

Digital Photography I

Optics & Sensors

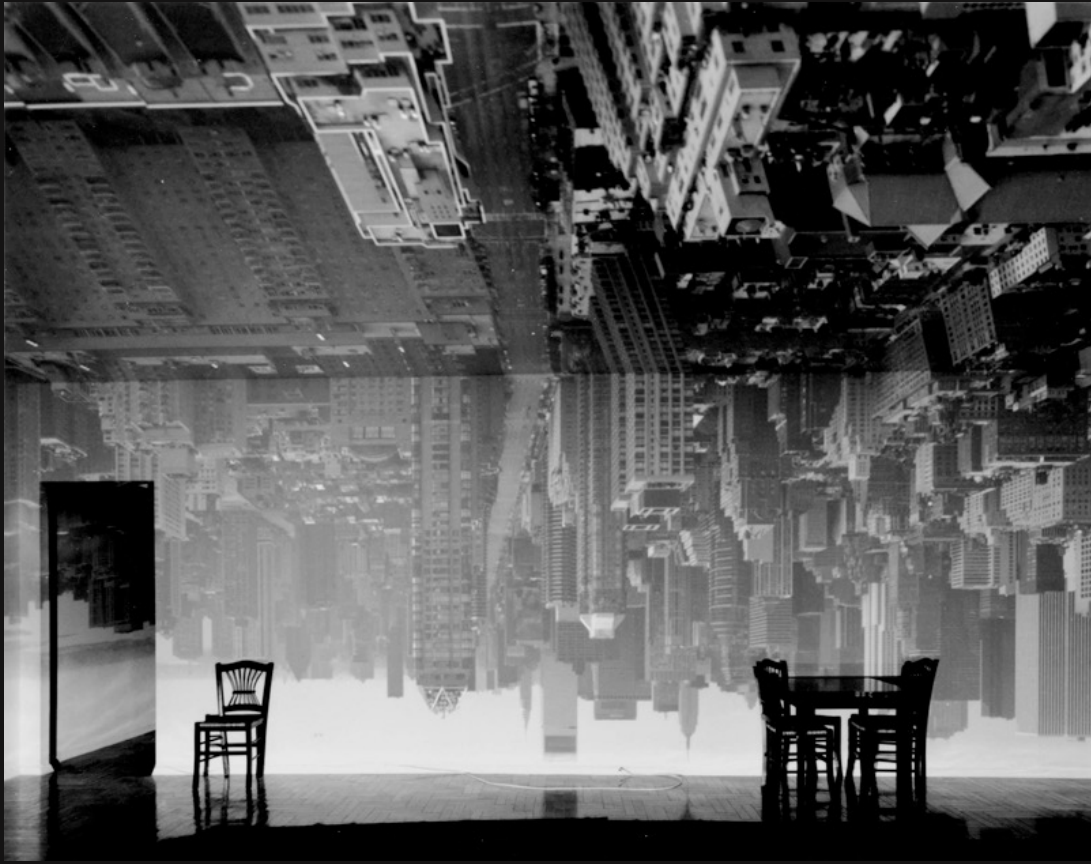
EE367/CS448I: Computational Imaging

stanford.edu/class/ee367

Lecture 3

Gordon Wetzstein
Stanford University



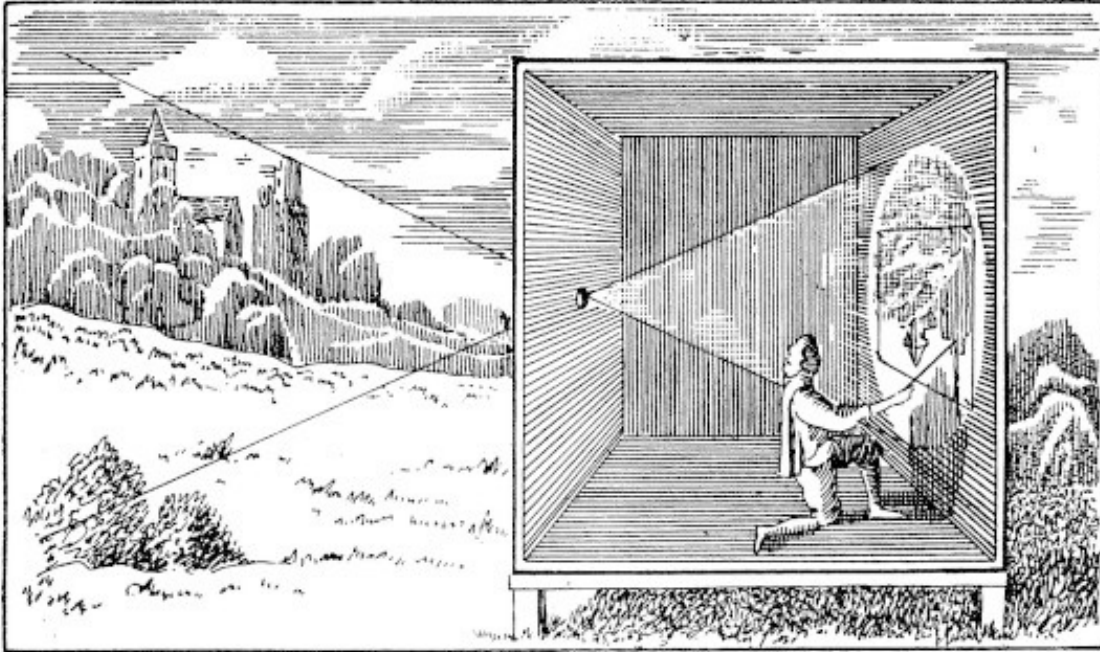






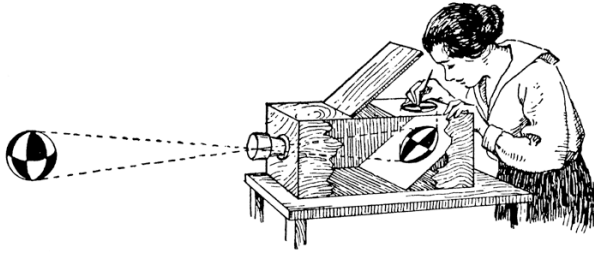
Abelardo Morell

Pinhole Camera / Camera Oscura



Mo-Ti (Chinese Philosopher) 470-390 BC

Pinhole Camera / Camera Oscura



J. Vermeer "The Milkmaid", 1658



同サイズの《牛乳を注ぐ女》が投影される額縁の前に立ち

Credit: ©Toppan Printing Co., Ltd.

Original photo data (Het melkmeisje [The Milkmaid] by Johannes Vermeer) :

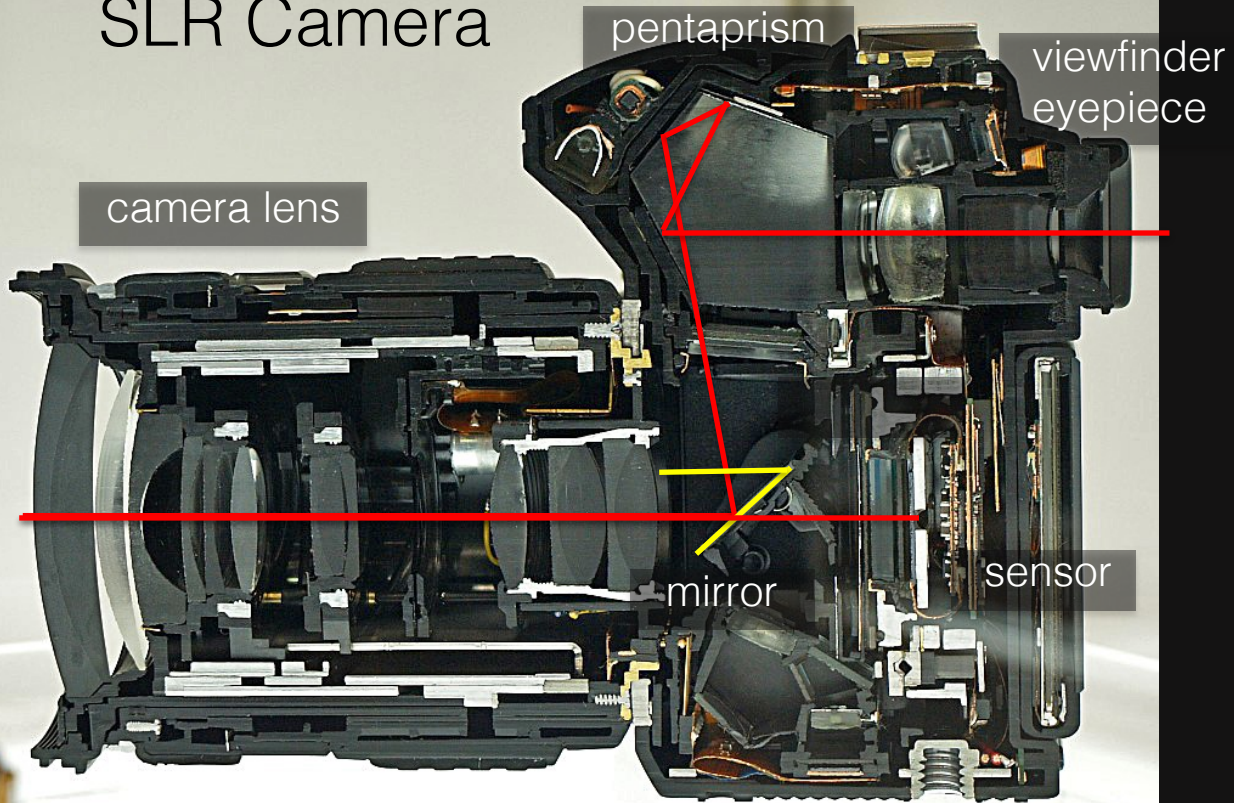
©Rijksmuseum Amsterdam. Purchased with the support of the Vereniging Rembrandt

Digital Photography - Overview

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



SLR Camera



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!

