Photons and sensors

(with an interlude on the history of color photography)

CS 178, Spring 2010

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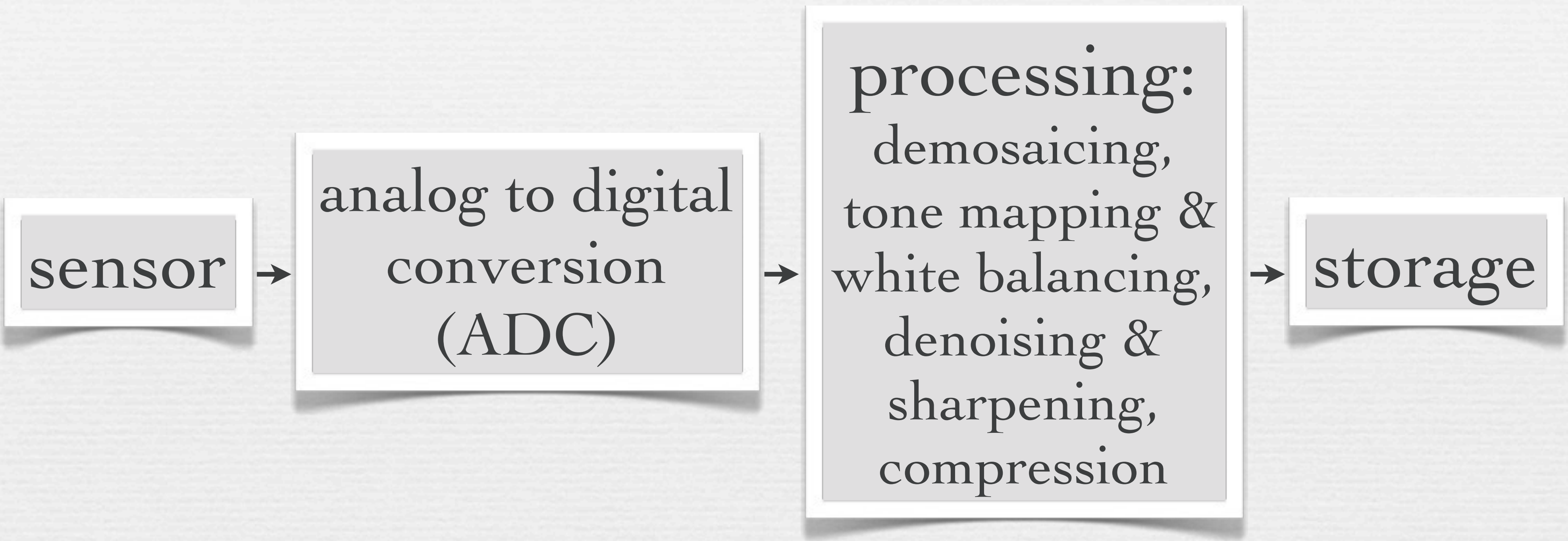
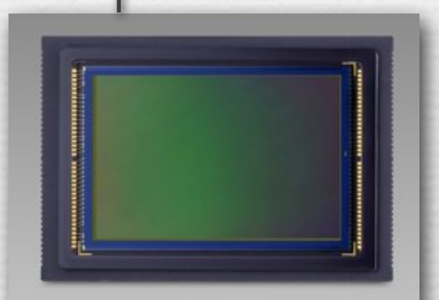
Camera pixel pipeline



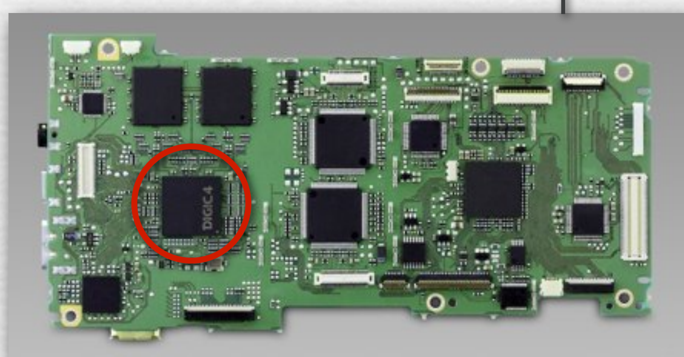
- every camera uses different algorithms
- the processing order may vary
- most of it is proprietary

