Digital Photography I

Optics & Sensors

EE367/CS448I: Computational Imaging

stanford.edu/class/ee367

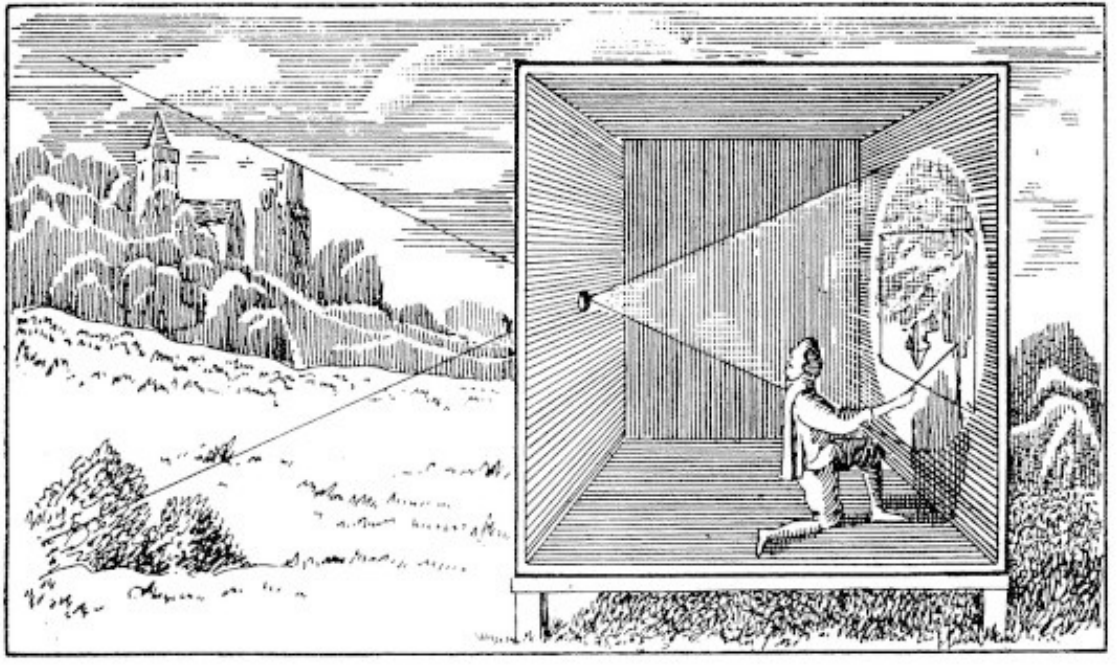
Lecture 3

Gordon Wetzstein

Stanford University

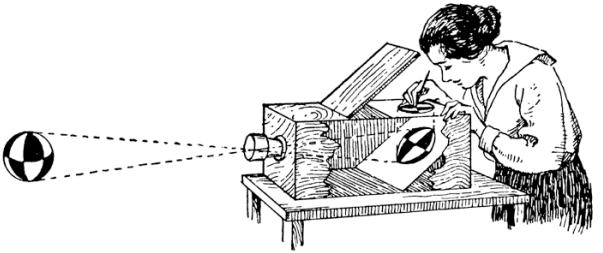
Abelardo Morell

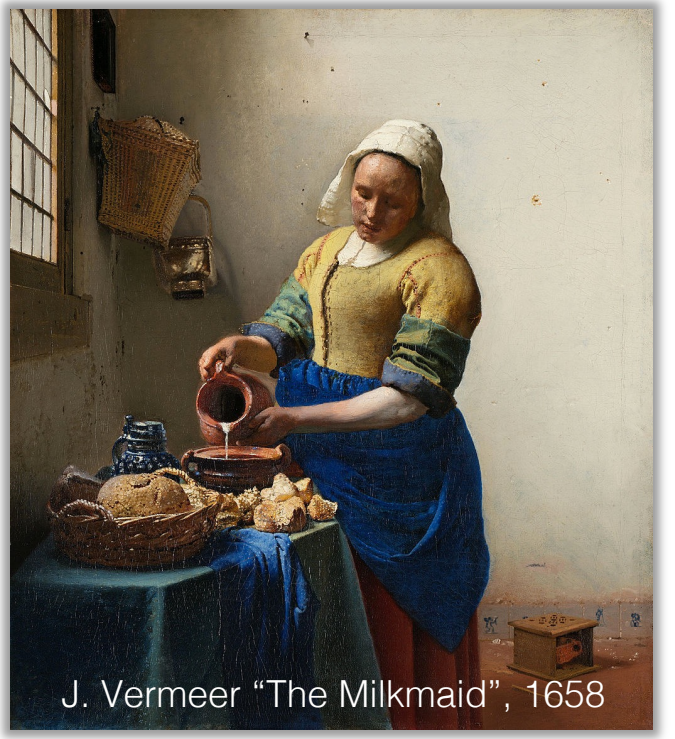
Pinhole Camera / Camera Oscura



Mo-Ti (Chinese Philosopher) 470-390 BC

Pinhole Camera / Camera Oscura





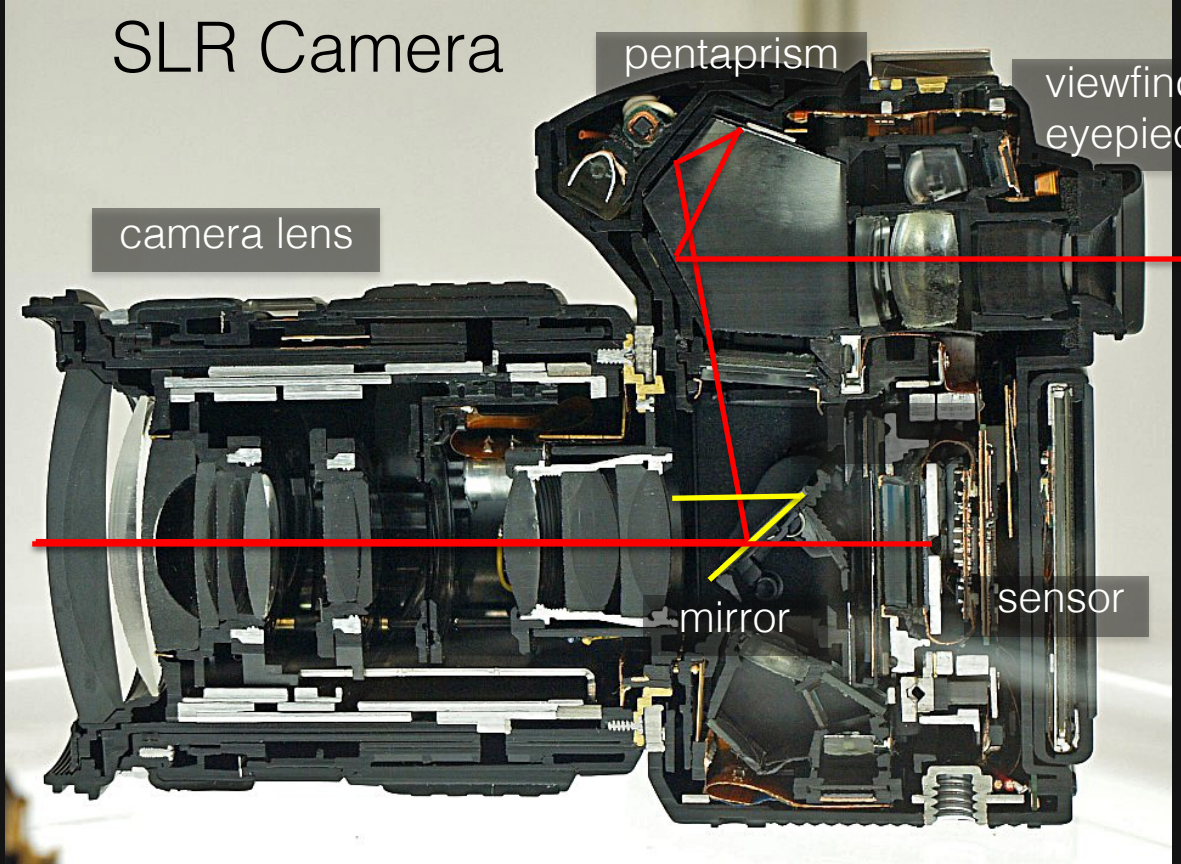
J. Vermeer “The Milkmaid”, 1658

Credit: ©Toppan Printing Co., Ltd.
Original photo data (Het melkmeisje [The Milkmaid] by Johannes Vermeer) :
©Rijksmuseum Amsterdam. Purchased with the support of the Vereniging Rembrandt

Digital Photography - Overview

- optics
- aperture
- depth of field
- field of view
- exposure
- noise
- color filter arrays
- image processing pipeline

SLR Camera


pentaprism
viewfinder
eyepiece
camera lens
mirror
sensor

Camera Optics

Niepce “View from the Window at Le Gras”, 1826

1826
8h exp

Daguerrotype

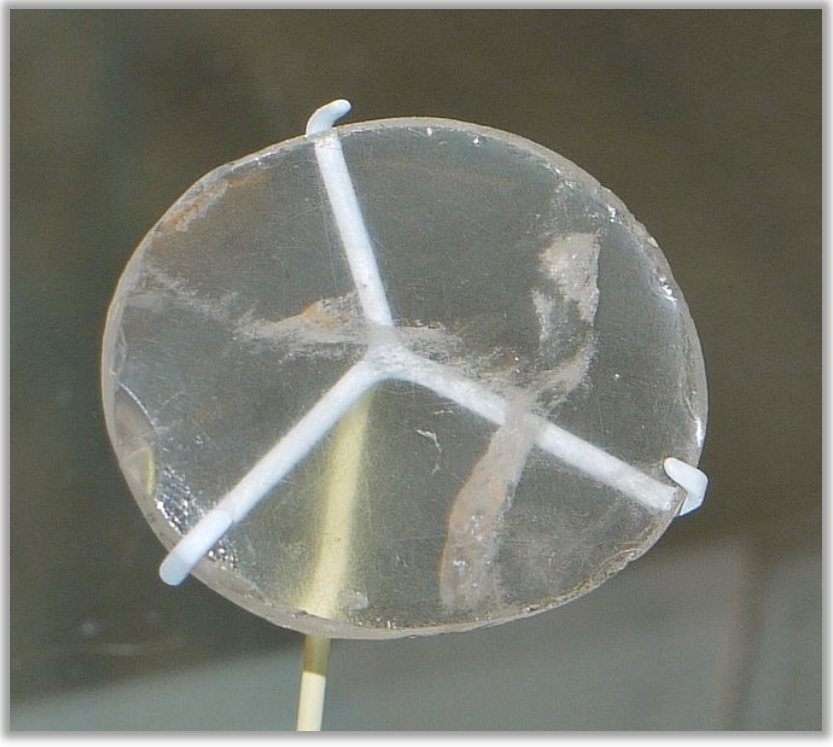
- invented in 1836 by Louis Daguerre
- lenses focus light, better chemicals!