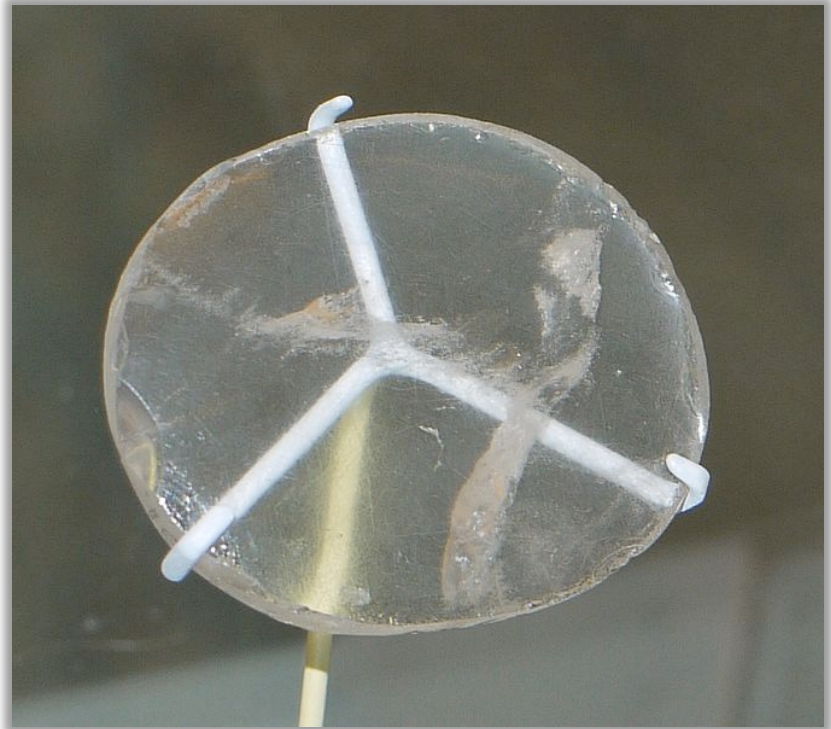
Daguerre "Boulevard du Temple", 1838



exposure
10-12 mins

Lenses

- focus light
- magnify objects

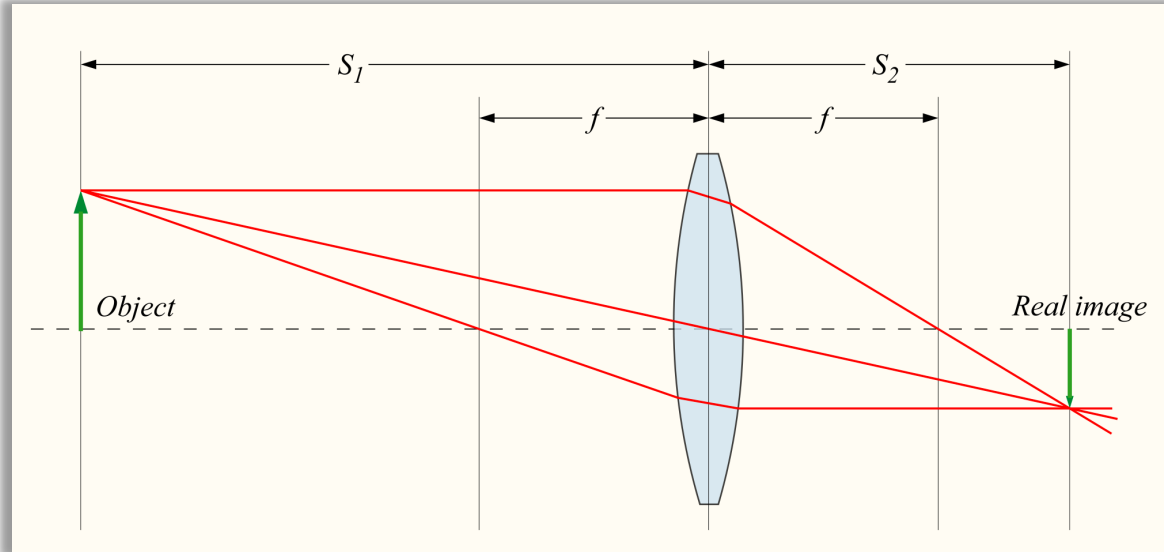


Nimrud lens - 2700 years old

Lenses

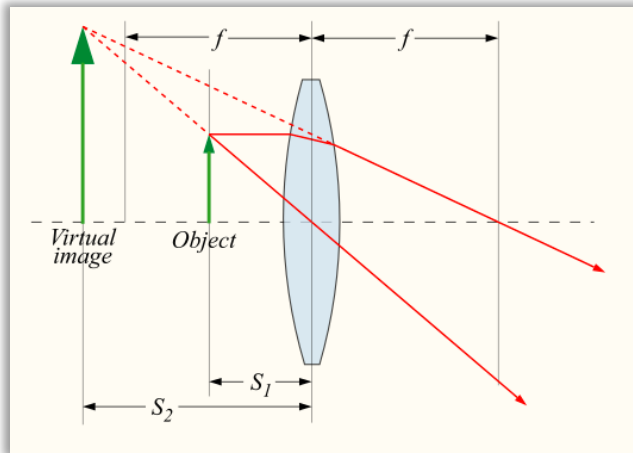
lensmaker's
equation: $\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2}$

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

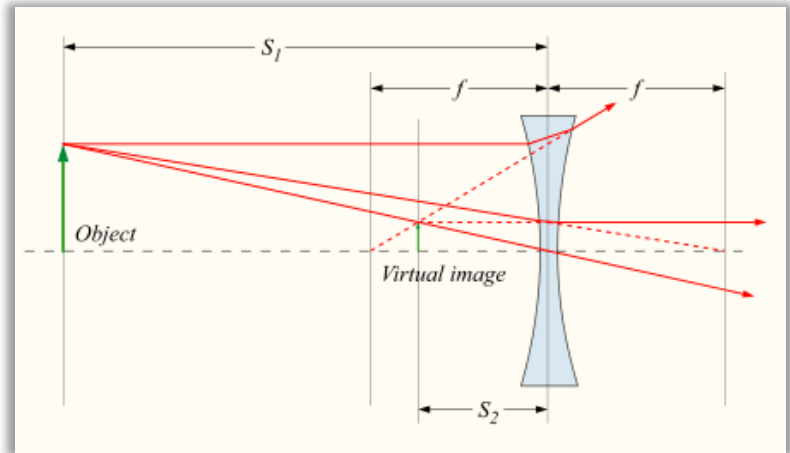


Lenses

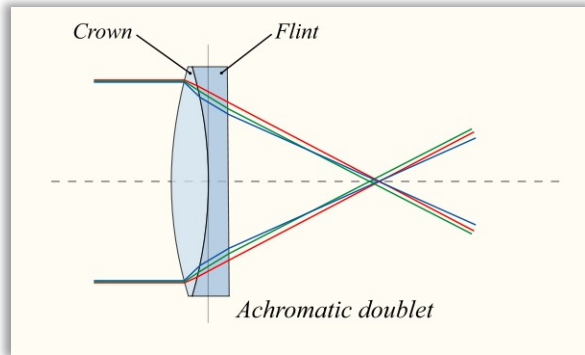
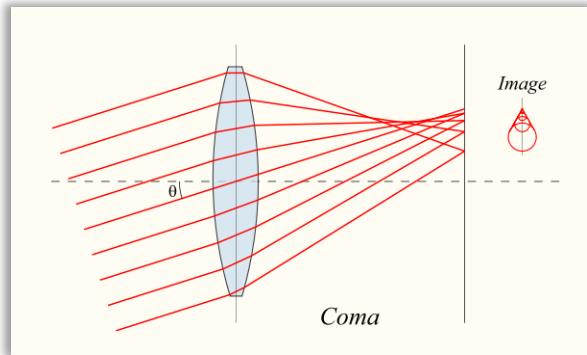
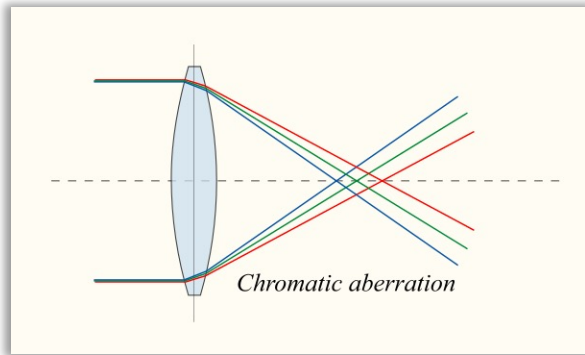
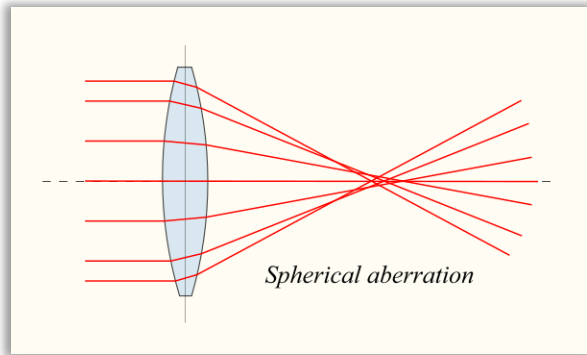
$S_1 < f$: magnifying glass