Example pipeline

sensor → analog to digital conversion (ADC) → processing: demosaicing, tone mapping & white balancing, denoising & sharpening, compression → storage



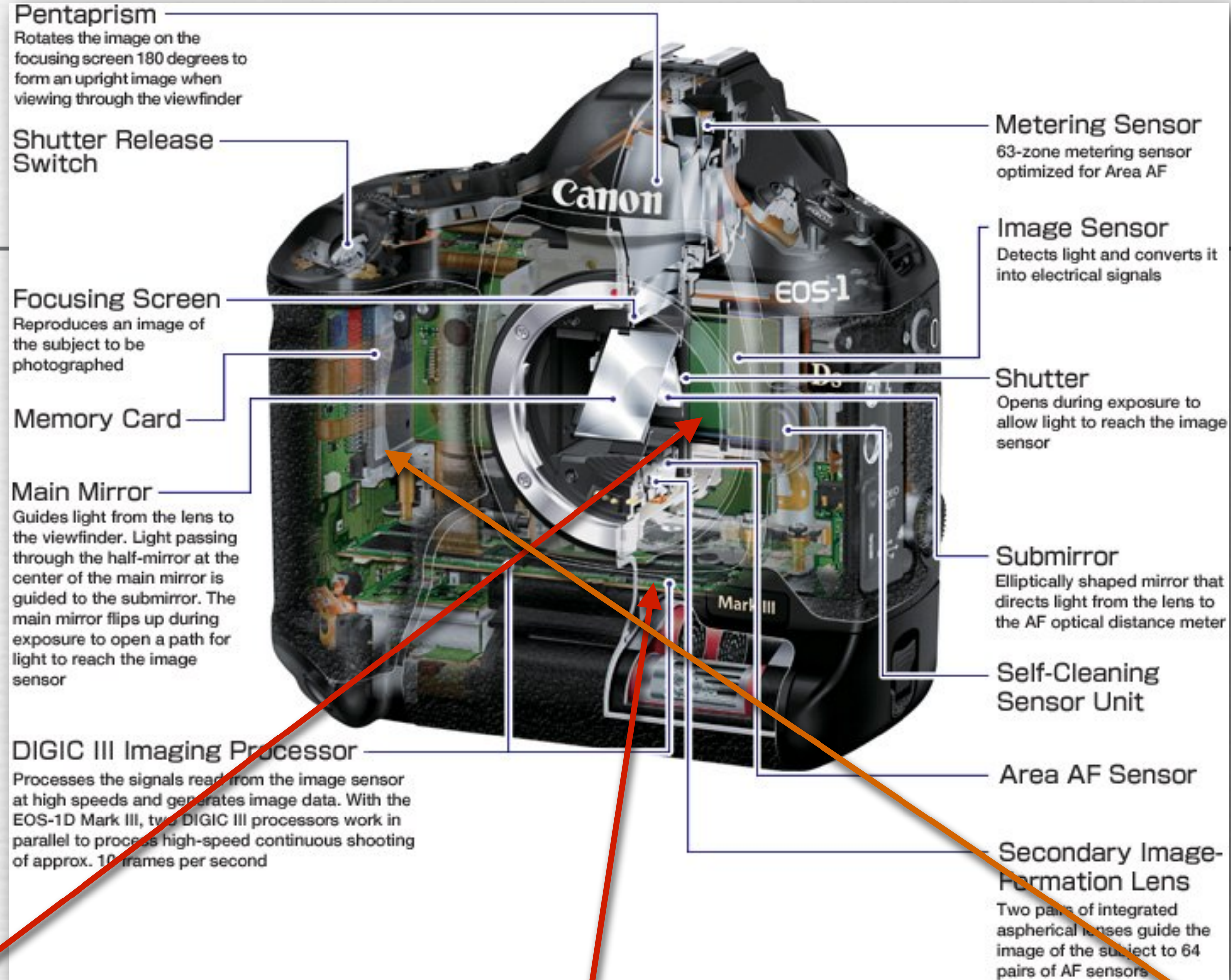
Canon 21 Mpix CMOS sensor

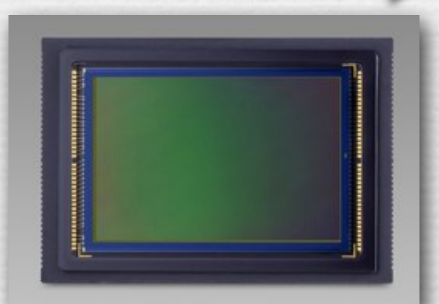


Canon DIGIC 4 processor

Compact Flash card

Example





Canon 21 Mpix CMOS sensor

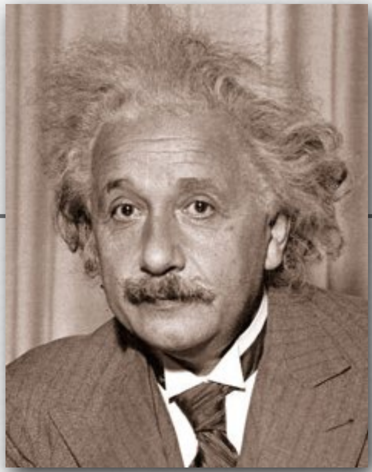
