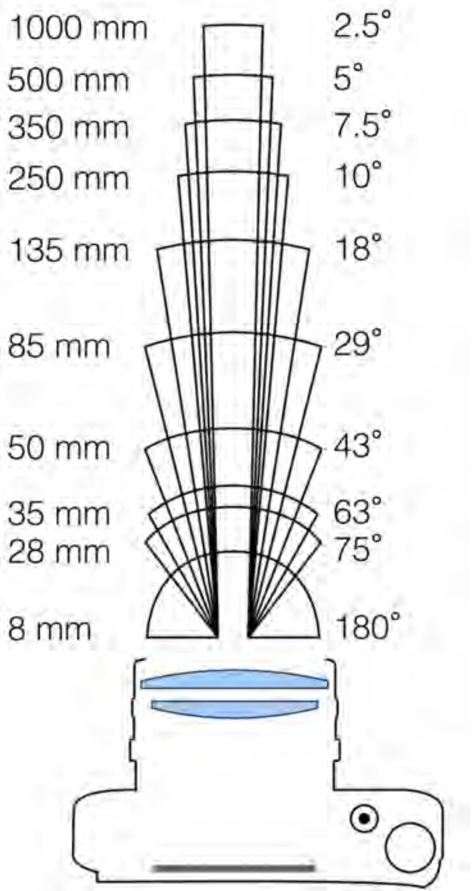
Camera Field of View (FOV)

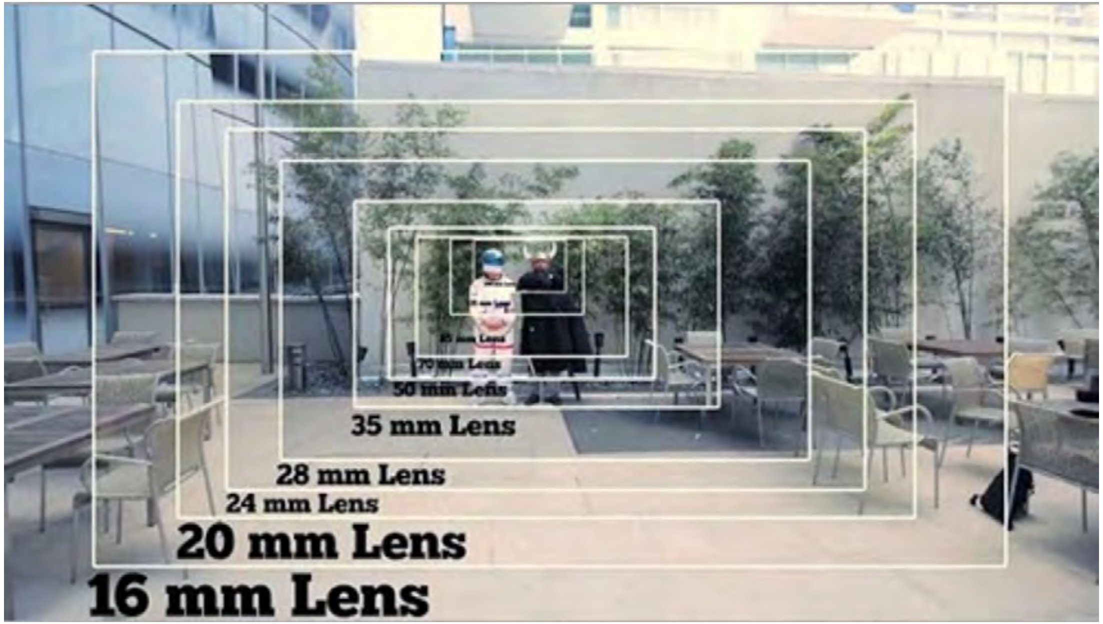
Mobile Phone: Maintain FOV on Smaller Sensor?



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

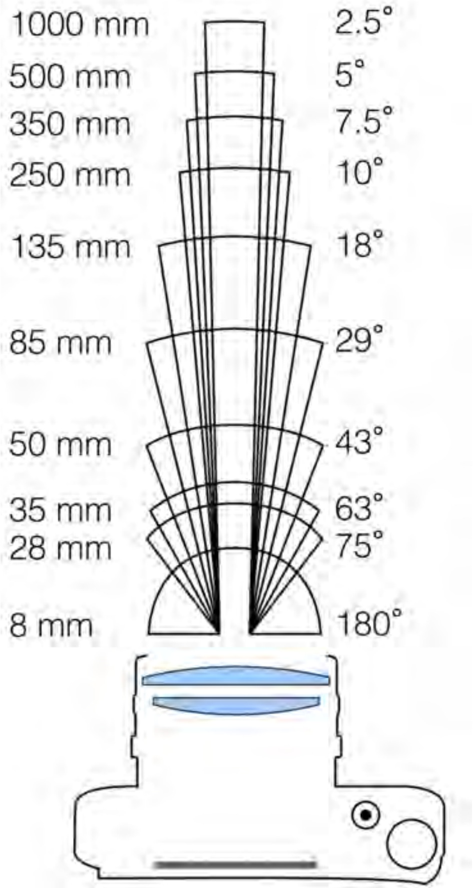
Camera Field of View (FOV)

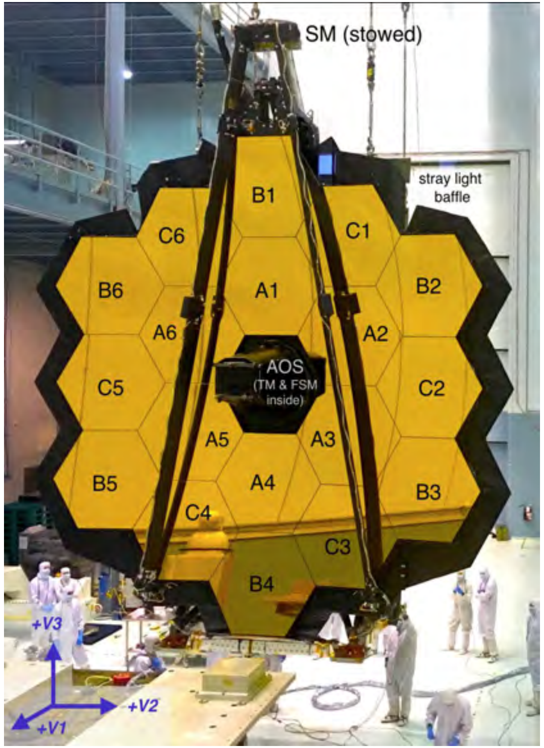




Andrew McWilliams

Camera Field of View (FOV)

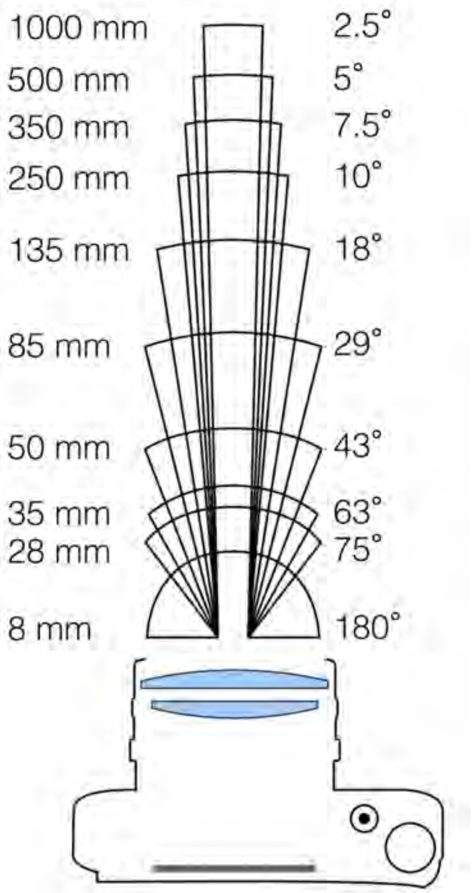




James Webb– What's the focal length?