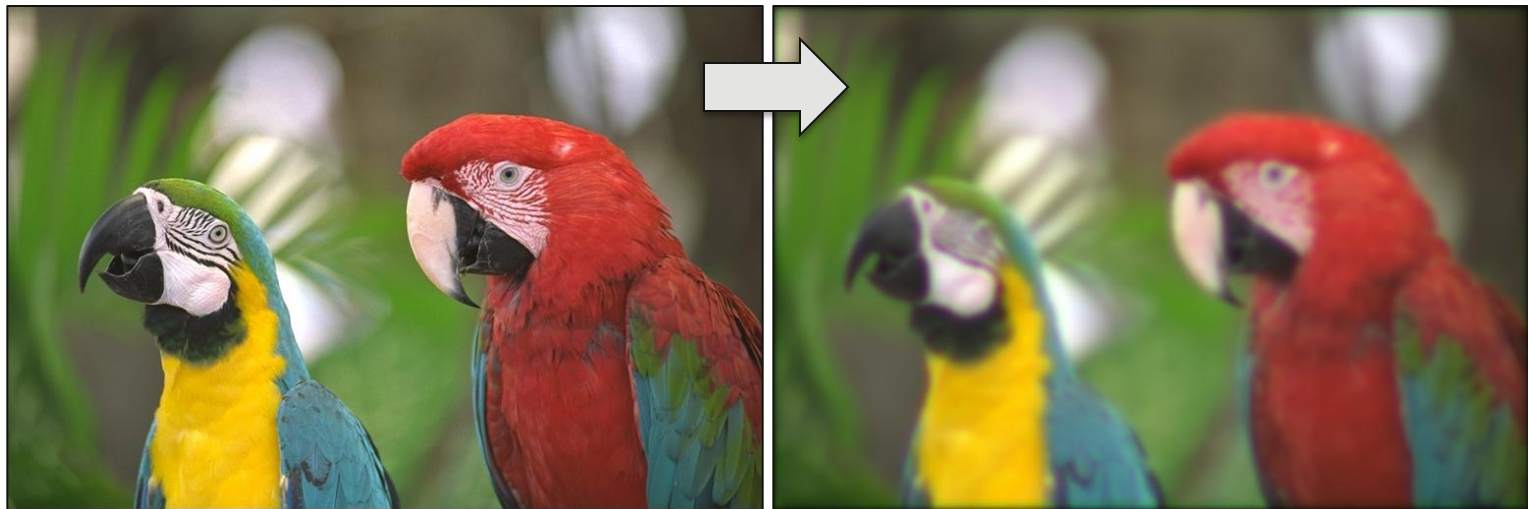
minification



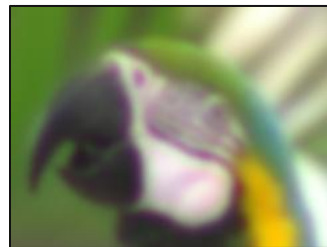
Lenses - Aberrations



Lenses - Aberrations

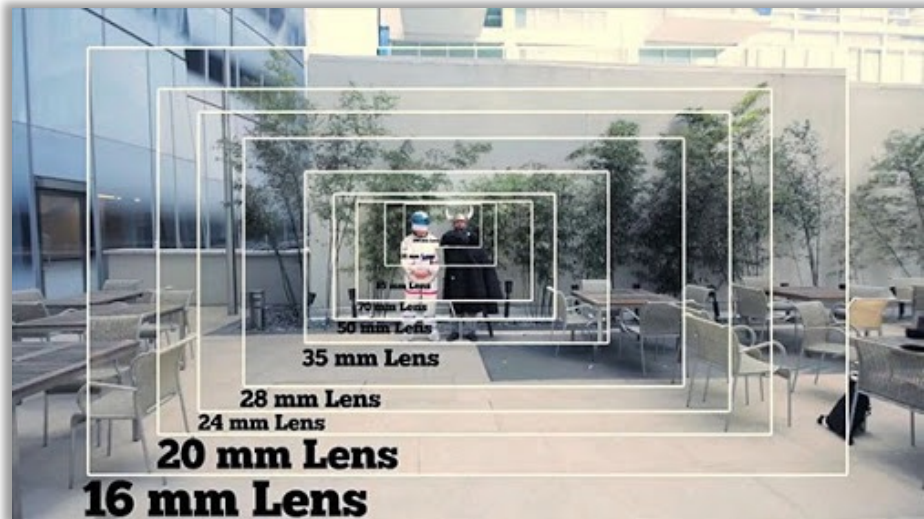
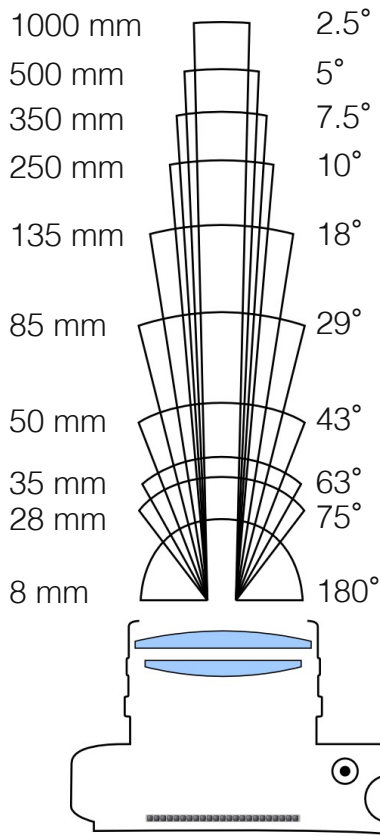


Sharp Image



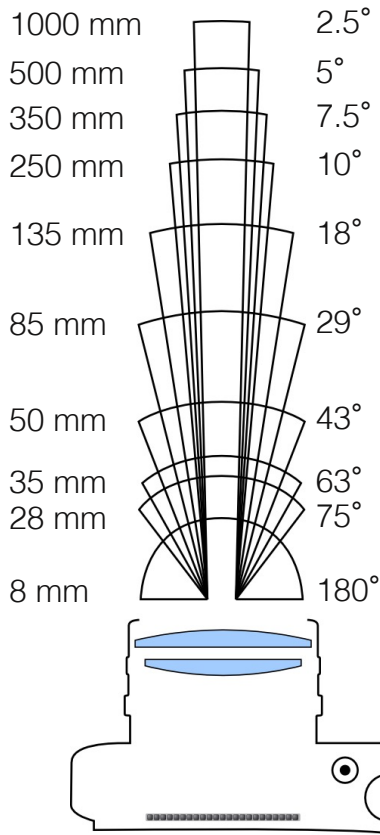
Blurred Image due to optical aberrations