Canon DIGIC 4 processor

Compact Flash card

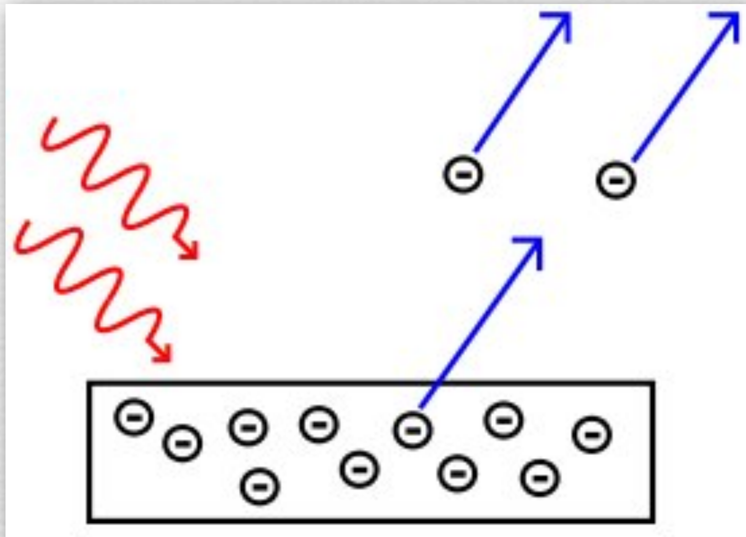
Outline

- converting photons to charge
- getting the charge off the sensor
  - CCD versus CMOS
  - analog to digital conversion (ADC)
- supporting technology
  - microlenses
  - antialiasing filters
- sensing color

The photoelectric effect



Albert Einstein



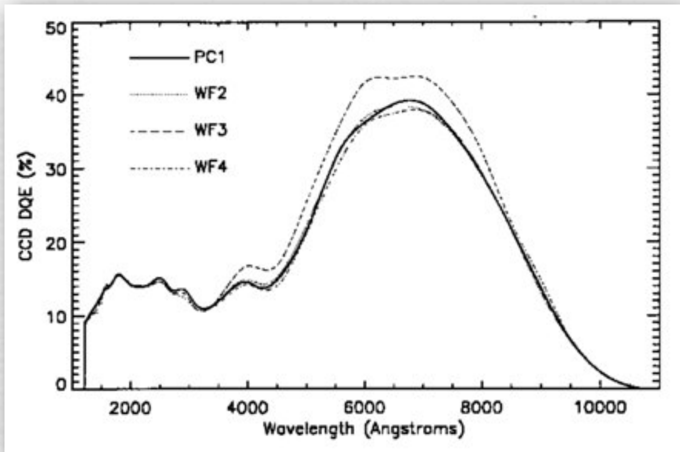
(wikipedia)