A: 131.4m

Camera Field of View (FOV)



- For historical reasons, usually refer to angular FOV 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°
- Note: 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

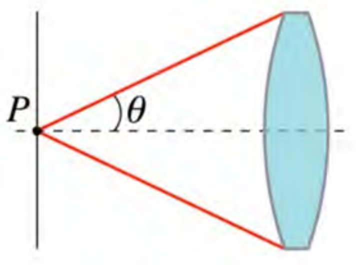
Ernst Abbe 1873:

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

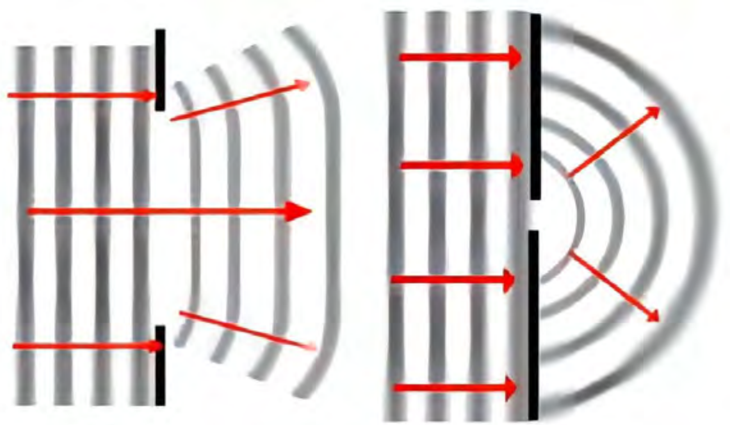
f-number

numerical aperture

spot radius (image space)



Diffraction



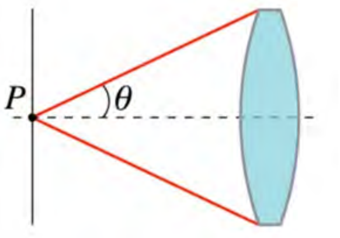
Airy pattern

Diffraction Limit

Ernst Abbe 1873:

$$d=\frac{\lambda}{2n\sin\theta}=\frac{\lambda}{\underbrace{2NA}_{\text{numerical aperture}}}\approx\lambda\overbrace{N}^{\text{f-number}}$$

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

From Canon EF Lens Work III

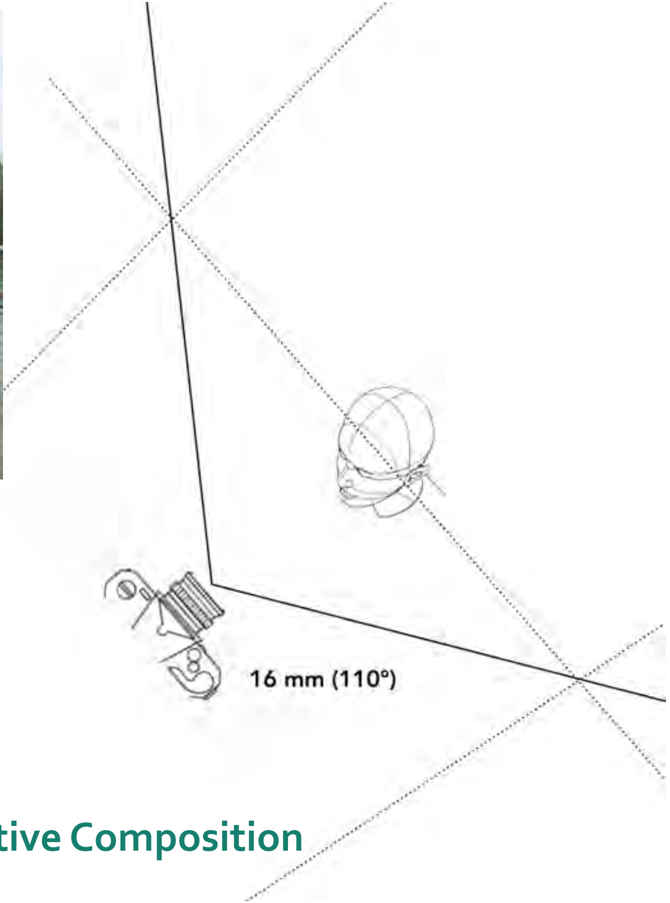
In this sequence,
distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

Perspective Composition – Camera Position / Focal Length

Tips: Photographer's Mindset

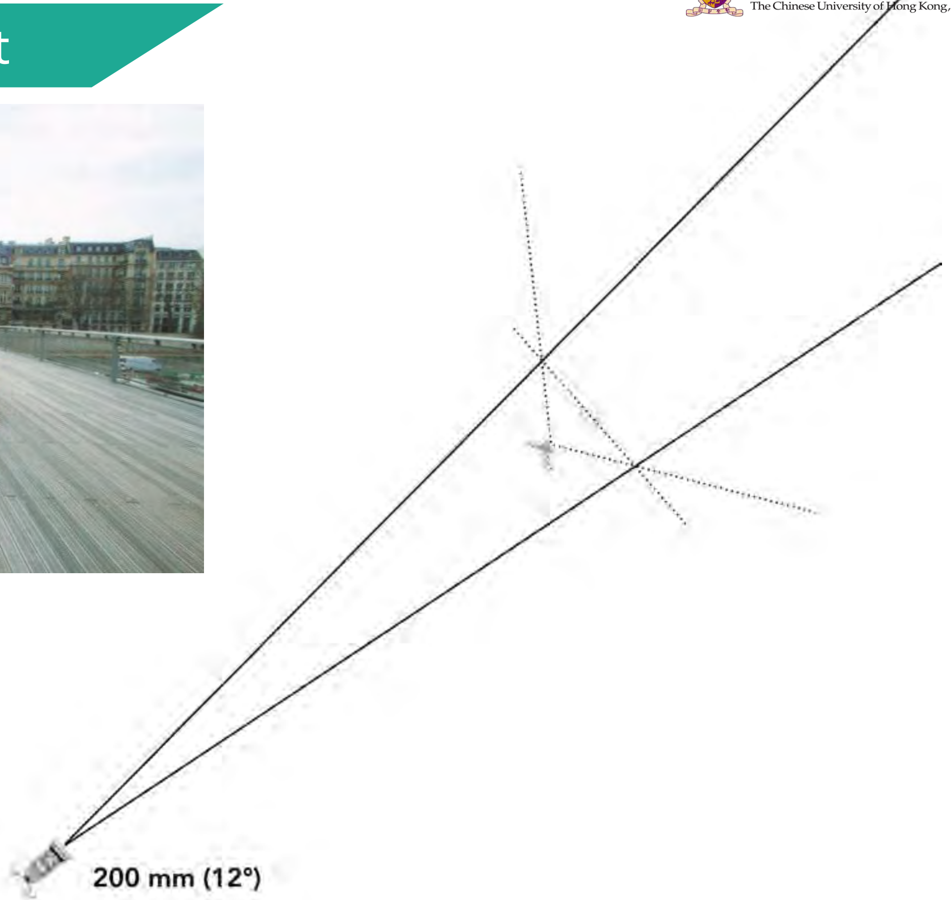
Up close and zoomed wide
with short focal length