Daguerre “Boulevard du Temple”, 1838

exposure
10-12 mins

Lenses

- focus light
- magnify objects

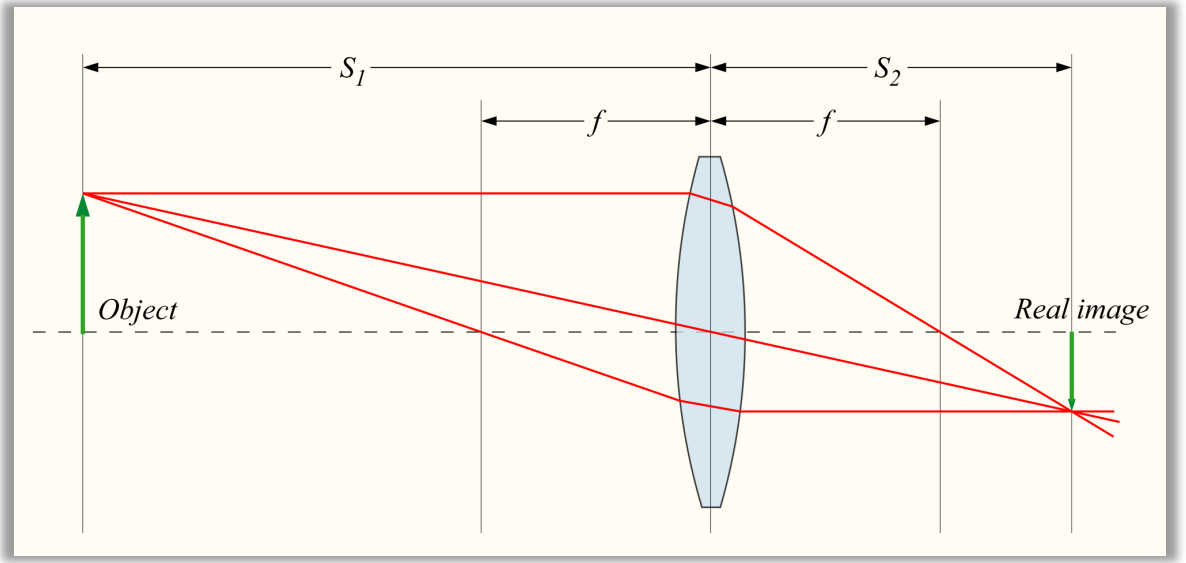


Nimrud lens - 2700 years old

Lenses

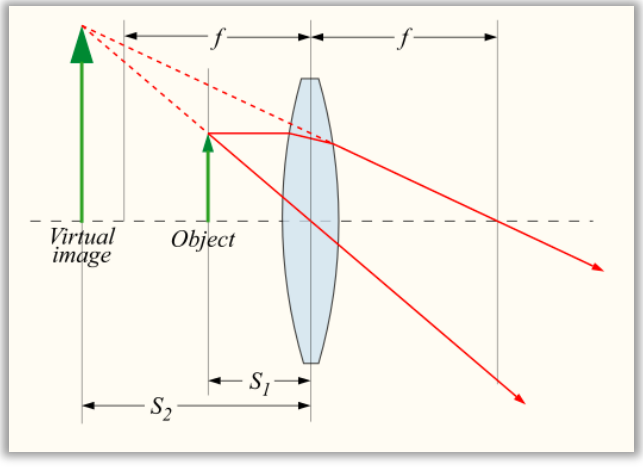
lensmaker's equation: $\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2}$