- when a photon strikes a material, an electron may be emitted
  - depends on the photon's energy, which depends on its wavelength

$$E_{photon} = \frac{h \times c}{\lambda}$$

  - there is no notion of "brighter photons", only more or fewer of them

Quantum efficiency



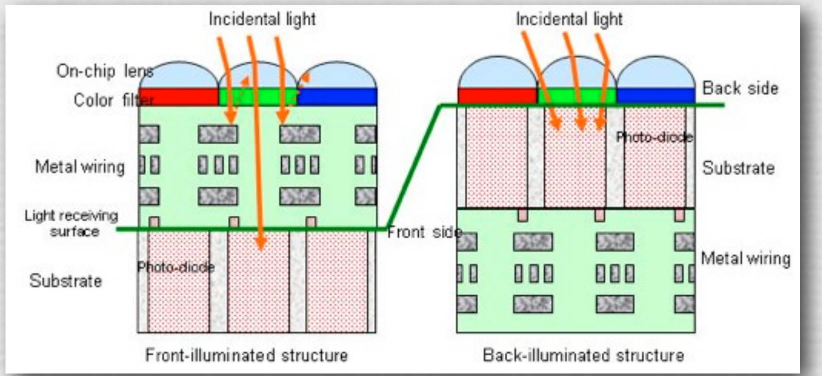
Hubble Space Telescope Camera 2

- not all photons will produce an electron
  - depends on quantum efficiency of the device

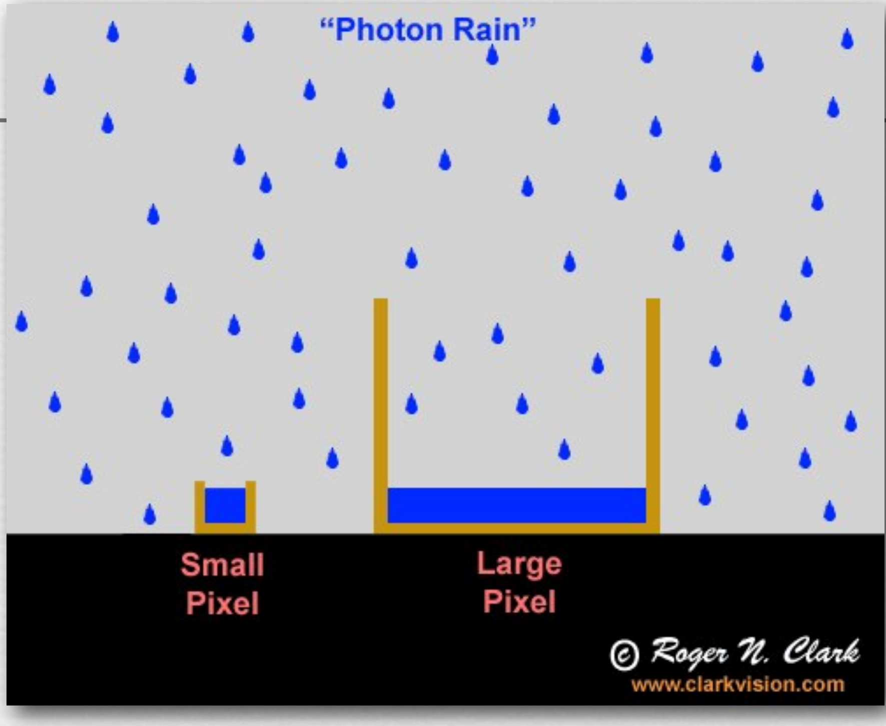
$$QE = \frac{\#\,electrons}{\#\,photons}$$