Perspective Composition

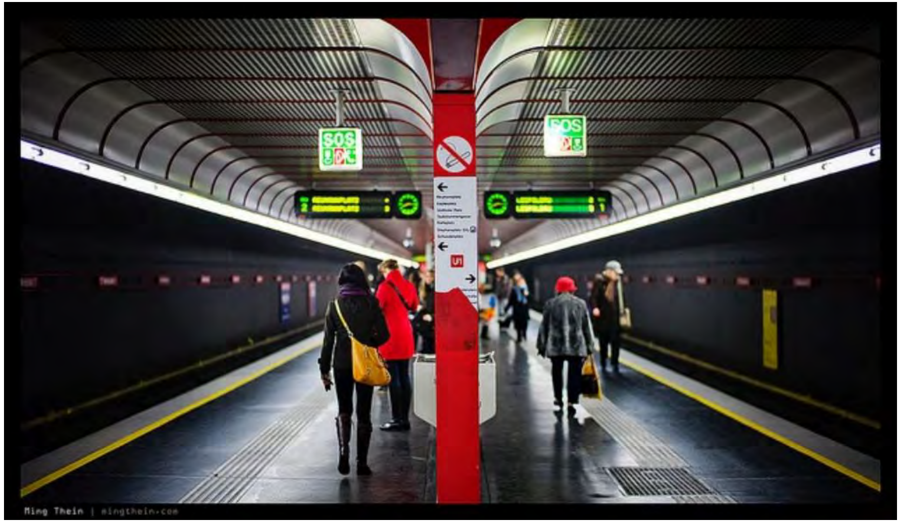
Tips: Photographer’s Mindset

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

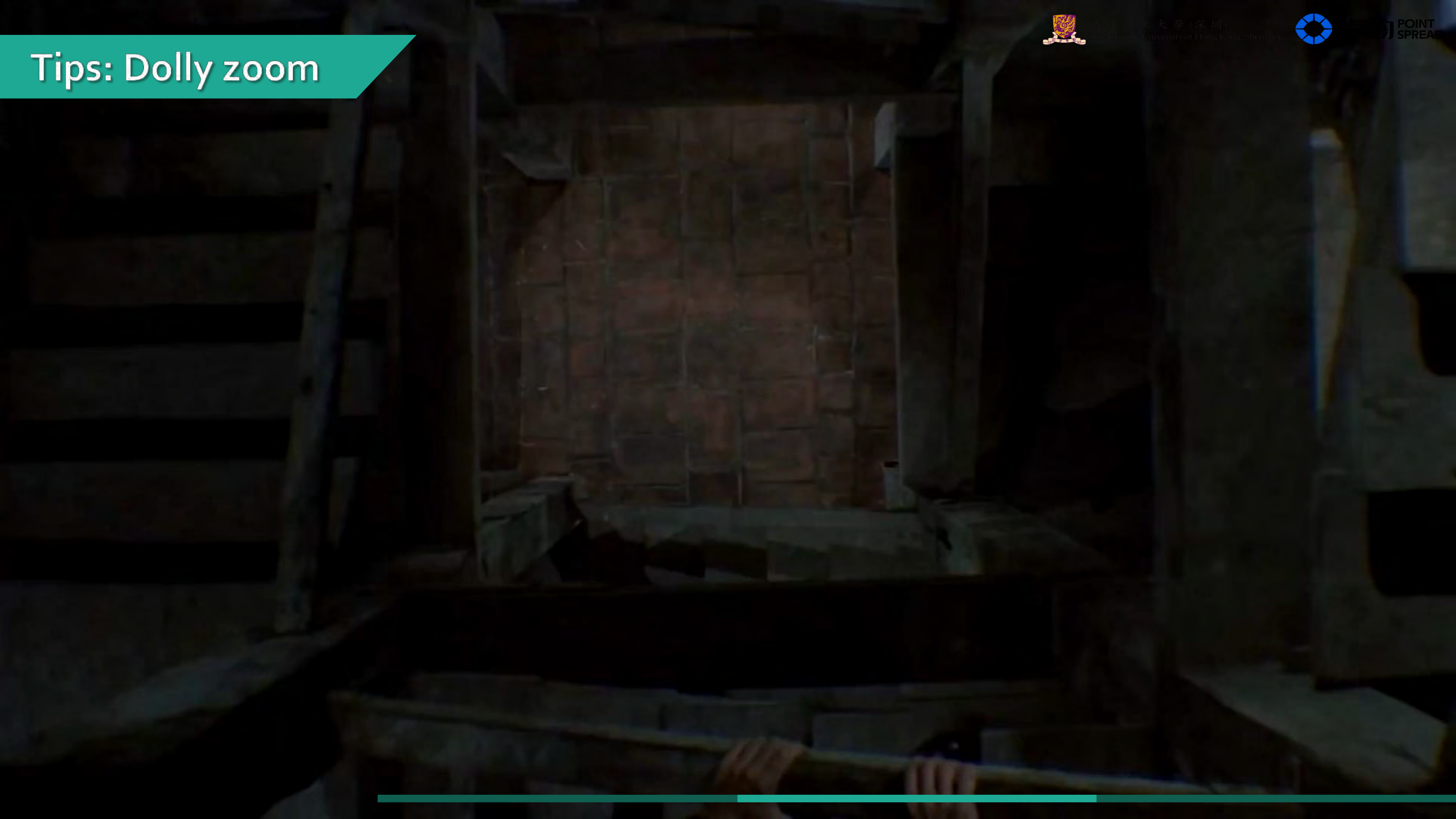
Tip 2: Choose a good perspective relationship (relative size) between your subject and background (or foreground)

- 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!

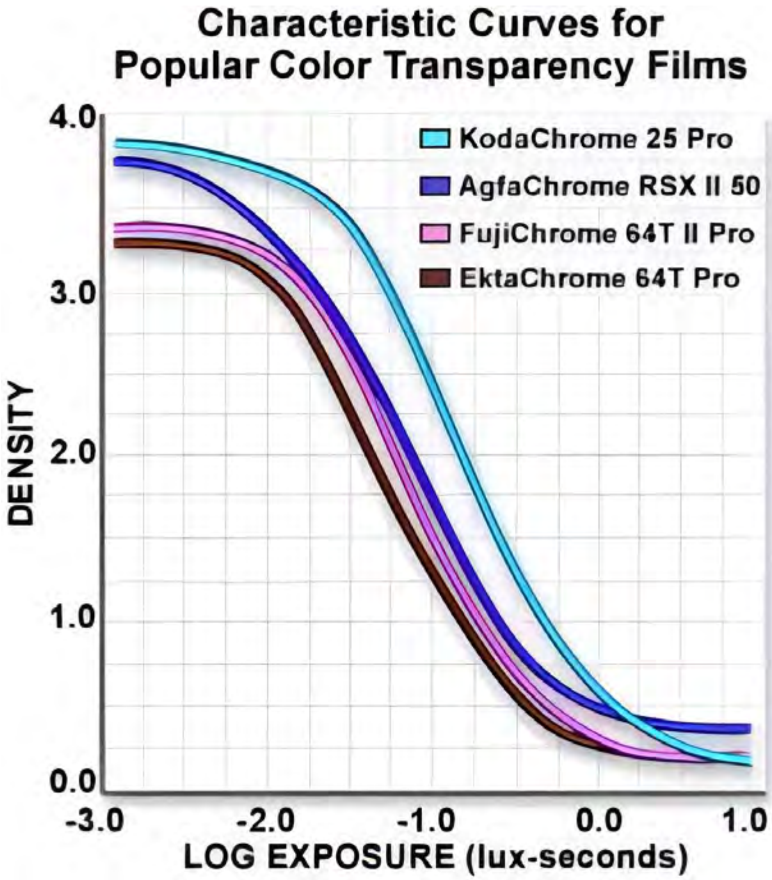
Tips: Dolly zoom



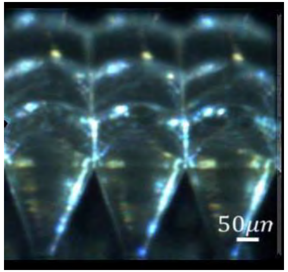
Sensors

Analog Film

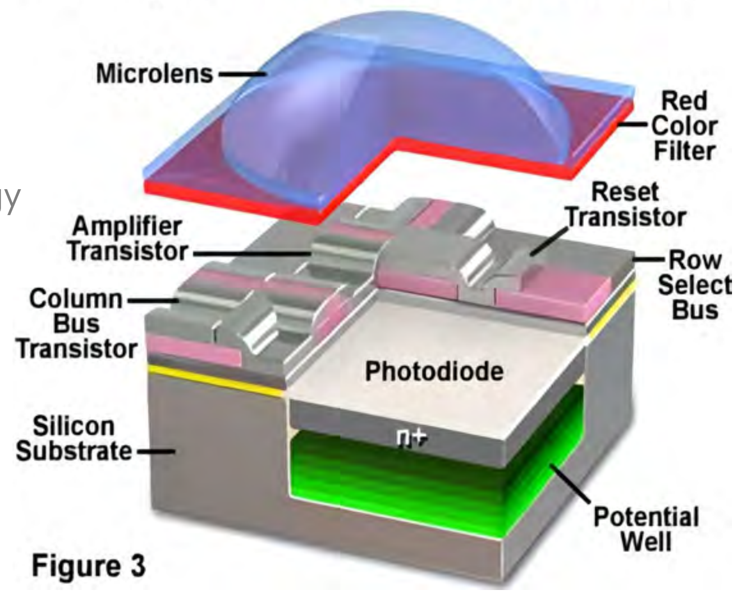
- Highly non-linear response:
  - Here shown for slide film
- Terminology:
  - Transmittance T: portion of light transmitted (0…1)
  - Density: log(1/T)
  - Contrast: ratio between max. and min. discernible intensity
- Example:
  - Transmittance 0.001
  - Density: 3
- Contrast of film:
  - 1,000:1 or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



Sensors: What's a Pixel?