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

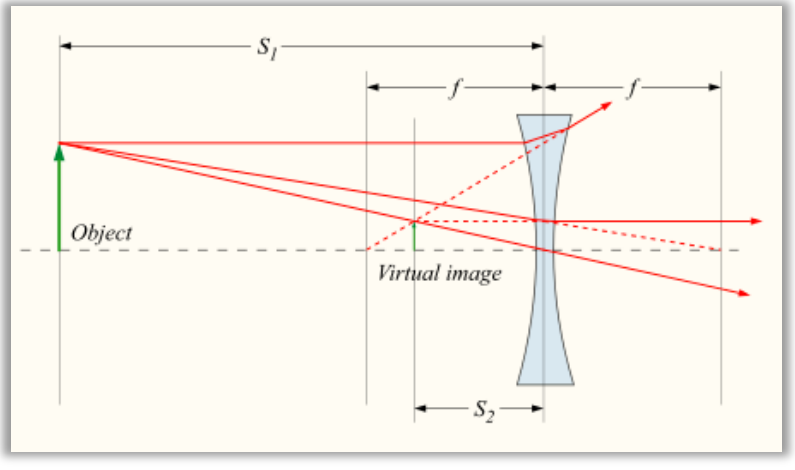


Lenses

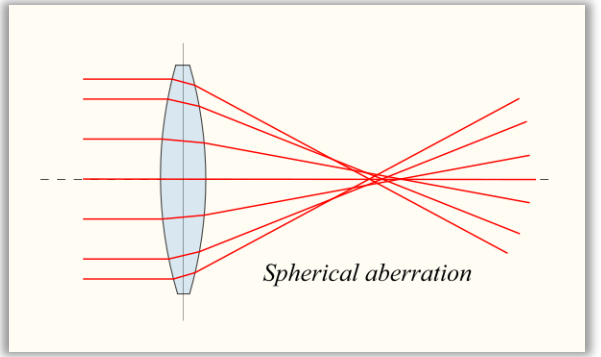
S1<f: magnifying glass

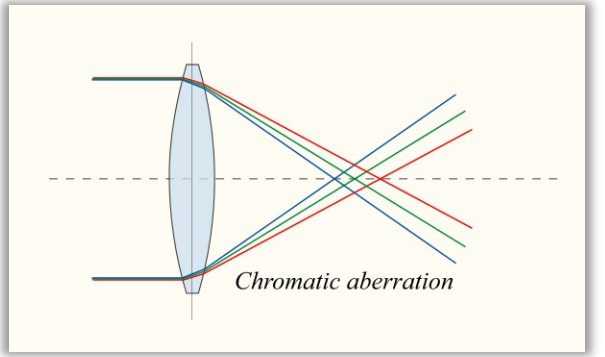


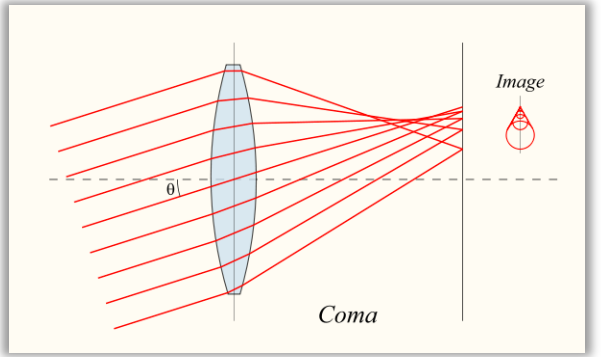
minification

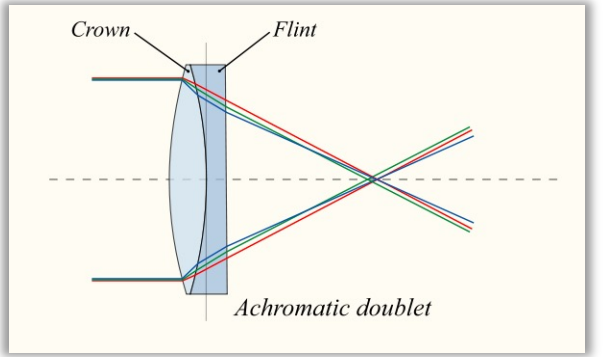


Lenses - Aberrations

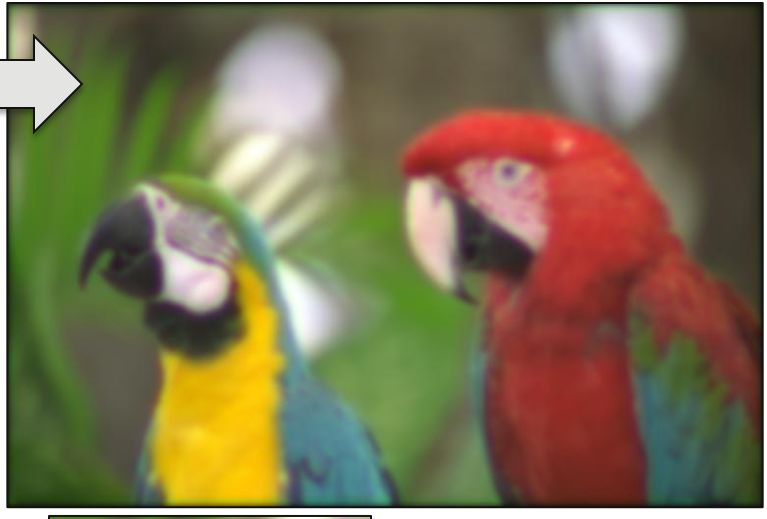




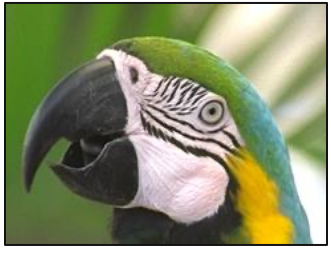


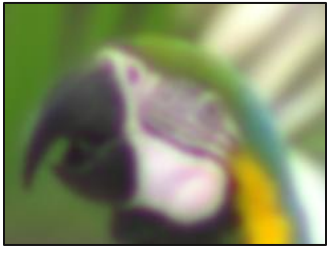


Lenses - Aberrations



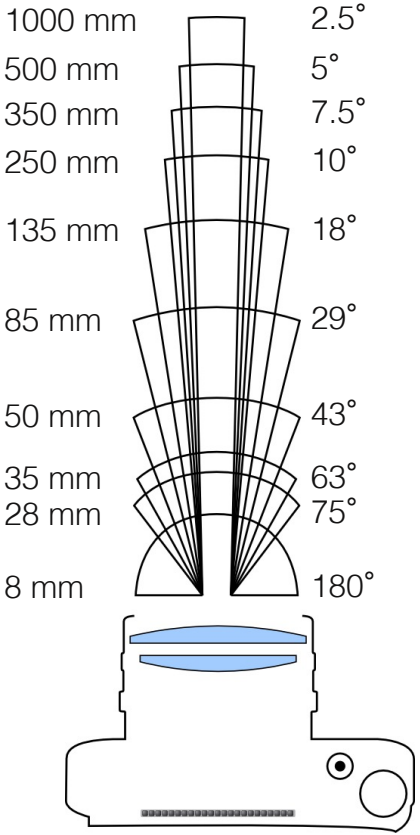
Sharp Image

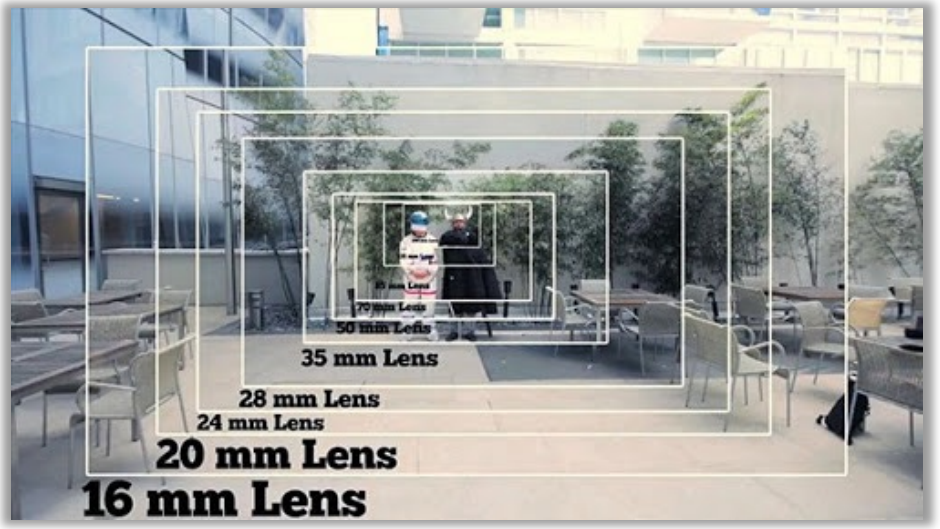




Blurred Image due to optical aberrations

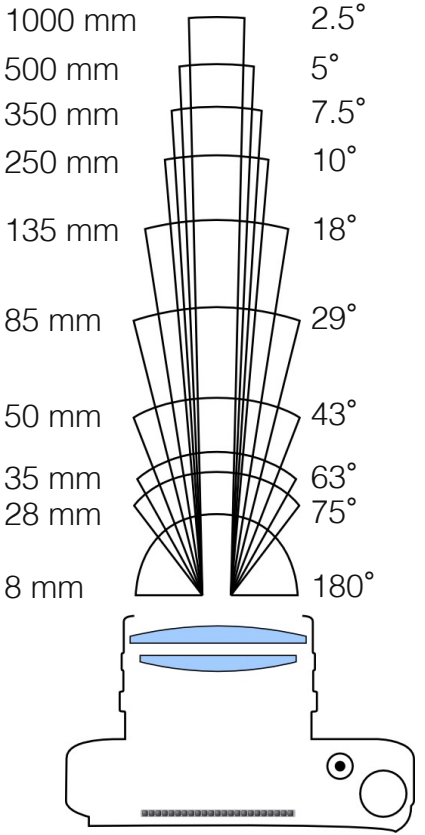
Field of View



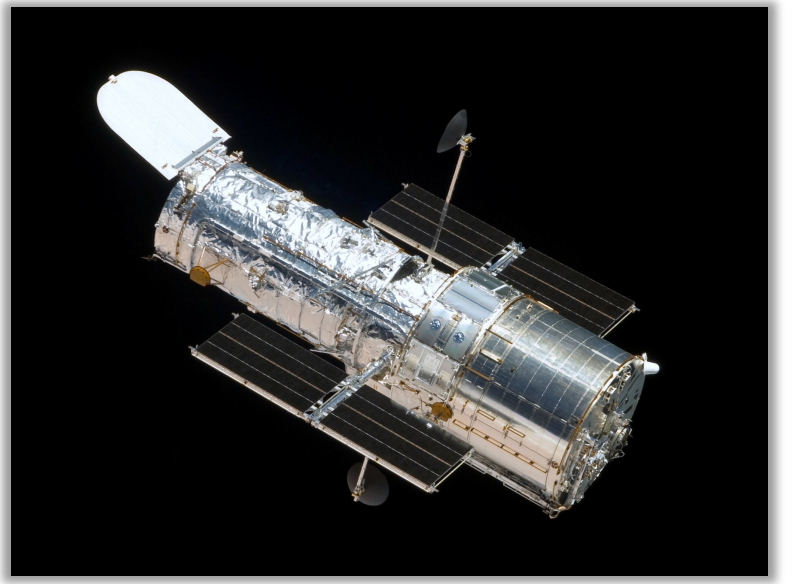


Andrew McWilliams

Field of View

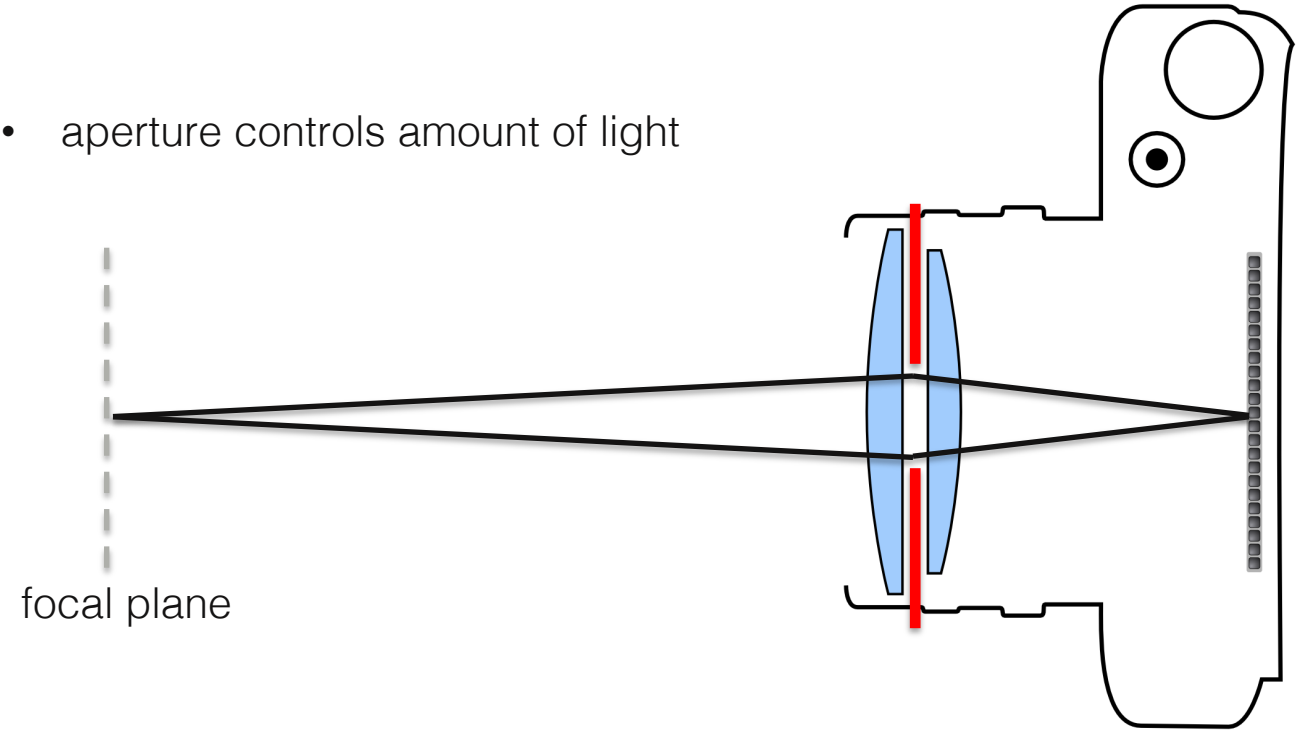


Hubble – what's the focal length?