Field of View

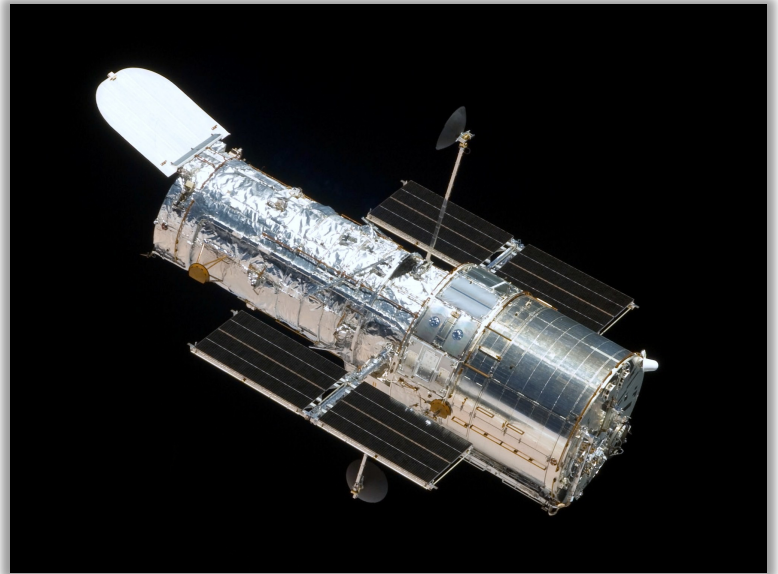


Andrew McWilliams

Field of View

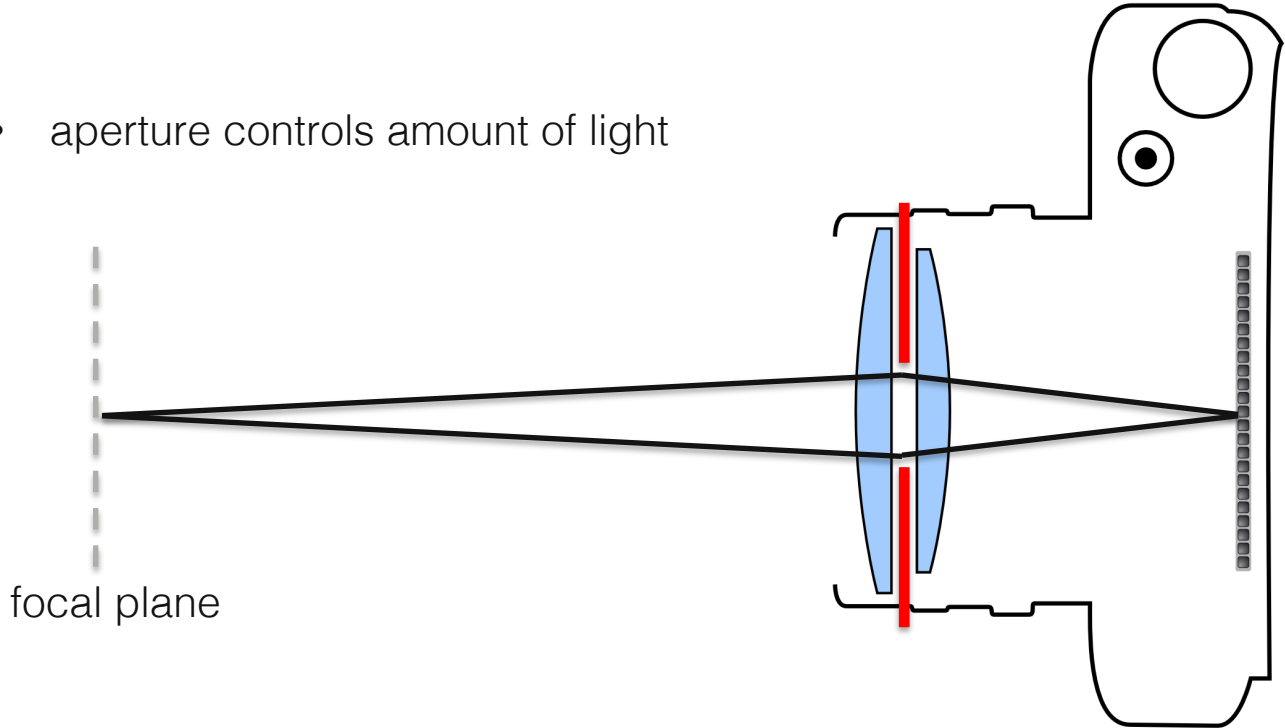


Hubble – what's the focal length?