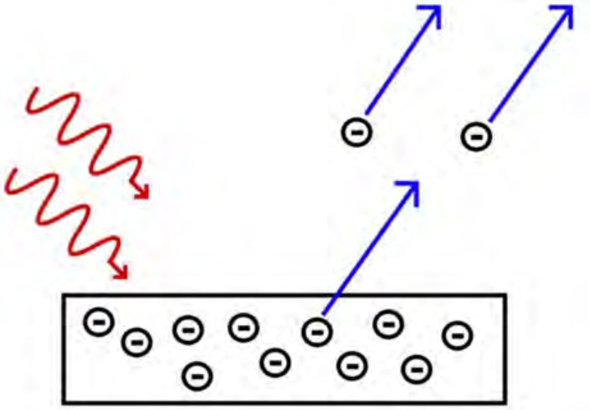


3D Micro Lens
Point Spread Technology



www.olympus-lifescience.com

Photon to electron converter photoelectric effect!



$$QE = \frac{\#\ electrons}{\#\ photons}$$

wikipedia

Photosite response

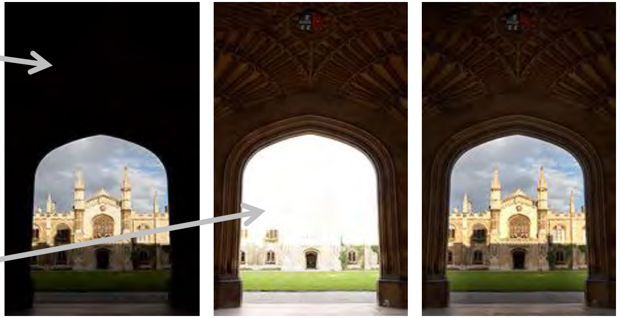
The photosite response is mostly linear

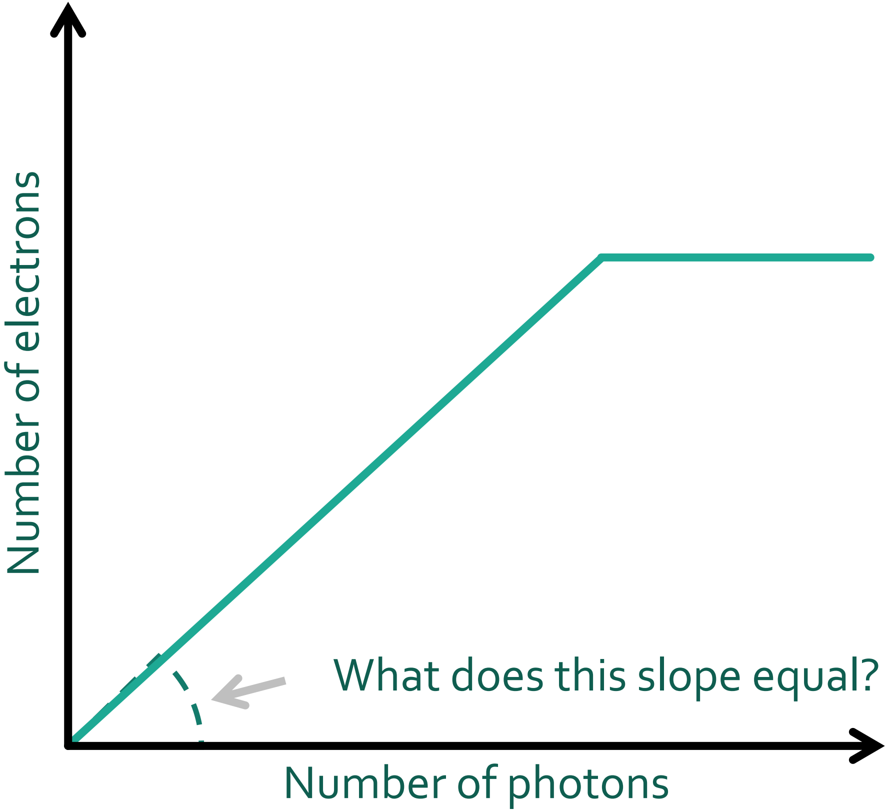
- non-linear when potential well is saturated (over-exposure)
- non-linear near zero (due to noise)

We will see how to deal with these issues in a later lecture (HDR imaging).

under-exposure (non-linearity due to sensor noise)

over-exposure (non-linearity due to sensor saturation)

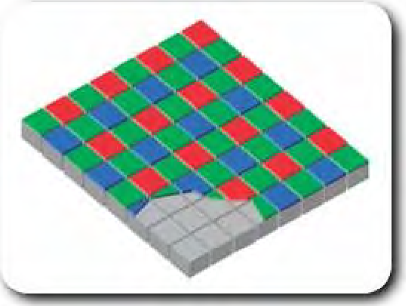




Color Filter Arrays

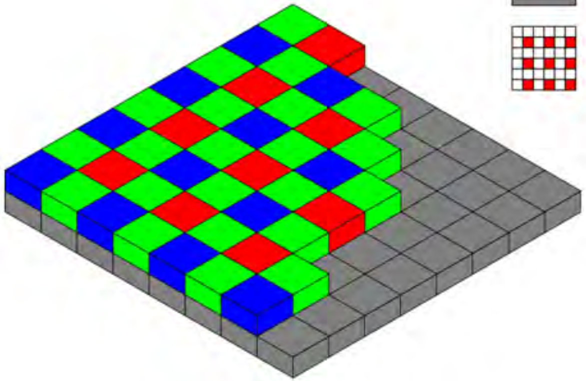
Approach

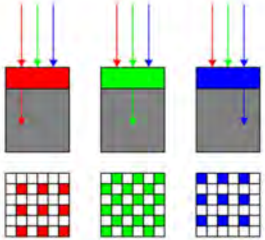
- Pixels are covered by color filters
  - Twice as many green pixels as red or blue ones
    - Interpreted as "intensity"
  - Missing color values are interpolated for every pixel
    - More in later lecture
  - Note: camera specs report the total number of pixels in a sensor
    - I.e, a image recorded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

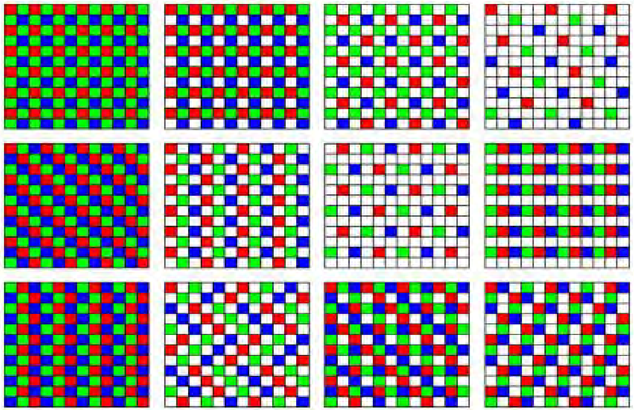


Color Filter Arrays

Bayer pattern







Any combination possible tradeoffs?