  - human vision: ~15%
  - typical digital camera: < 50%
  - best back-thinned CCD: > 90%

back-illuminated CMOS (Sony)

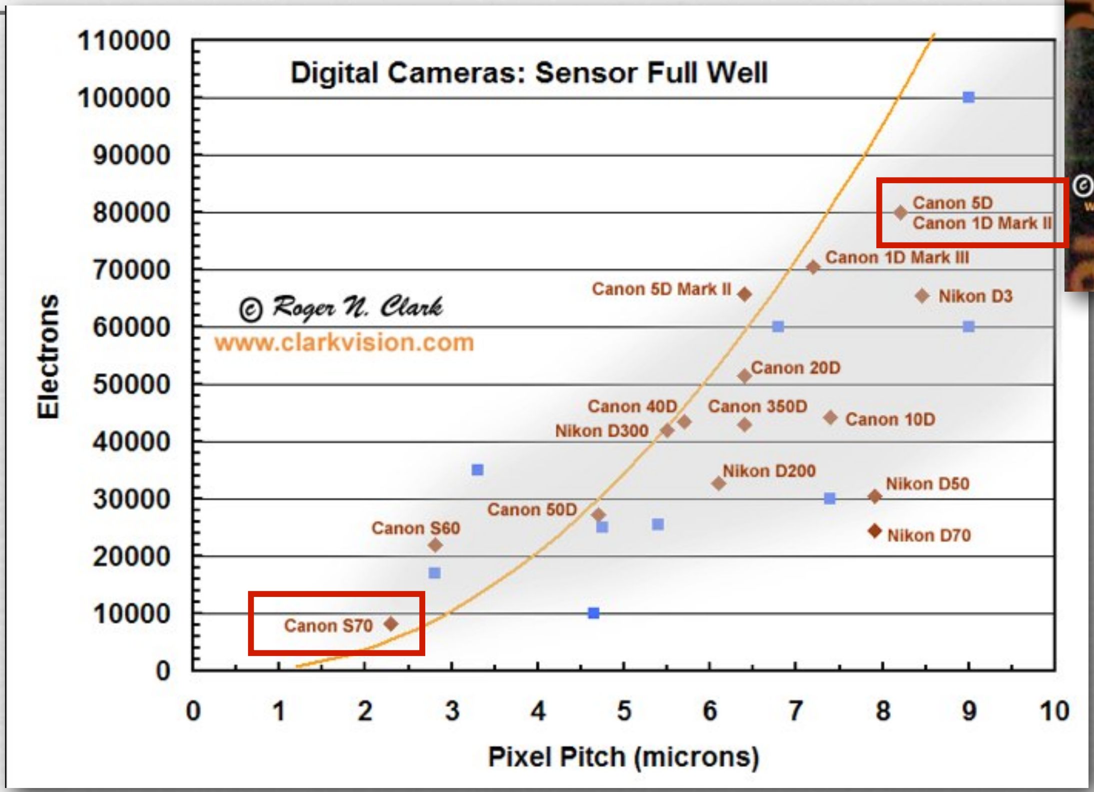


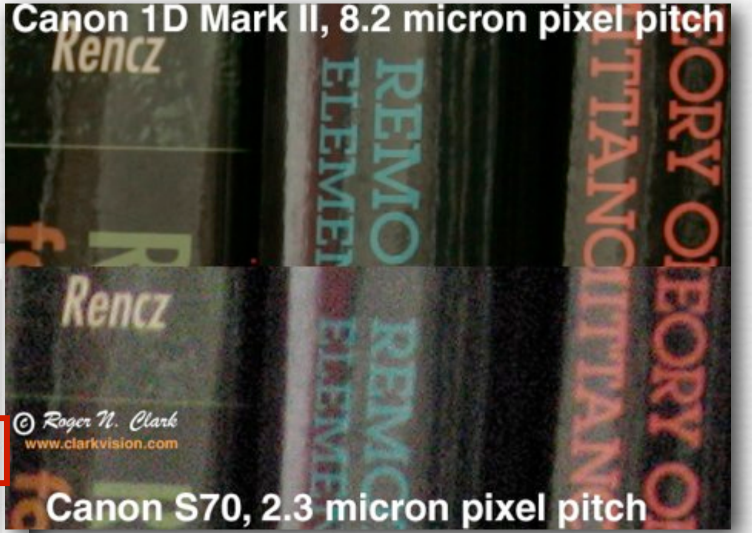
Pixel size



- the current from one electron is small (10-100 fA)
  - so integrate over space and time (pixel area × exposure time)