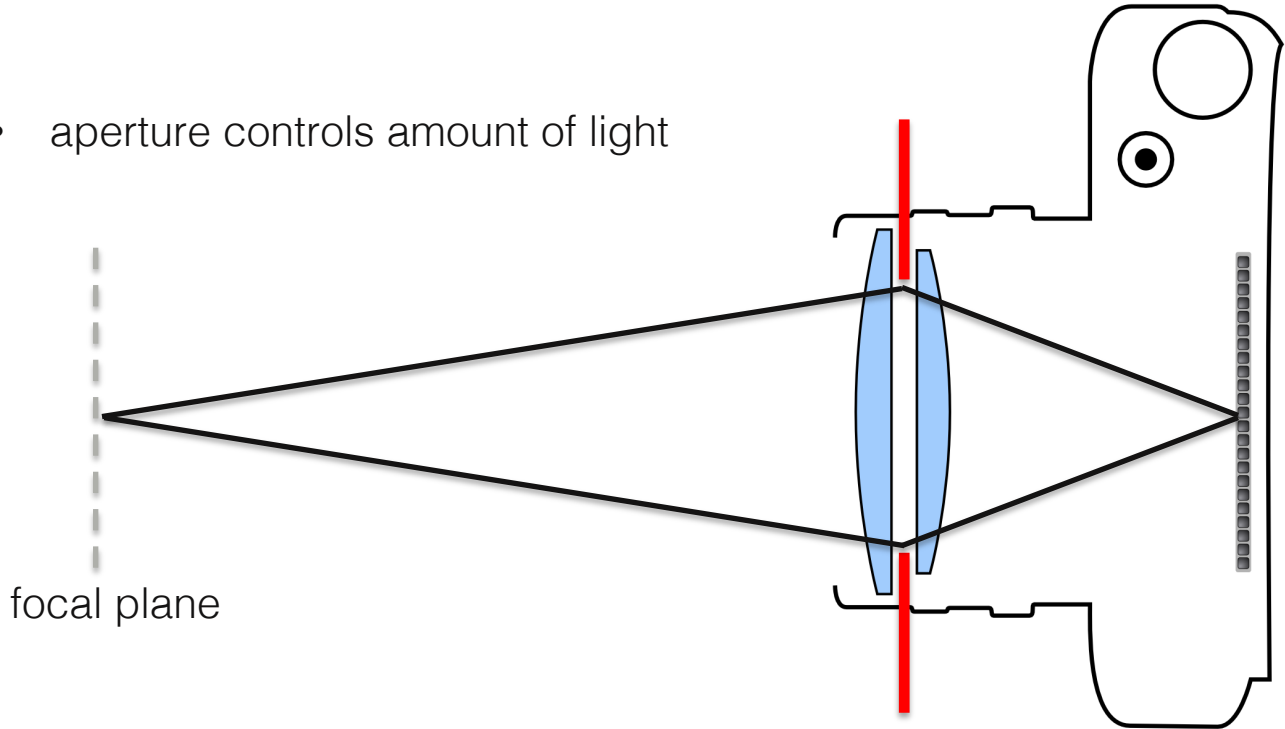
Aperture

- aperture controls amount of light



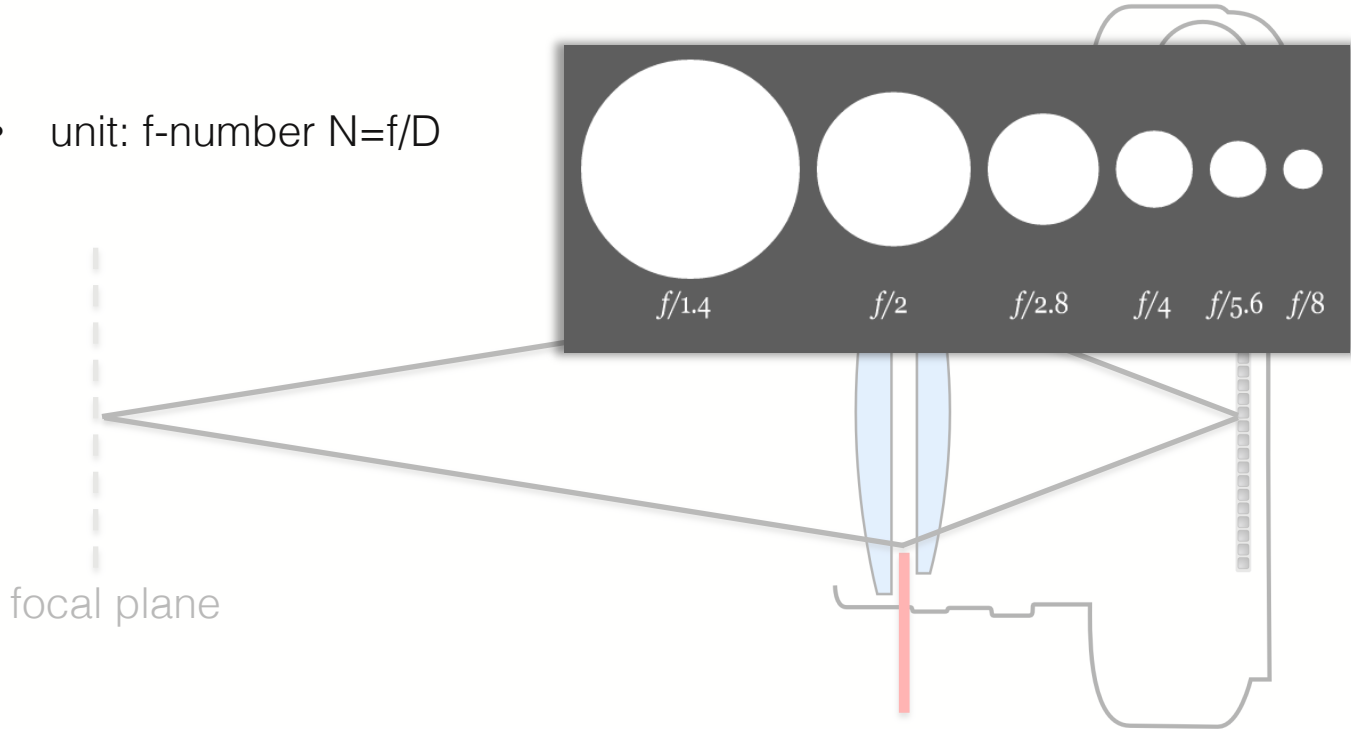
Aperture

- aperture controls amount of light



Aperture

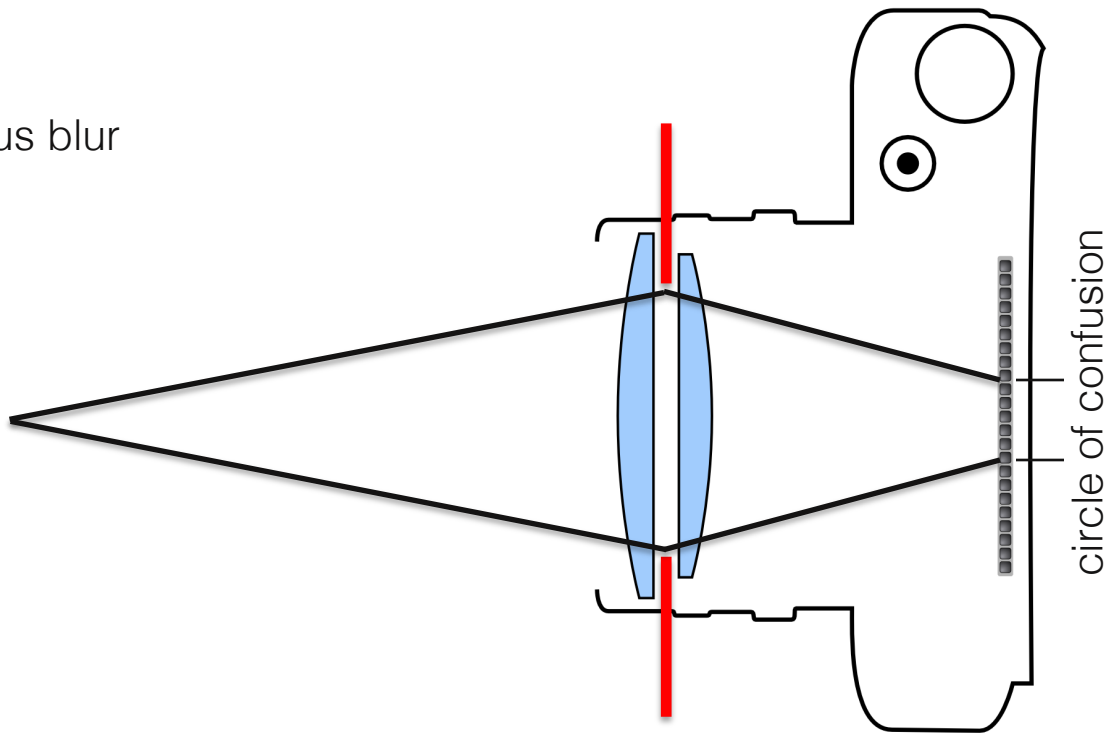
- unit: f-number $N=f/D$



Aperture

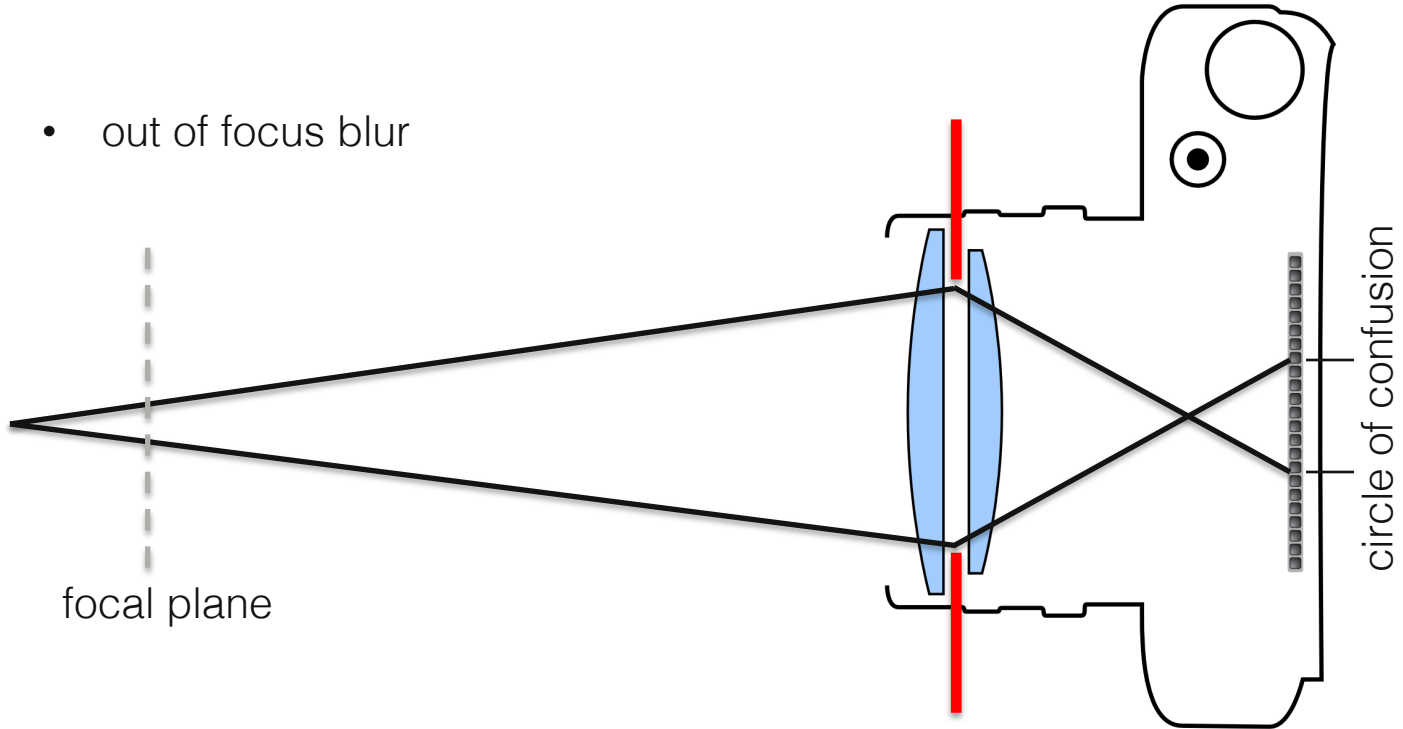
- out of focus blur

focal plane



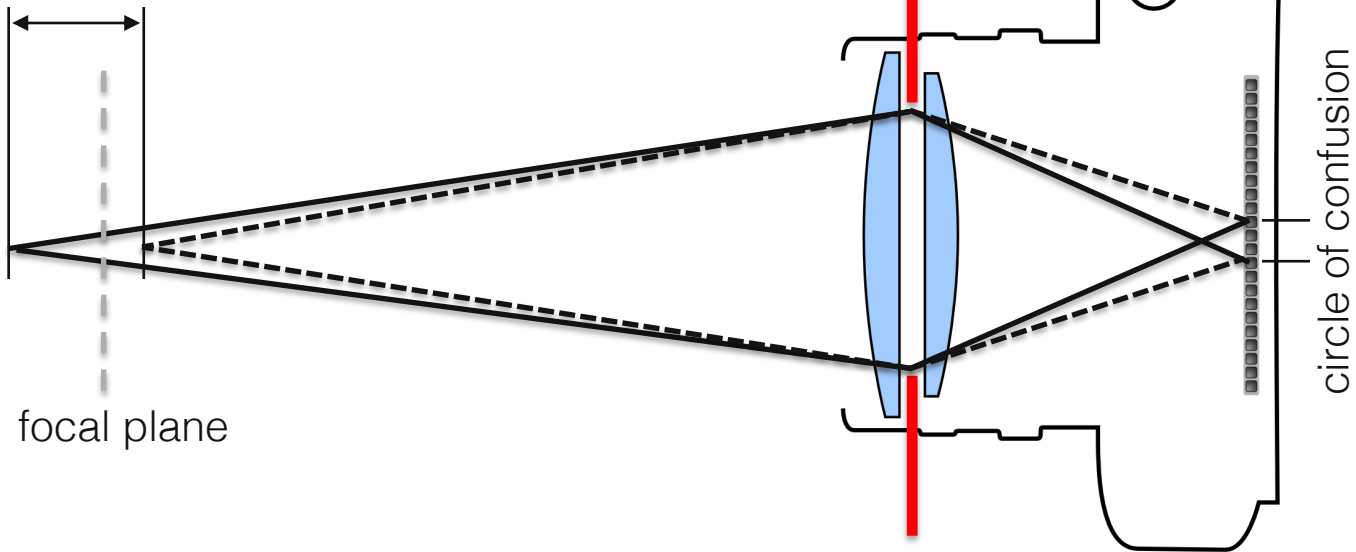
Aperture

- out of focus blur



Depth of Field

depth of field: max circle of confusion

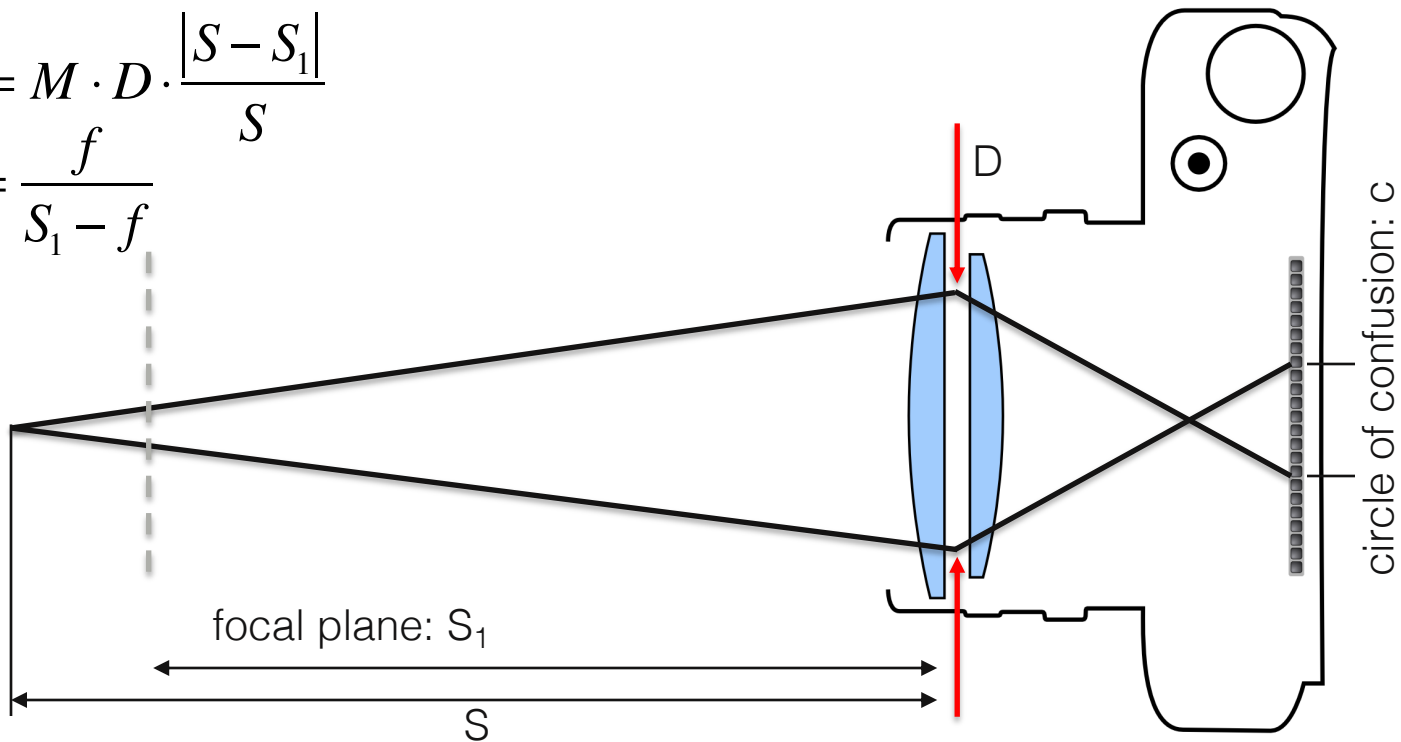


focal plane

circle of confusion

Circle of Confusion

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

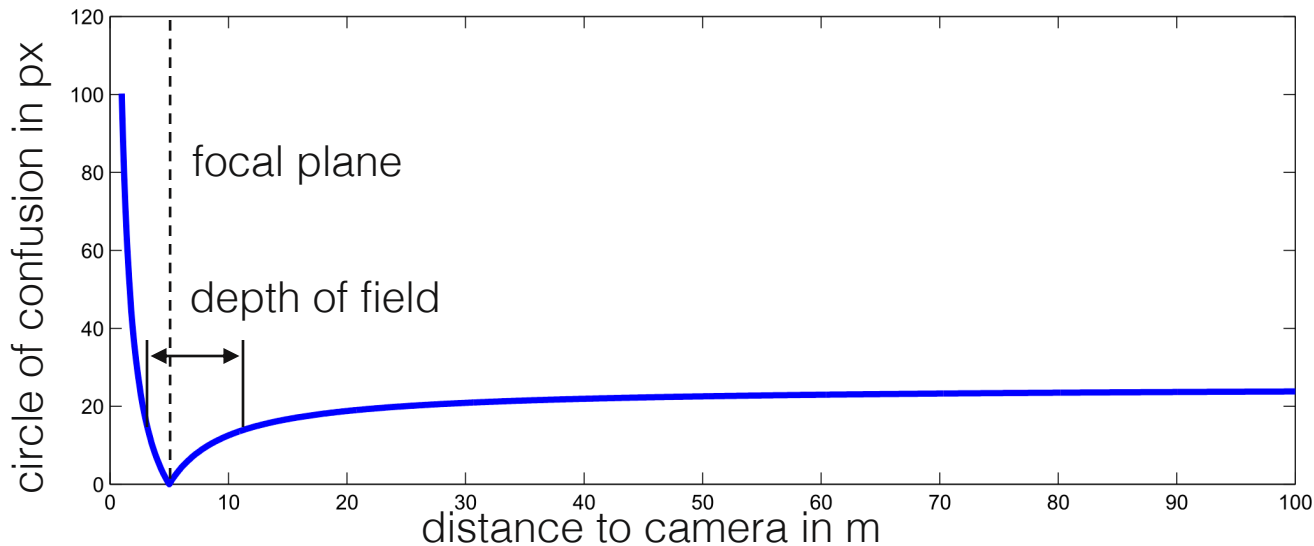


Circle of Confusion

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

Canon 5D Mark III: $f=50\text{mm}$, $f/2.8$ ($N=2.8$),