wikipedia

Sensors

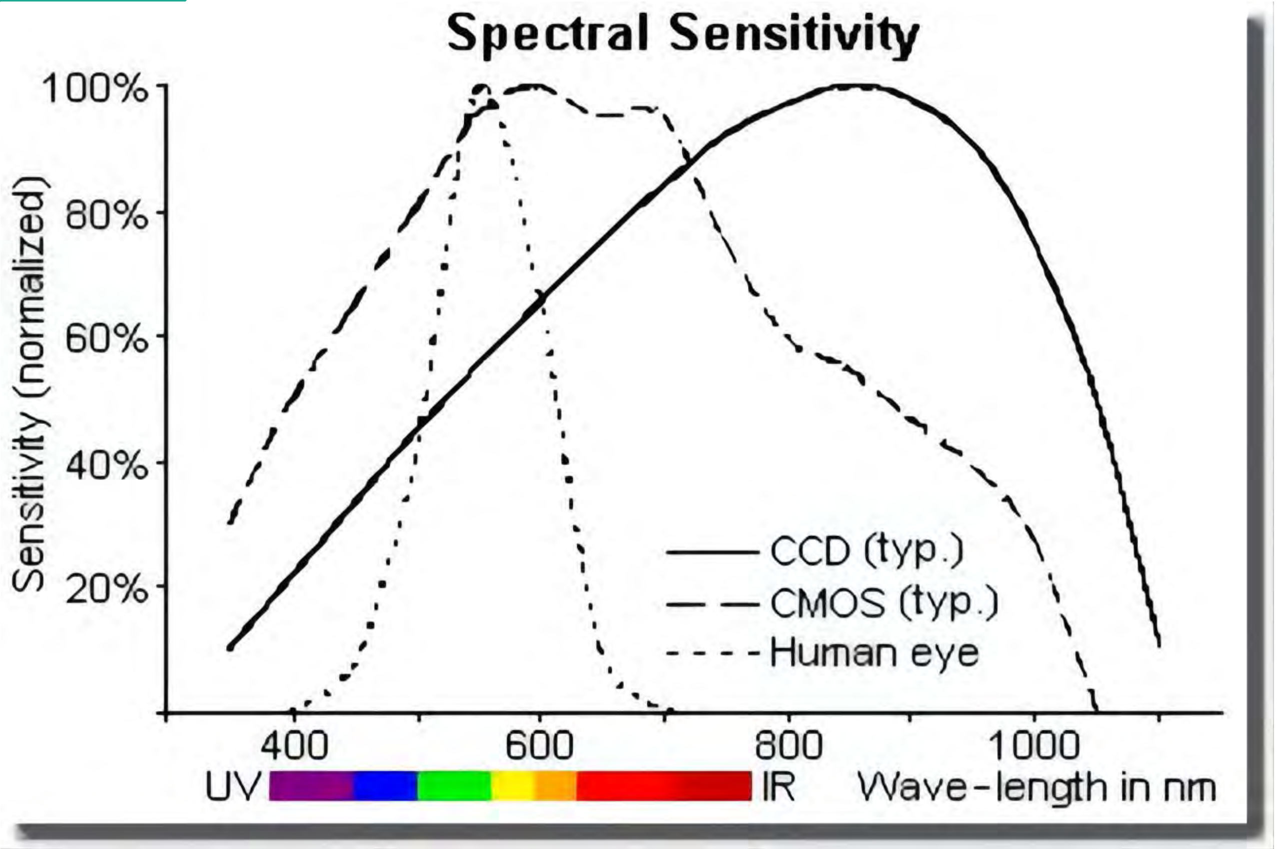
Common Semiconductor sensors used in cameras:

- 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)
- …

Spectral Sensitivity



CCD: High Sensivity for infrared

Noise Introduction

Photons to RAW Image

photon noise

sensor defects = fixed pattern noise

additive noise

quantization “noise”

photons

RAW image

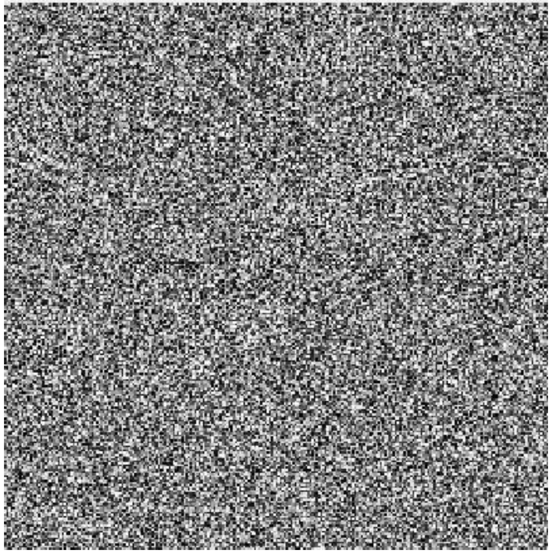
Sensor Noise

- Noise is (usually) bad!
- Many sources of noise: heat, electronics, amplifier gain, photon to electron conversion, pixel defects, read, …
- Different noise follows different statistical distributions, two crucial ones:
  - Gaussian
  - Poisson

Gaussian Noise

- Thermal, read, amplifier
- Additive, signal-independent!

+



=

Photon or Shot Noise

- Signal dependent

- Poisson distribution:

$$f(k;\lambda)=\frac{\lambda^k e^{-\lambda}}{k!}$$

$$\sigma=\sqrt{\lambda}$$

N photons: $\sigma = \sqrt{N}$

2N photons: $\sigma = \sqrt{2}\sqrt{N}$

nonlinear!

wikipedia

Signal-to-Noise Ratio (SNR)

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma} \quad \begin{array}{l} \leftarrow \text{signal} \\ \leftarrow \text{noise} \end{array}$$

$$= \frac{PQ_e t}{\sqrt{PQ_e t + Dt + N_r^2}}$$

P = incident photon flux (photons/pixel/sec)

Q_e = quantum efficiency

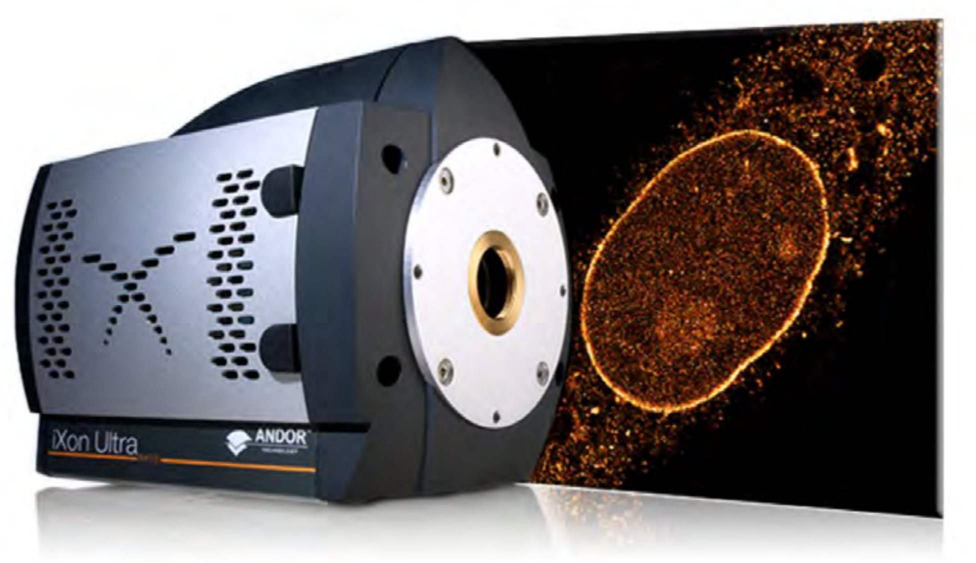
t = eposure time (sec)

D = dark current (electroncs/pixel/sec), including hot pixels

N_r = read noise (rms electrons/pixel), including fixed pattern noise

Scientific Sensors

- e.g., Andor iXon Ultra 897: cooled to -100° C
- Scientific CMOS & CCD
- Reduce pretty much all noise, except for photon noise