Aperture

- aperture controls amount of light



Aperture

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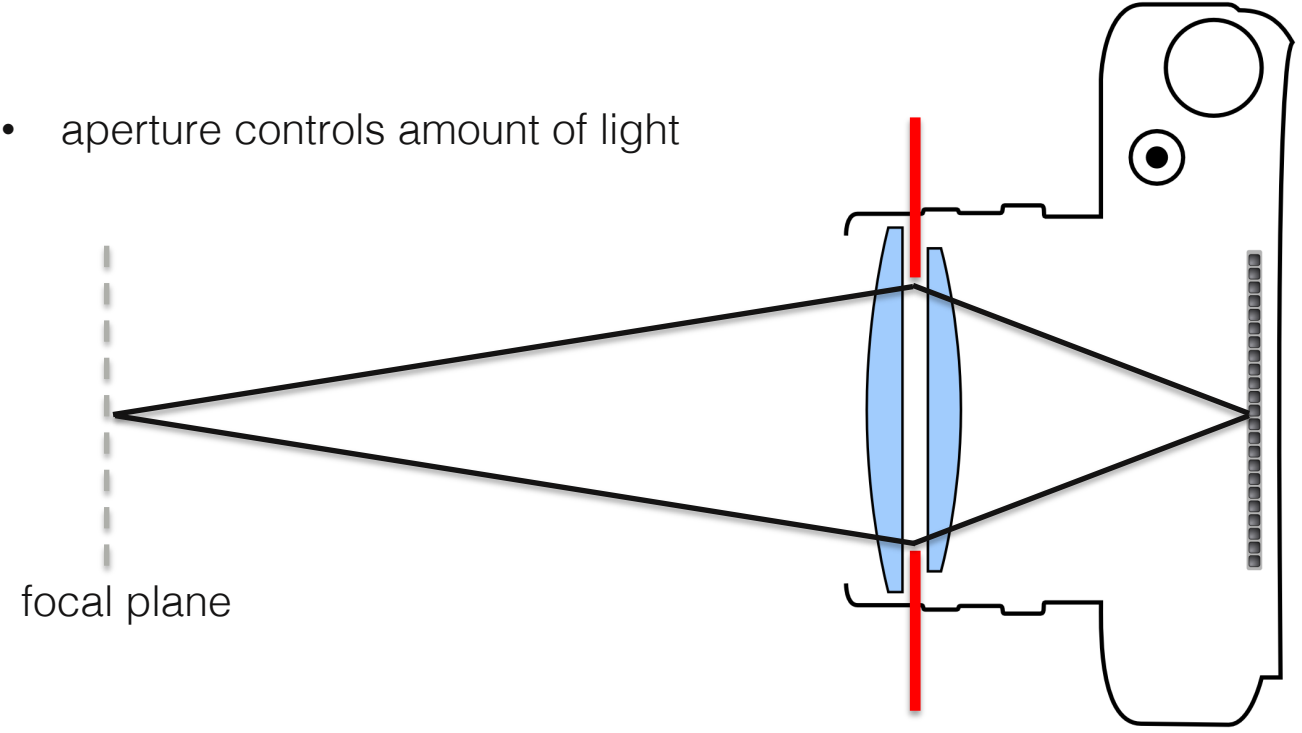
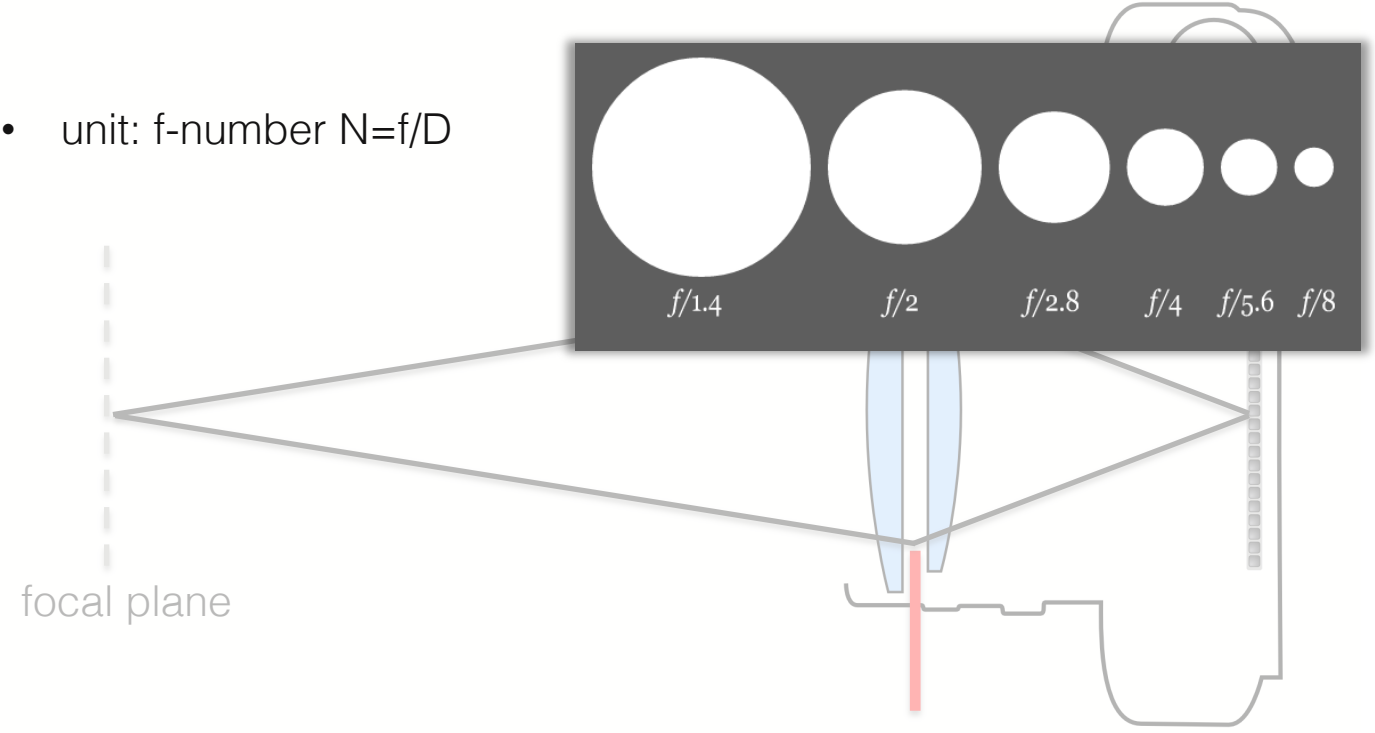