focused at 5m , pixel size= $7.5\mu\text{m}$



Depth of Field

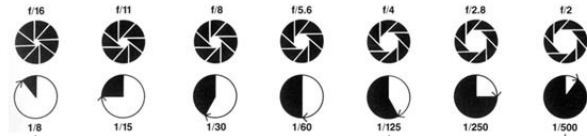


aperture....f 1.8
shutter.....1/500
ISO.....100
distance...~3ft

aperture....f 4
shutter.....1/125
ISO.....100
distance...~3ft

aperture....f 8
shutter.....1/40
ISO.....125
distance...~3ft

Depth of Field & Motion Blur



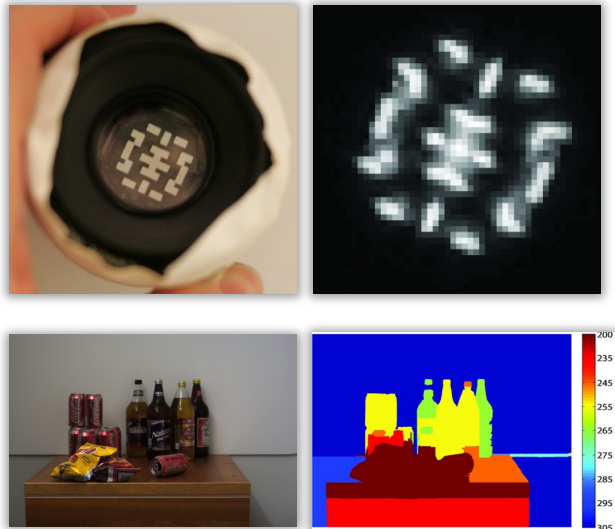
Bokeh

artistic use



two delighted blog

coded aperture



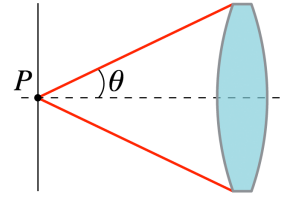
Levin et al., SIGGRAPH 2007

Diffraction Limit

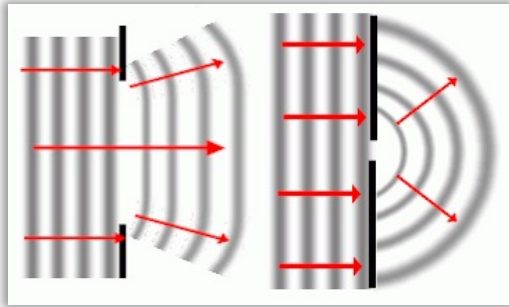
- Ernst Abbe 1873: $d = \frac{\lambda}{2n \sin \theta}$
spot radius (image space)

numerical aperture

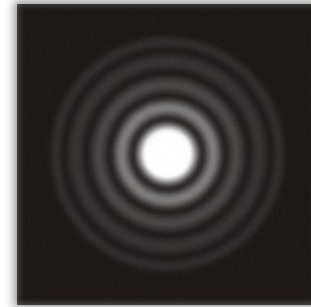
f-number
↓



diffraction



Airy pattern



Sensors

What's a Pixel?