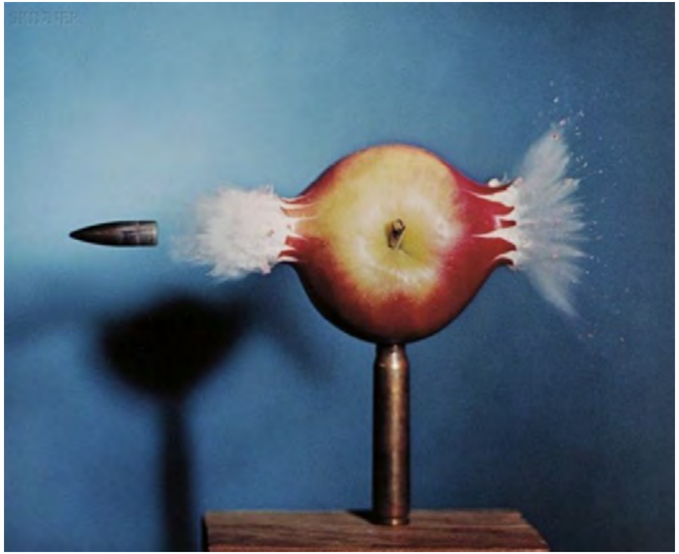


Exposure

Exposure

High-Speed Photography

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



Harold Edgerton

Mark Watson

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,

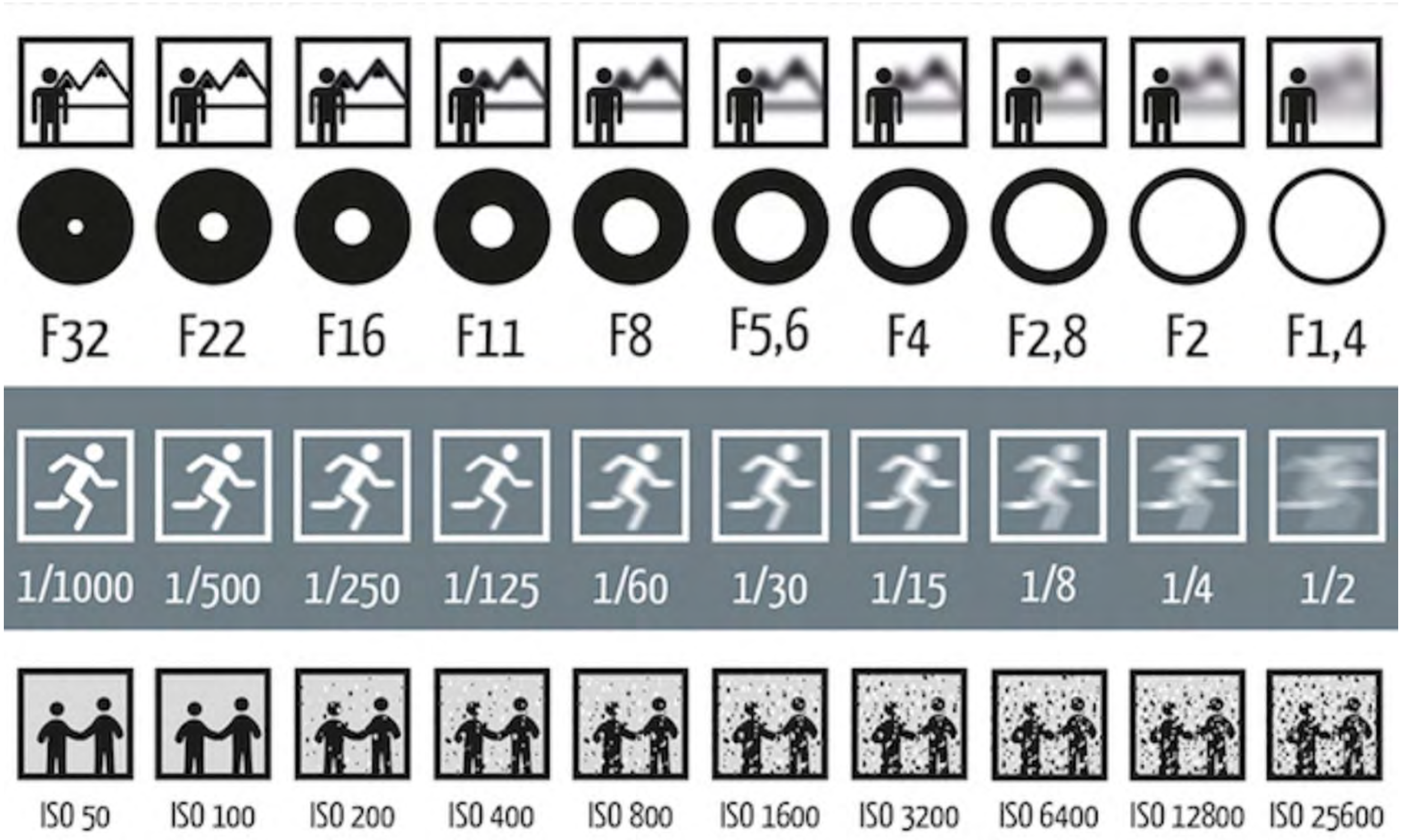
wikipedia

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

- **F-Number**

$$f/\# = N = f/D$$

where f is the focal length, and D is the diameter of the entrance pupil

- **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

Sensor sensitivity – Analog gain applied before ADC!

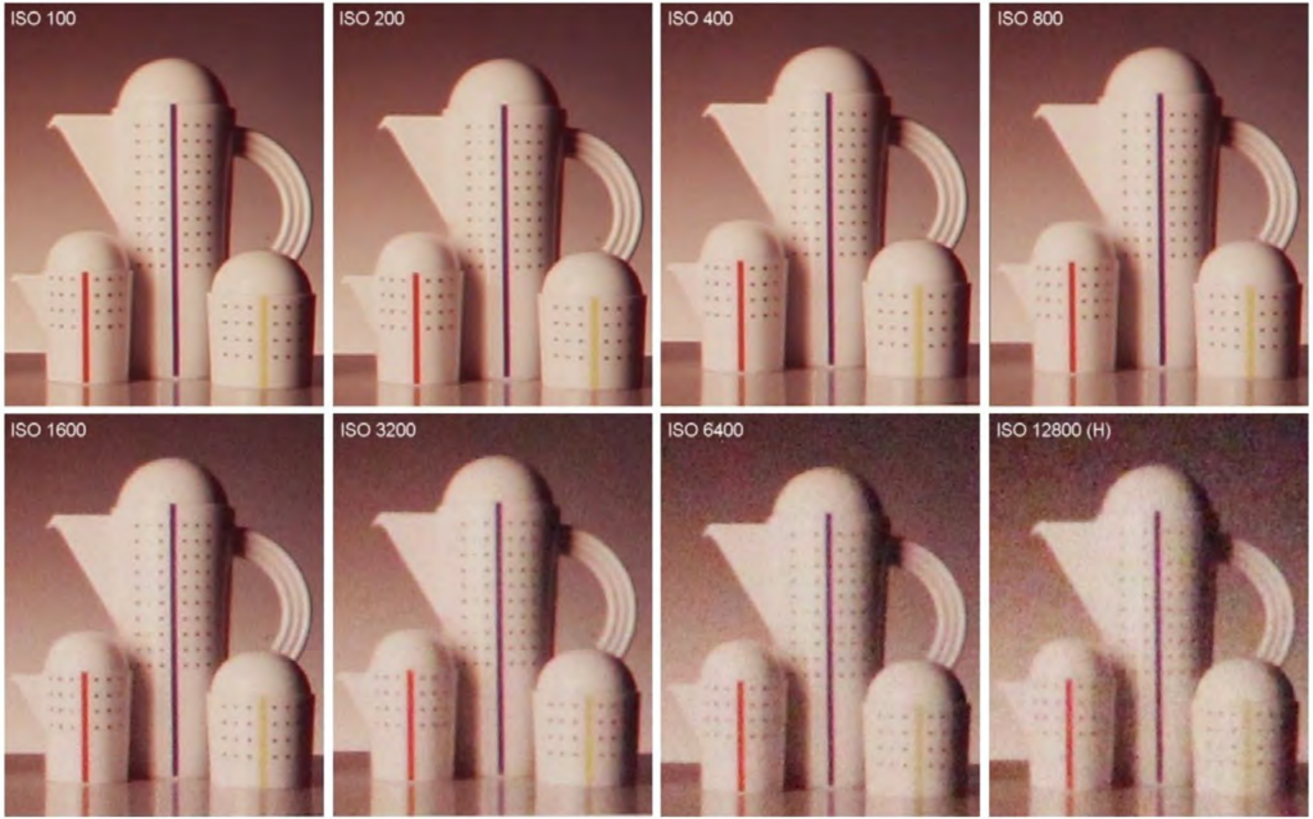


Image becomes very grainy because noise is amplified.