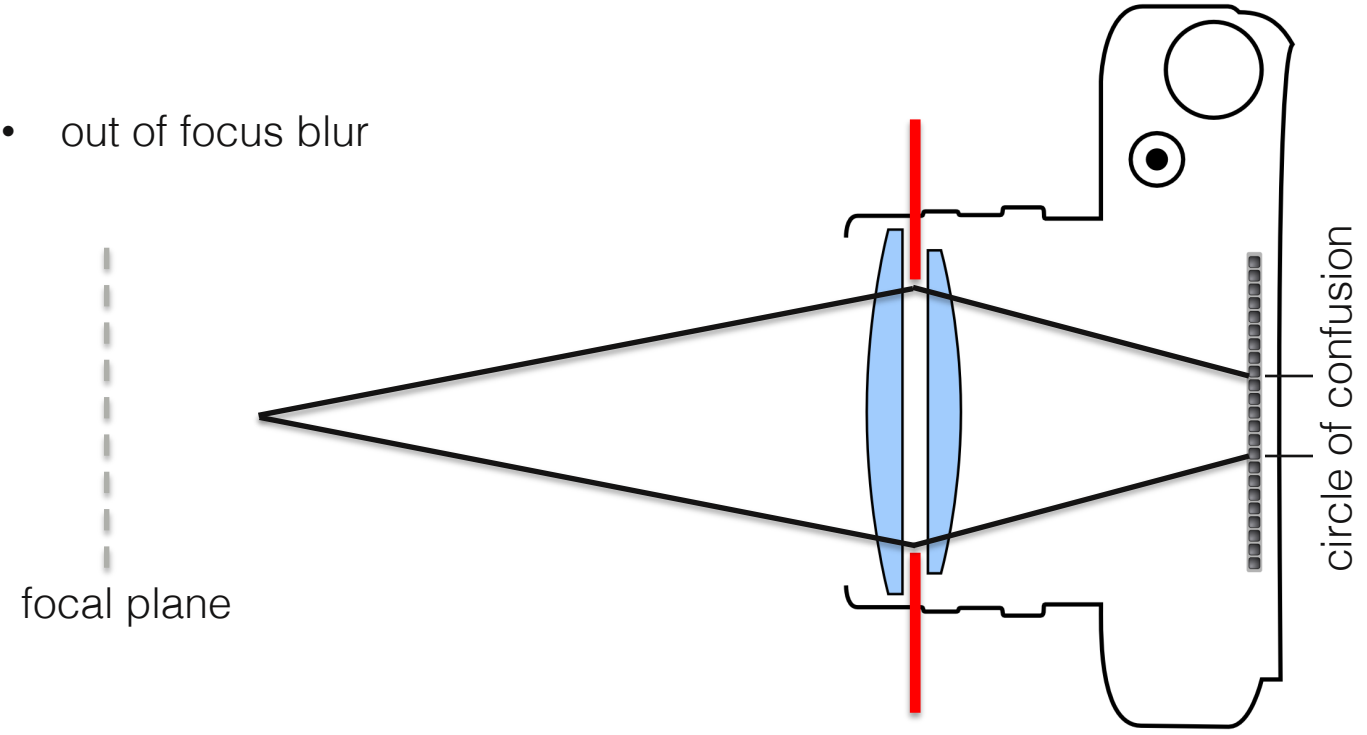
Aperture

- unit: f-number N=f/D



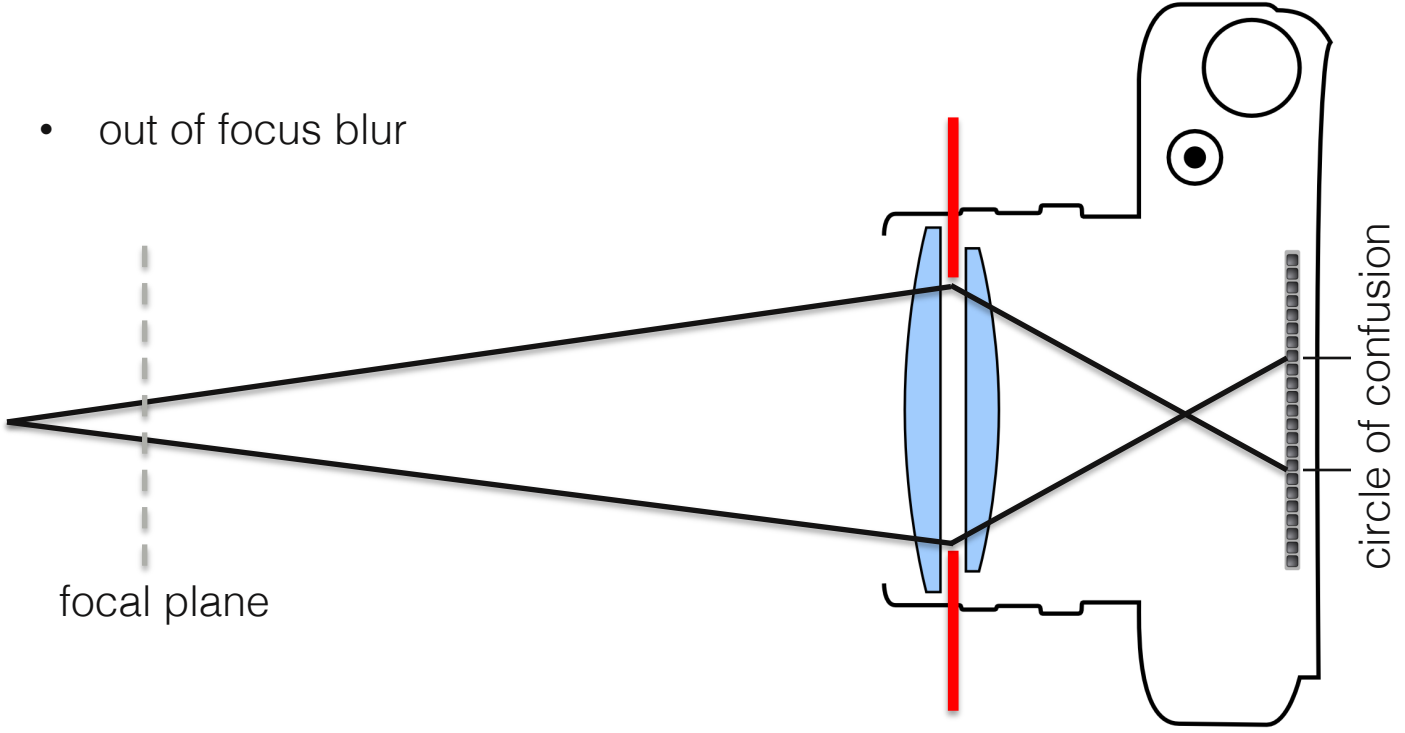
Aperture

- out of focus blur

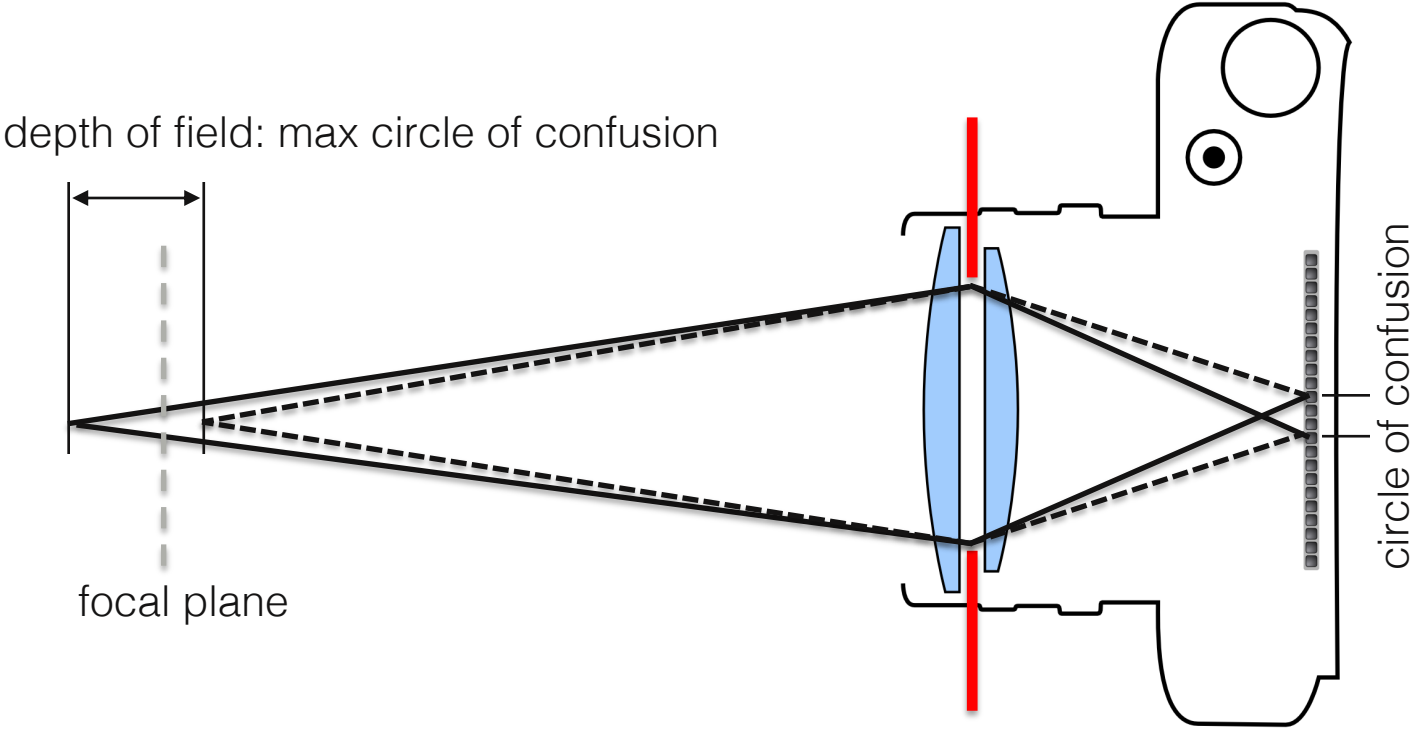


Aperture

- out of focus blur



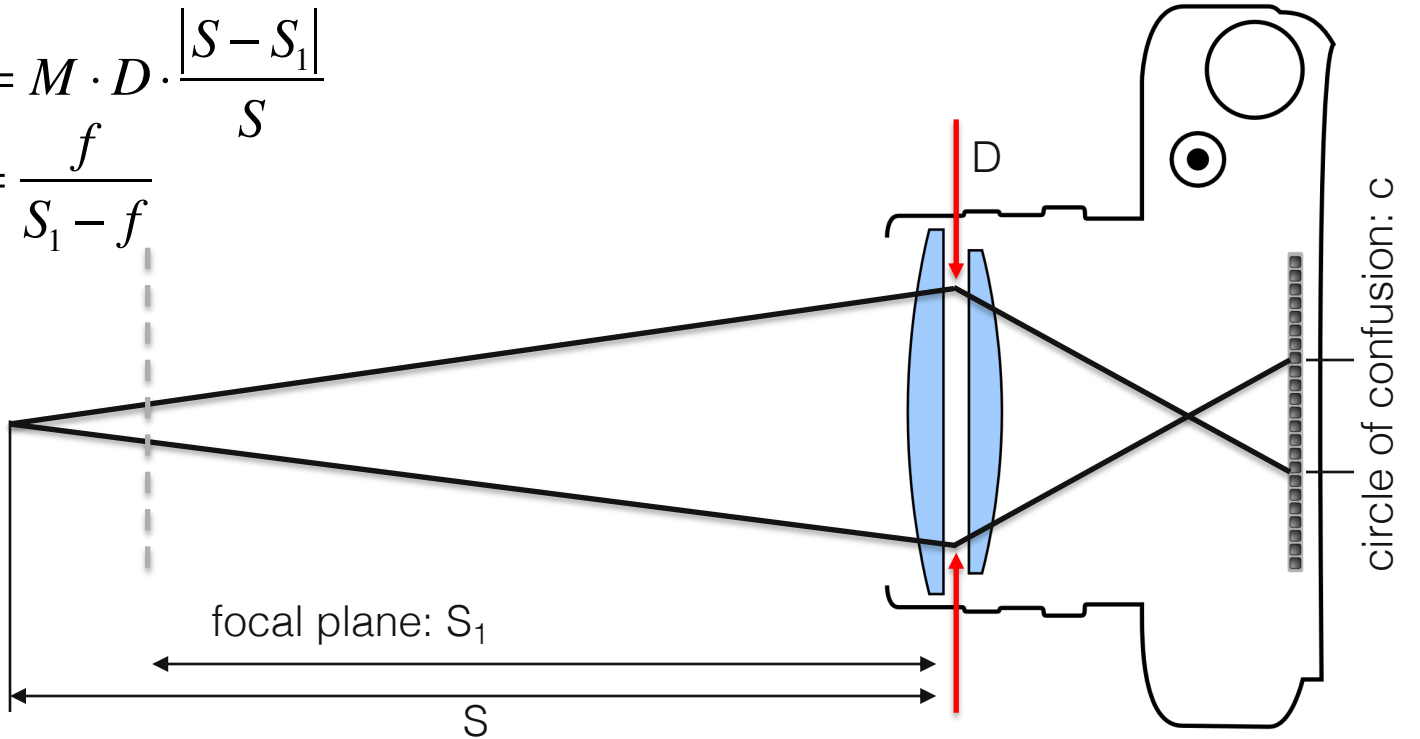
Depth of Field



Circle of Confusion

$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

$$M = \frac{f}{S_1 - f}$$

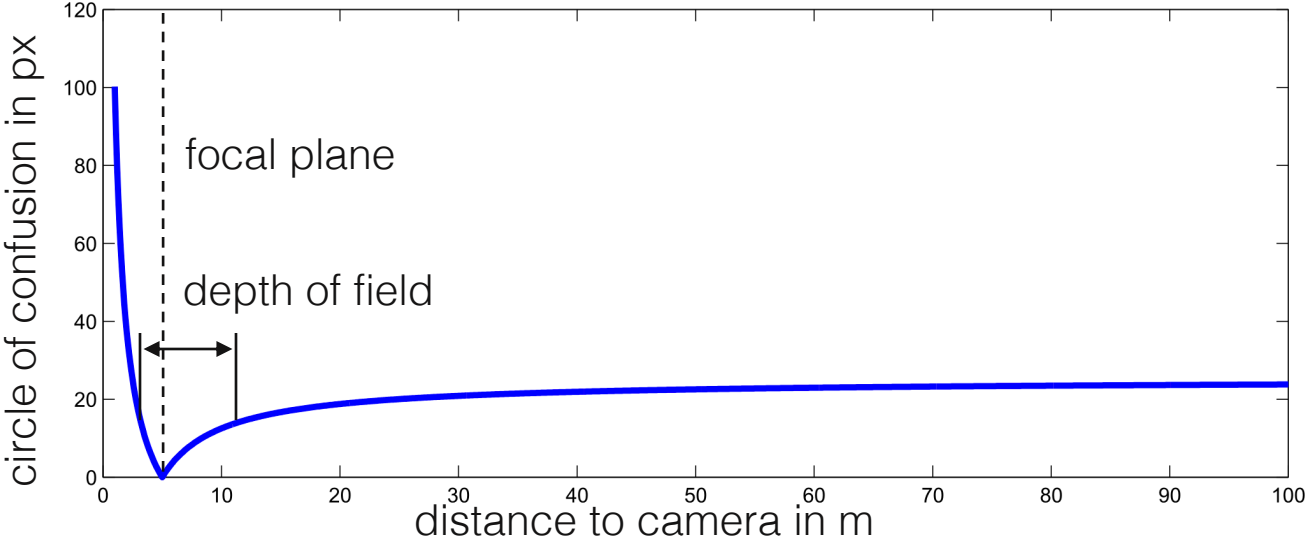


Circle of Confusion

$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

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

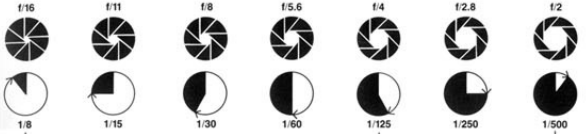
focused at 5m, pixel size=7.5um

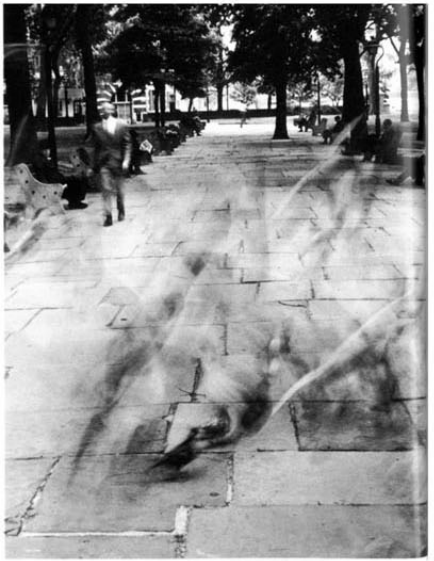


Depth of Field

http://photographywisdom.com/

Depth of Field & Motion Blur





London, Photography

Bokeh

artistic use

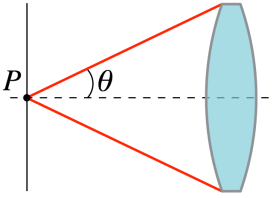
two delighted blog

coded aperture

Levin et al., SIGGRAPH 2007

Diffraction Limit

f-number

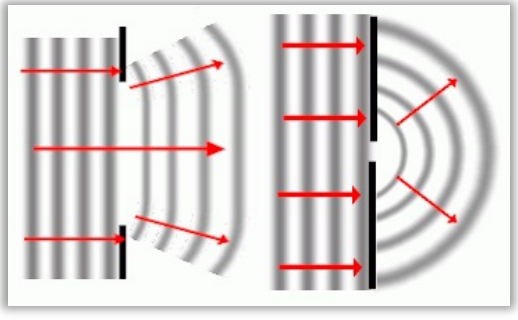