Anatomy of the Active Pixel Sensor Photodiode

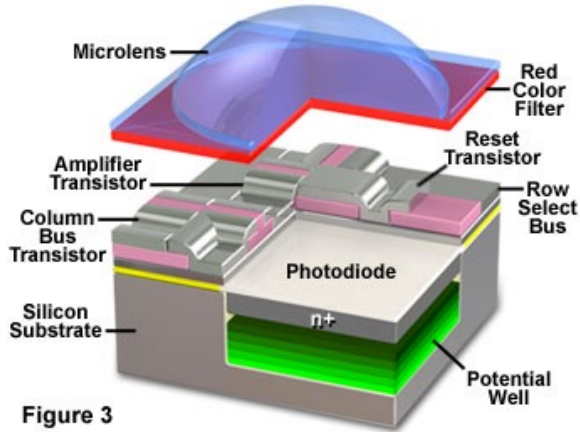
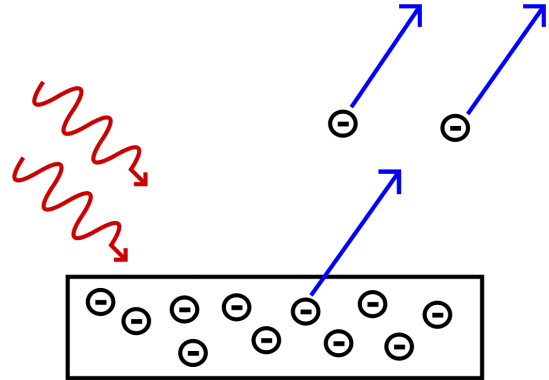


Figure 3

source: Molecular Expressions

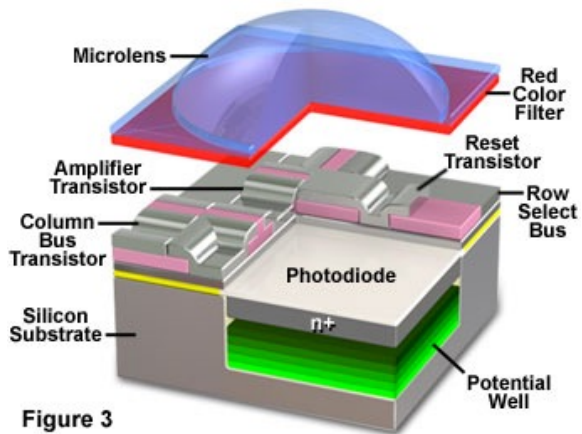
photon to electron converter
→ photoelectric effect!



wikipedia

What's a Pixel?

Anatomy of the Active Pixel Sensor Photodiode



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

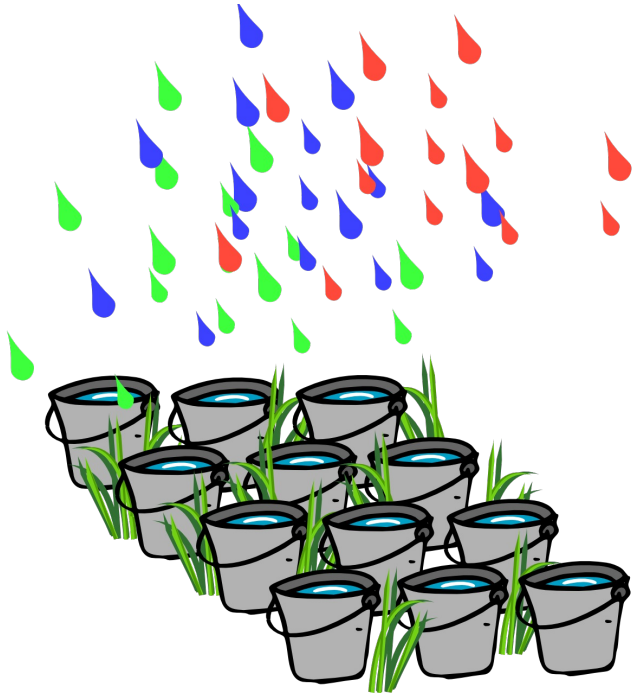
What's a Pixel?



What's a Pixel?



What's a Pixel?

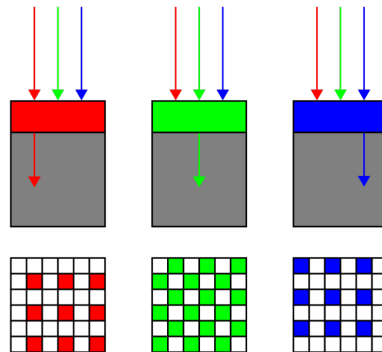
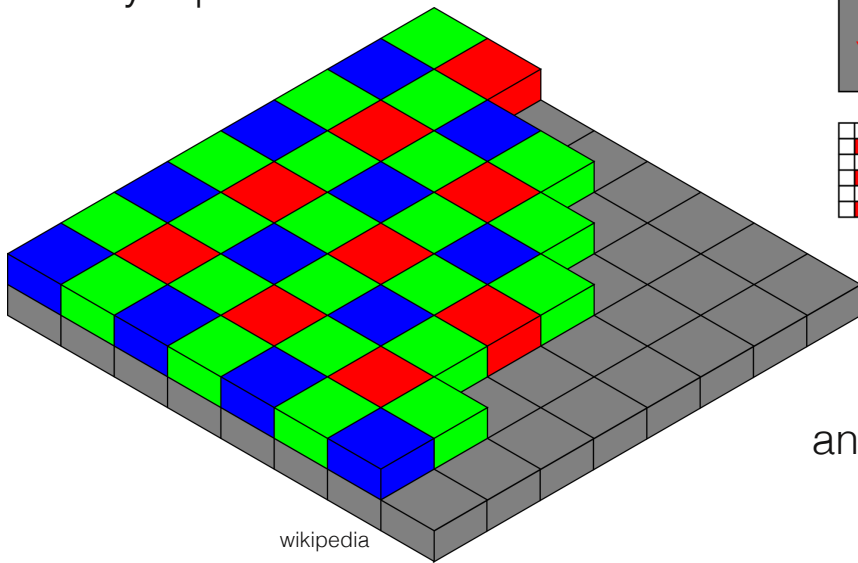


What's a Pixel?



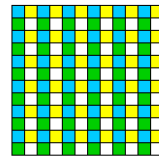
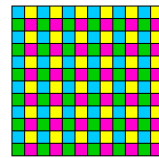
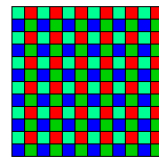
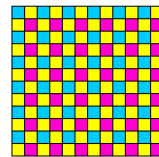
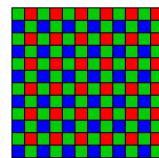
Most Common: Color Filter Arrays

Bayer pattern

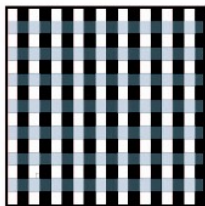
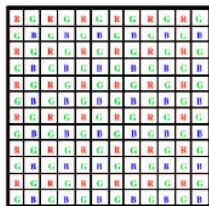


any combination possible

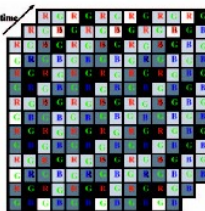
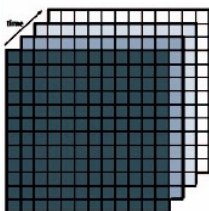
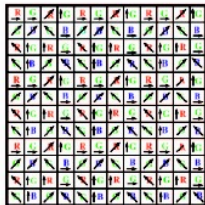
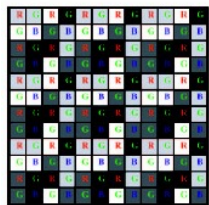
tradeoffs?