bobatkins.com

Shutters: Physical

Main Side Effect of Shutter Speed

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

Motion blur: handshake, subject movement

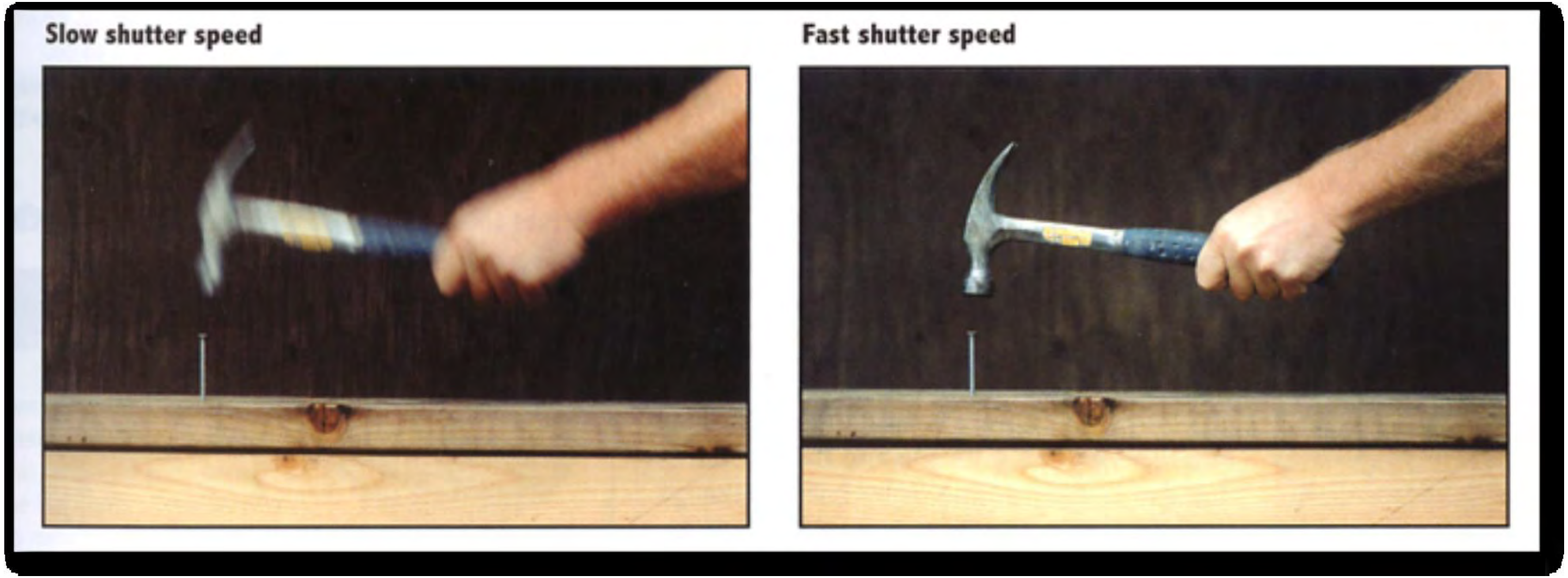
Doubling shutter time doubles motion blur

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

Main Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur



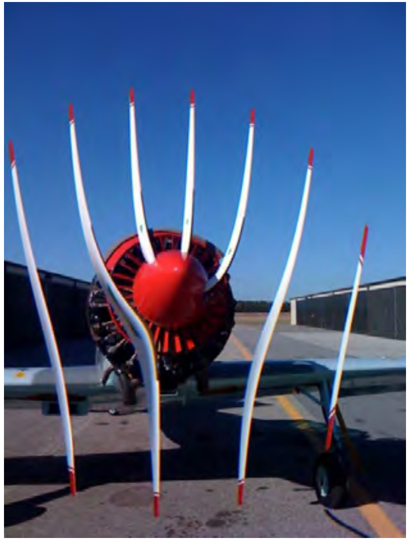
London

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

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

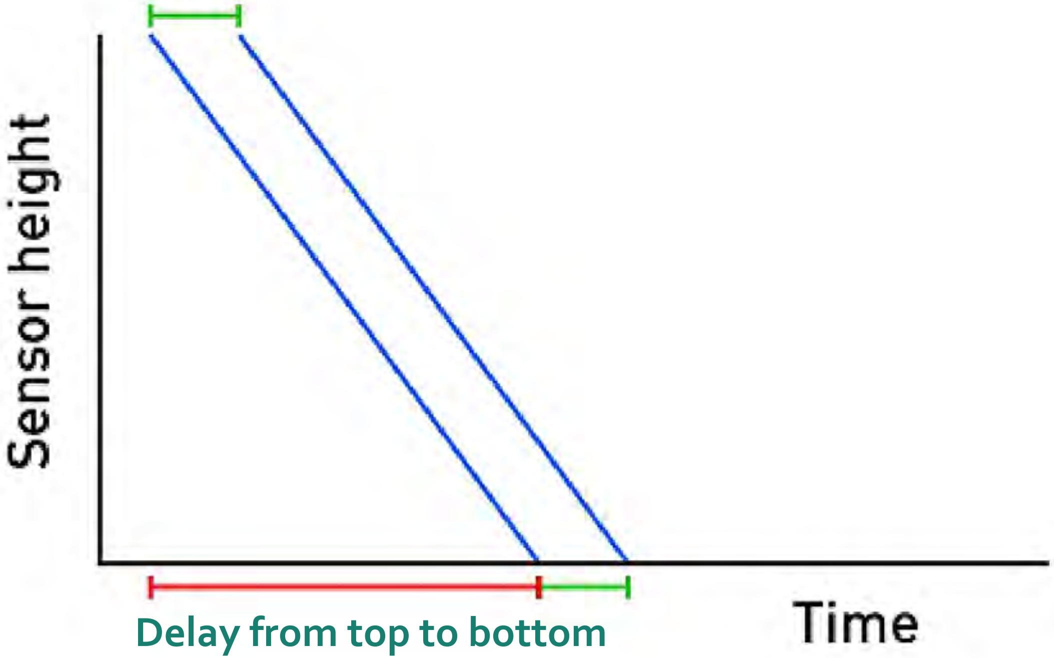


Credit: Soren Ragsdale
https://flic.kr/p/5S6rKw

Electronic Rolling Shutter

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

Electronic Rolling Shutter



Delay from top to bottom of sensor (e.g. 1/30 sec)

dpreview.com

Focal Plane Shutter (Fast Exposures)

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

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

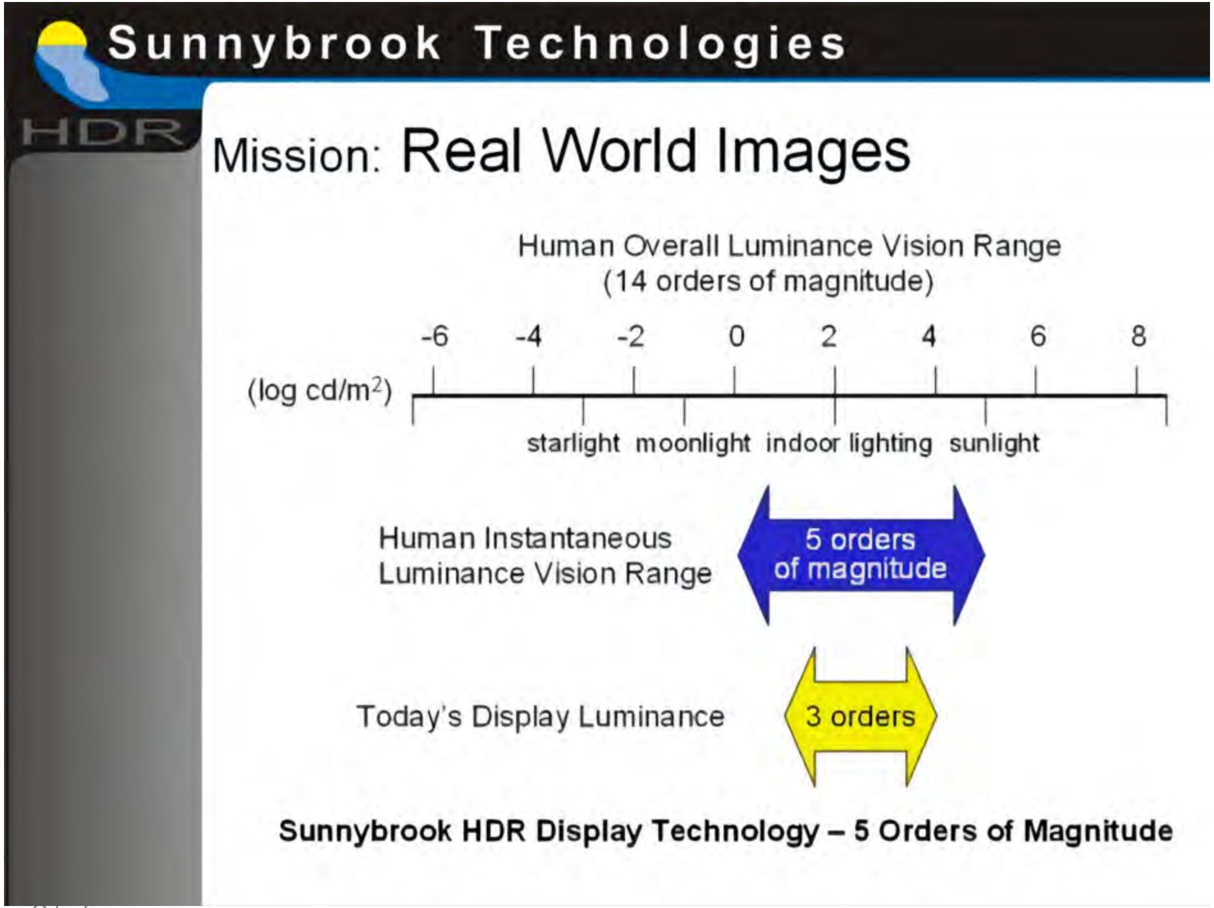
Exposure Tradeoffs: Depth of Field vs Motion Blur