- Ernst Abbe 1873: $d = \frac{\lambda}{2n\sin\theta}$

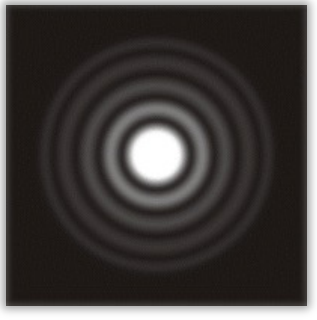
spot radius (image space)

numerical aperture

diffraction

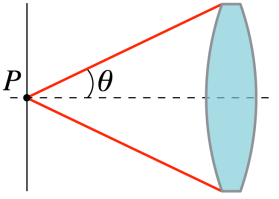


Airy pattern



wikipedia

Diffraction Limit



- Ernst Abbe 1873: $d = \frac{\lambda}{2n\sin\theta} = \frac{\lambda}{2NA} \approx \lambda N$

f-number

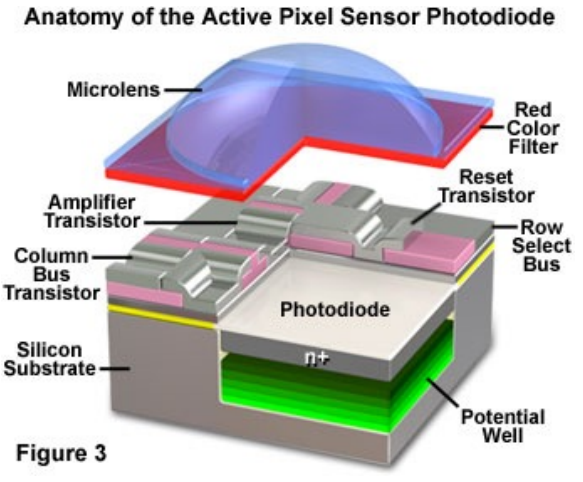
numerical aperture

- microscope objectives today: NA 1.4-1.6 → 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)

Sensors

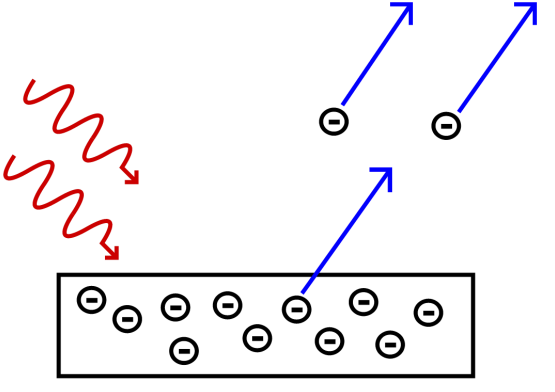
What's a Pixel?



source: Molecular Expressions

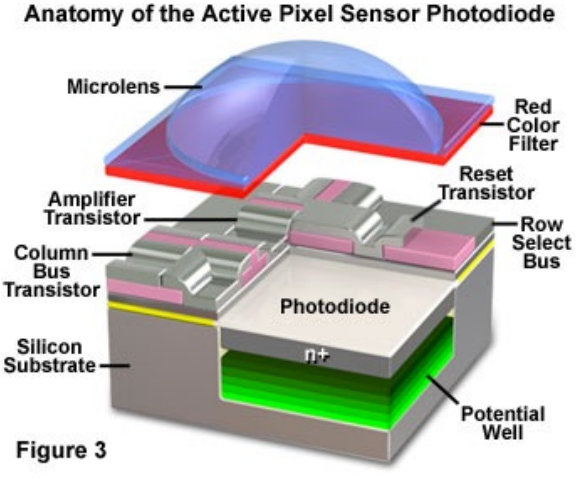
photon to electron converter

→ photoelectric effect!



wikipedia

What's a Pixel?



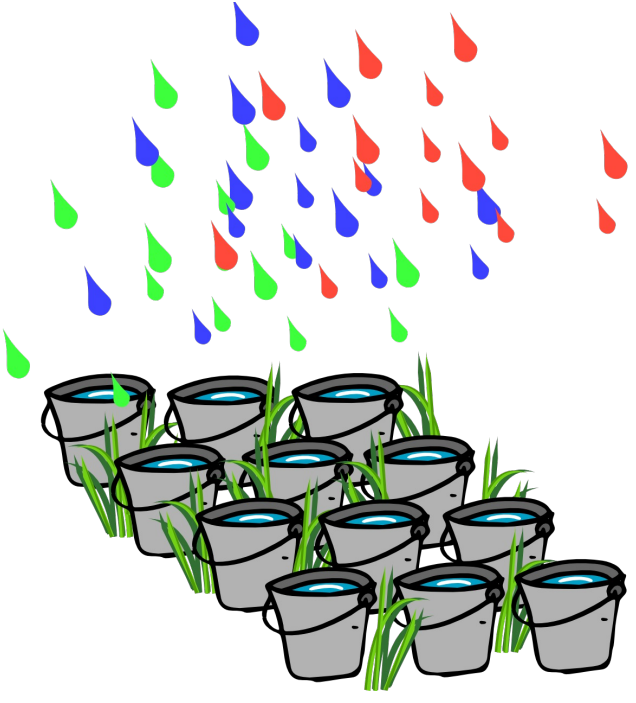
source: Molecular Expressions

- microlens: focus light on photodiode
- color filter: select color channel
- quantum efficiency: ~50%
- fill factor: fraction of surface area used for light gathering

What's a Pixel?