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

1/4 sec, f/3.3



2 sec, f/6.3

ISO (“film speed”)

sensor

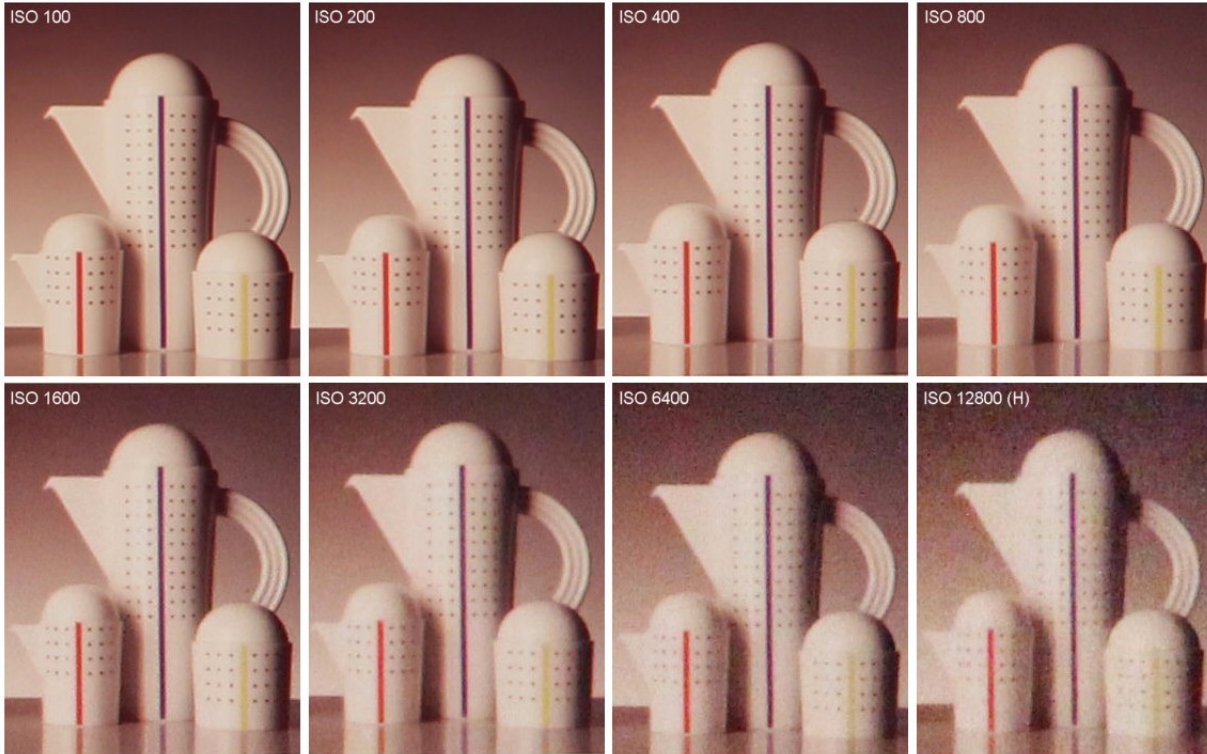
sensitivity

–

analog gain

applied before

ADC!



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



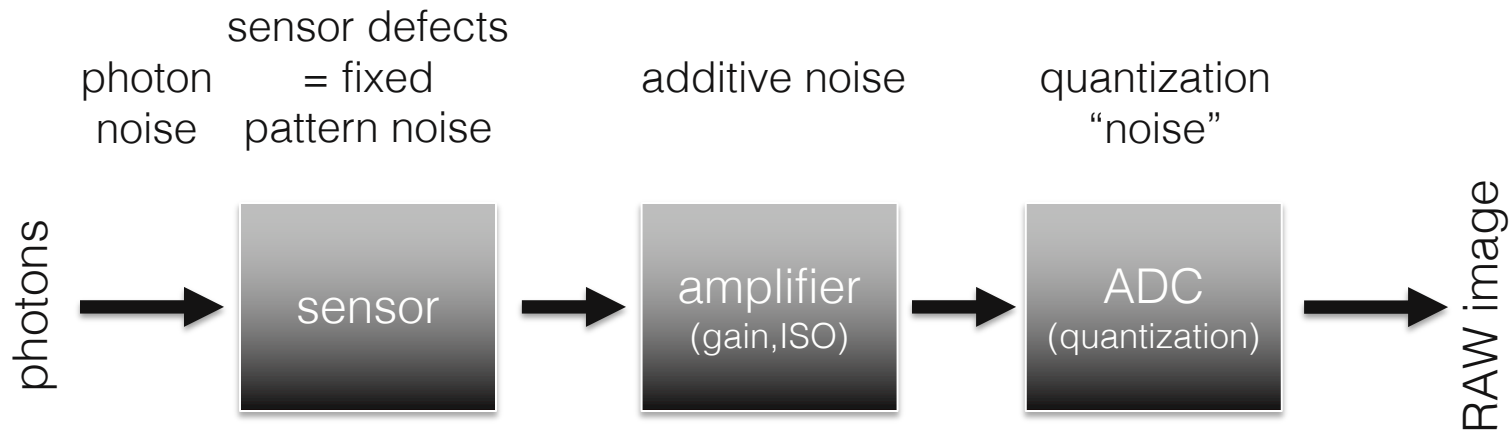
All sensor pixels exposed at same time



Row-by-row readout of image

- shorter exposure times per pixel
- motion artifacts

Photons to RAW Image

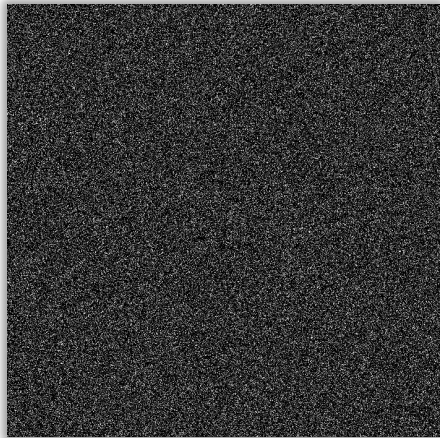


Sensor Noise

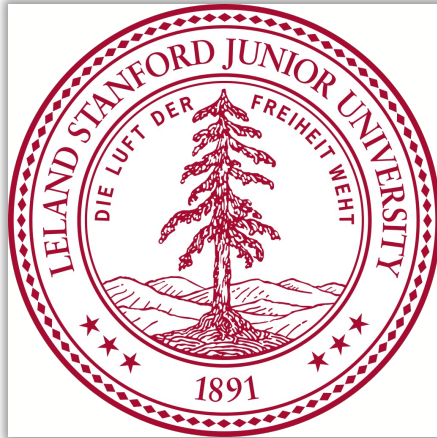
- noise is (usually) bad!
- many sources of noise: heat, electronics, amplifier gain, photon to electron conversion, pixel defects, read, ...
- different noise follows different statistical distributions, two crucial ones:
 - Gaussian
 - Poisson

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!



Signal-to-Noise Ratio (SNR)

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

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

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

Q_e = quantum efficiency

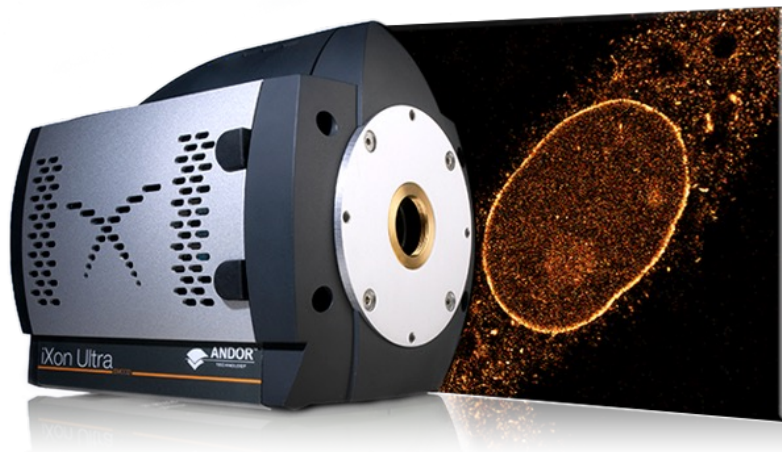
t = exposure time (sec)

D = dark current (electrons/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

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

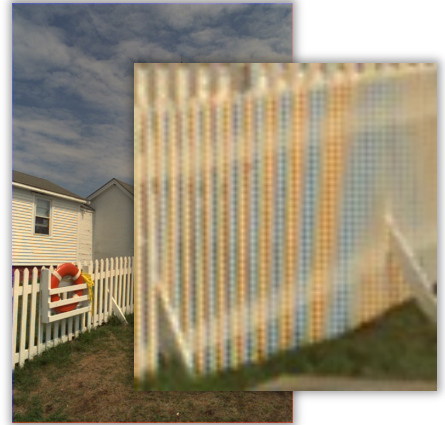
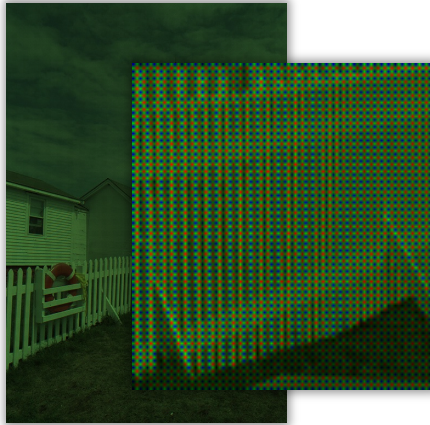


Digital Photography – Additional Resources

- 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