Shallow Depth of Field Can Create a Stronger Image

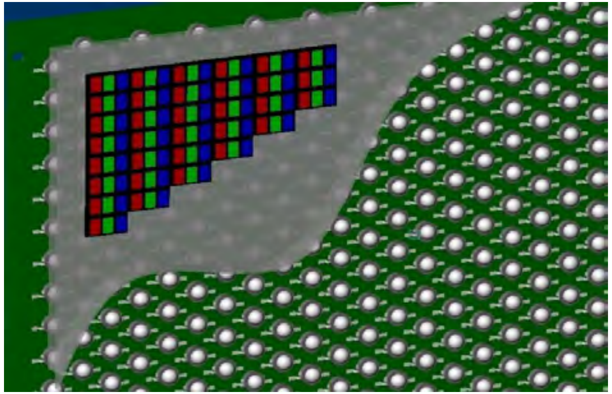
From Peterson, Understanding Exposure
200mm, f/4, 1/1000 (left) and f/11, 1/125 (right)

Dynamic Range

Dynamic Range



High Dynamic Range Displays



- Low Resolution LED Array
  - About 1000-2000 LEDs
- Conventional LCD
- Diffusion Optics

Wolfgang Heidrich [BrightSite Technology]

Ray Tracing Real Lens

Ray Tracing Through Real Lens Designs

200 mm telephoto

35 mm wide-angle

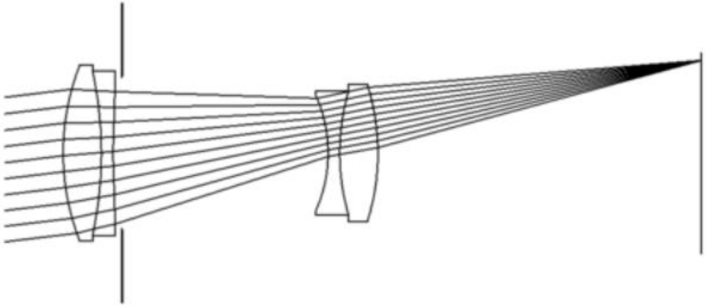
50 mm telephoto

16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)

Ray Tracing Through Real Lens Designs

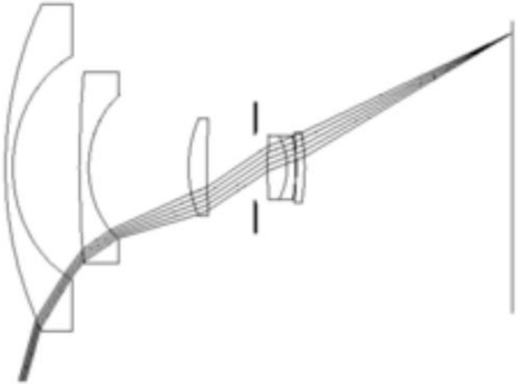
200 mm telephoto



Notice shallow depth of field (out of focus background)

Ray Tracing Through Real Lens Designs

16 mm fisheye



Notice distortion in the corners (straight lines become curved)

Ray Tracing Real Lens Designs

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The Chinese University of Hong Kong, Shenzhen
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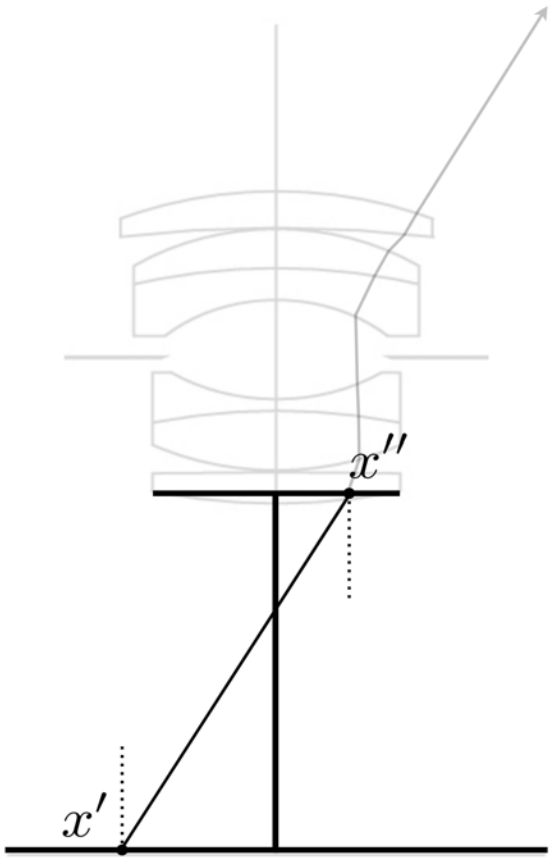
Monte Carlo approach

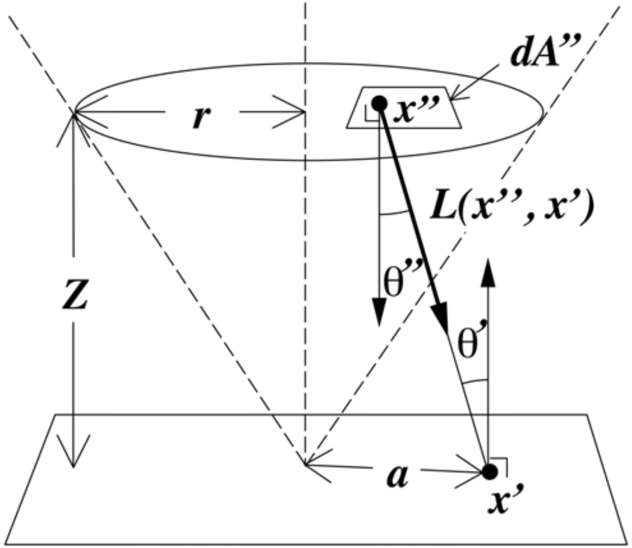
- At every sensor pixel, compute integral of rays incident on pixel area arriving from all paths through the lens

Algorithm (for a pixel)

- Choose N random positions in pixel
- For each position x', choose a random position o the back element of the lens x''
- Trace a ray through from x' to x'', trace refractions through lens elements until it misses the next element (kill ray) or exits the lens (path trace through the scene)
- Weight each ray according to radiometric calculation on next slide to estimate irradiance E(x')



Radiometry for Tracing Lens Designs



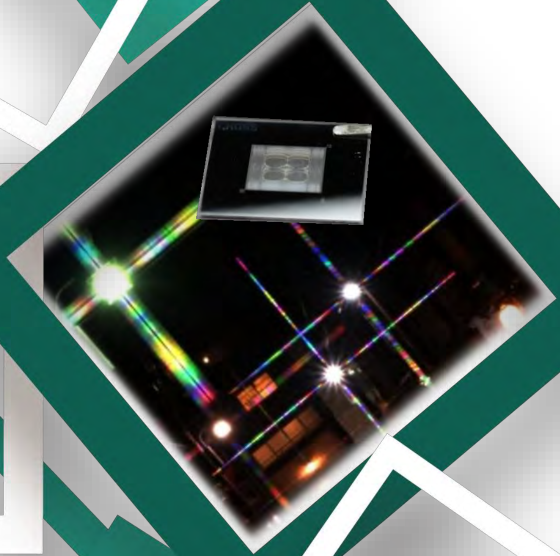
Back element of lens

Sensor Plane

$$E(x') = \int_{x'' \in D} L(x'' \to x') \frac{\cos\theta' \cos\theta''}{||x'' - x'||^2} dA''$$
$$= \frac{1}{Z^2} \int_{x'' \in D} L(x'' \to x') \cos^4 \theta dA''$$

Todays Topic

- Introduction
- Imaging Optics
- Aperture
- Depth of Field
- Field of View
- Tips for Photography
- Diffraction Limit
- Sensors
- Exposure
- Ray Tracing Thin Lens
- Ray Tracing Real Lens
- Noise



GAMES 204

Thank You!

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点昀技术（Point Spread Technology）