What's a Pixel?

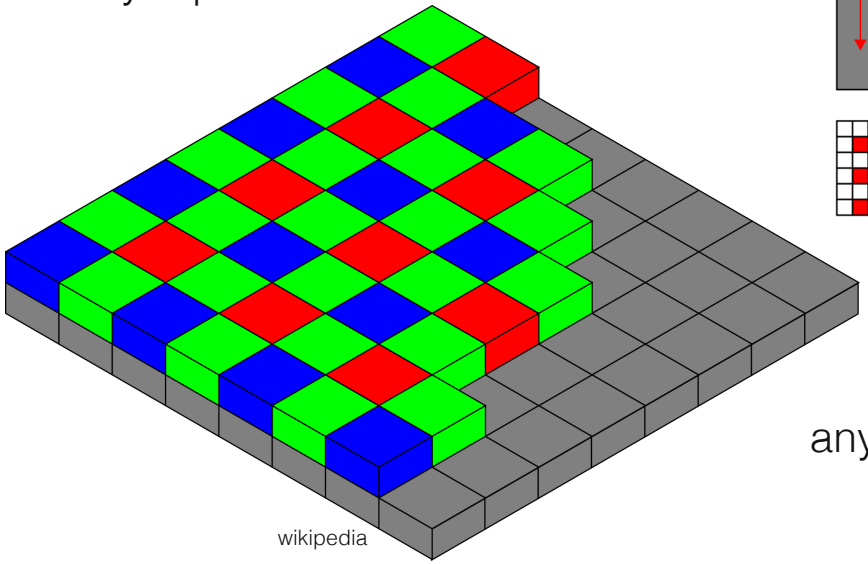
What's a Pixel?



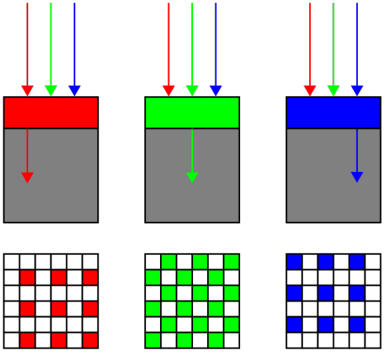
What's a Pixel?

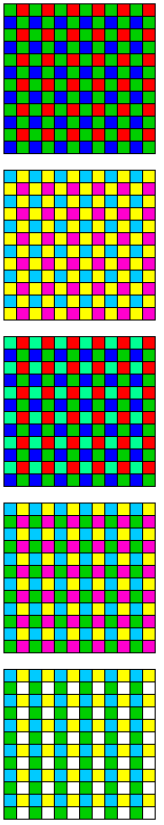
Most Common: Color Filter Arrays

Bayer pattern



wikipedia

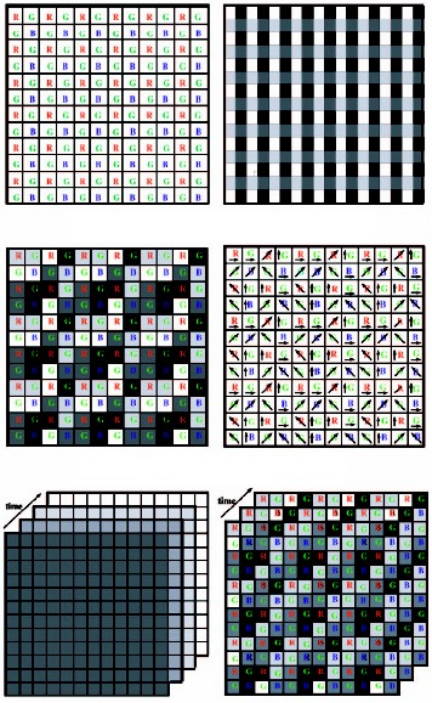




any combination possible

tradeoffs?

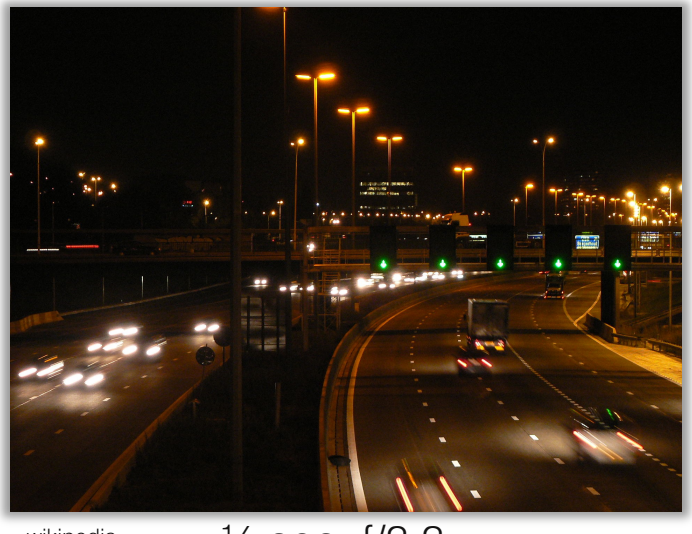
Assorted Pixels



- Narasimhan & Nayar @ Columbia
- multiplex anything: polarization, color, time, ND, …

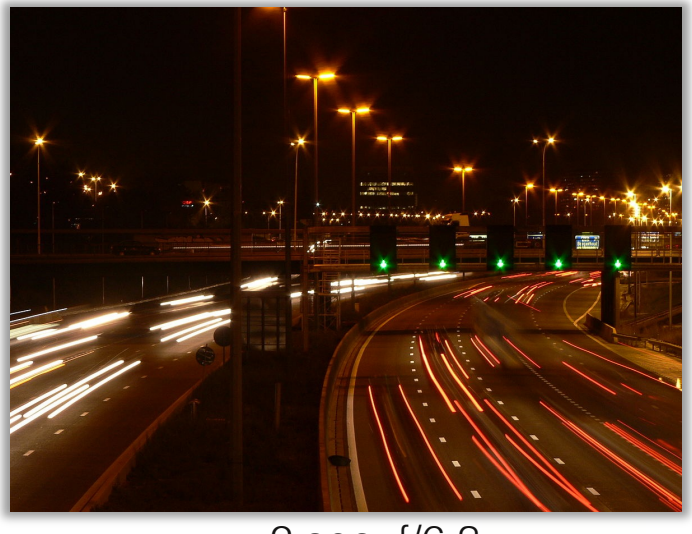
Exposure (shutter speed)

- exposure = irradiance * time (e.g. 1/250, 1/60, 1, 15, bulb)



wikipedia

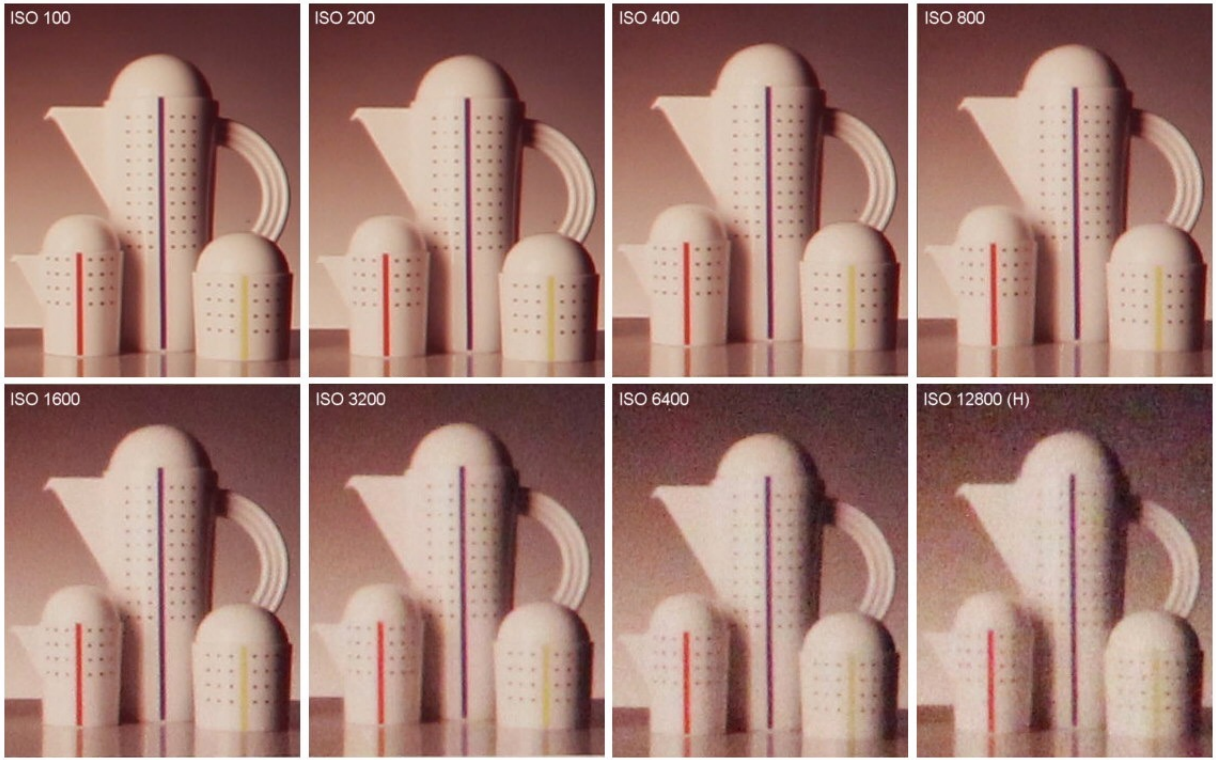
¼ sec, f/3.3



2 sec, f/6.3

ISO (“film speed”)

sensor sensitivity – analog gain applied before ADC!



bobatkins.com

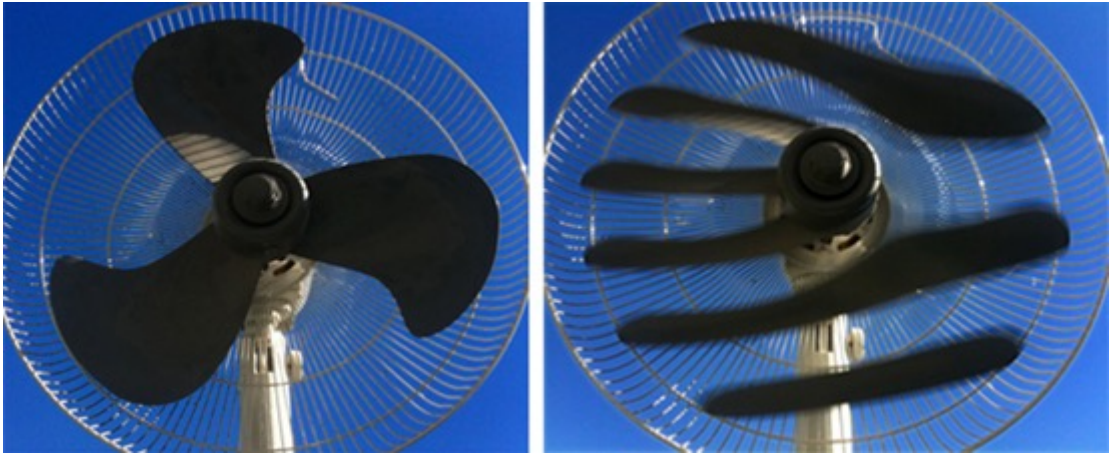
Dynamic Range

- ratio between largest and smallest possible value
- bit depth also important! common bit depths: 12-14 bits RAW / 8 bits JPEG

high dynamic range →

Kevin McCoy

Global Shutter vs. Rolling Shutter



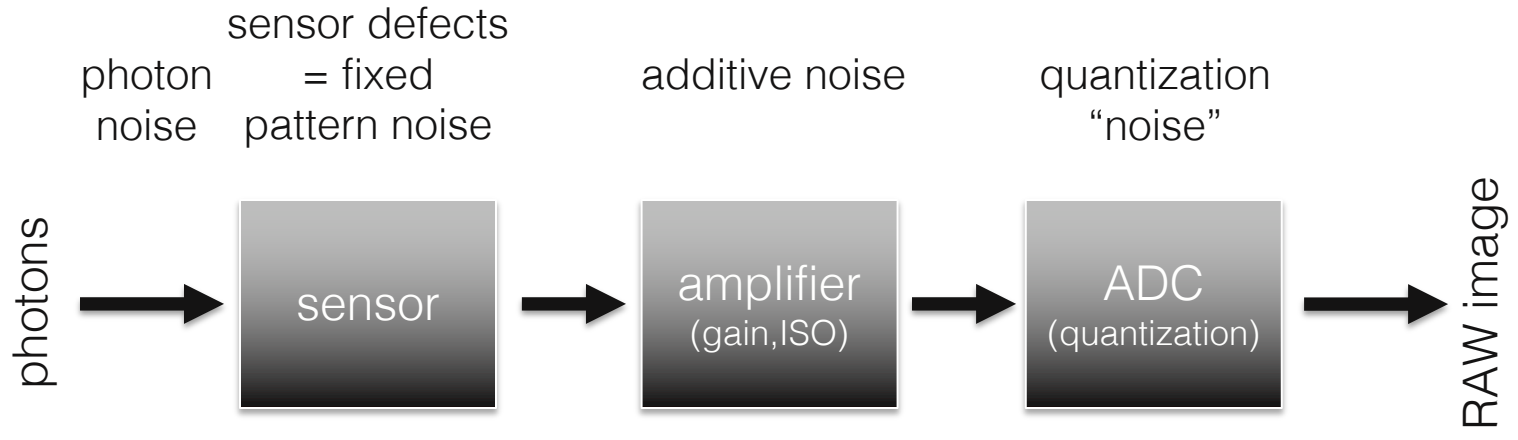
All sensor pixels exposed at same time

Row-by-row readout of image

- shorter exposure times per pixel
- motion artifacts

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

Photons to RAW Image



Sensor Noise

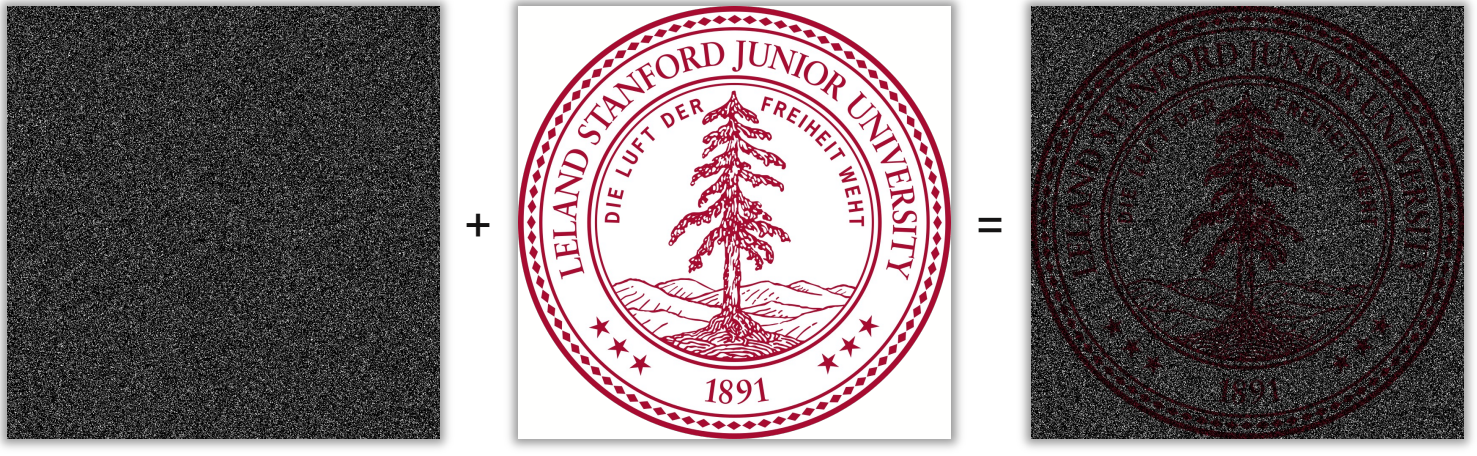
- noise is (usually) bad!

- 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)

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma} \longleftarrow \begin{matrix}\text{signal} \\ \text{noise}\end{matrix}$$

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

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

Q_e = quantum efficiency

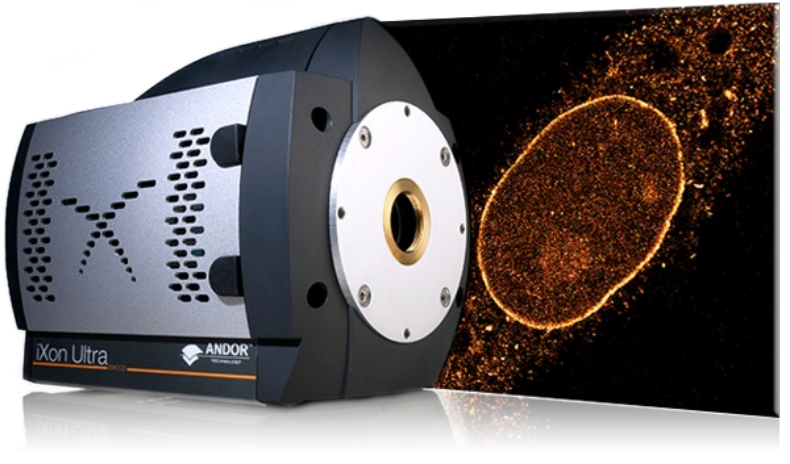
t = eposure time (sec)

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



Digital Photography

- optics
- aperture
- depth of field
- field of view
- exposure
- noise
- color filter arrays
- image processing pipeline

Digital Photography – Additional Resources

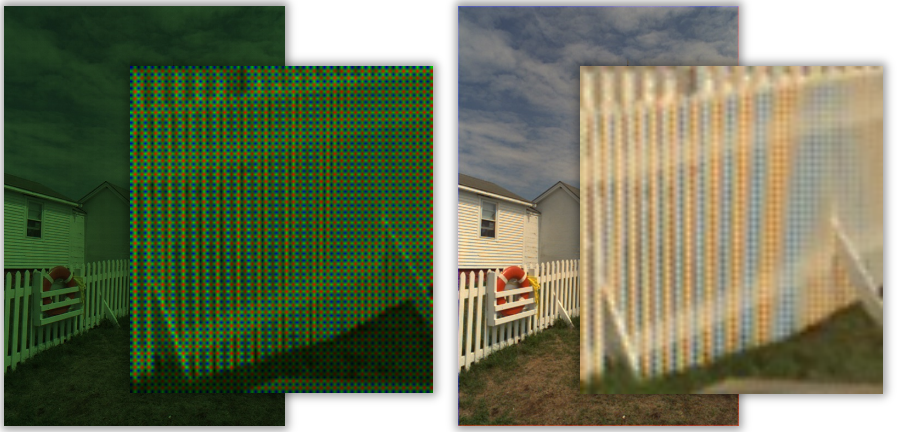
- What we left out: metering, autofocus, autoexposure, anti-aliasing filter, IR filter (and probably much more)

- Stanford CS 178 – Digital Photography: slides, applets, and other material online

- looking for a camera? check dpreview.com

Next: The Image Processing Pipeline

- RAW images
- demosaicking
- denoising
- deblurring
- white balancing
- gamma correction
- compression



Homework 2

- calculate and plot depth of field of different cameras (today's lecture)

- implement a simple image processing pipeline in Python and explore demosaicking, denoising, etc. (next lecture)

References and Further Reading

- London, Upton, Stone, “Photography”, Pearson, 11th edition, 2013
- Stanford CS 178, “Digital Photography”, Course Notes
- wikipedia