  - larger pixel × longer exposure means more accurate measure
- typical pixel sizes
  - casio EX-F1: $2.5\mu \times 2.5\mu = 6\mu^2$
  - Canon 5D II: $6.4\mu \times 6.4\mu = 41\mu^2$

Full well capacity





(clarkvision.com)

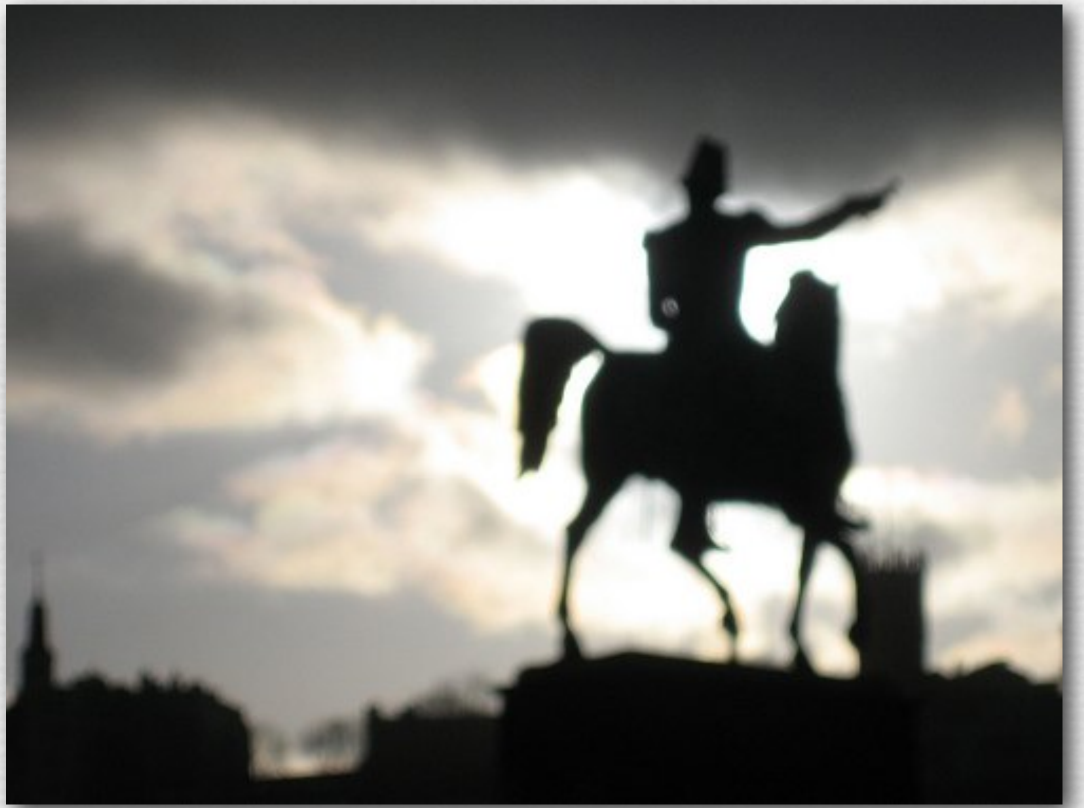
- how many electrons can a pixel hold?
  - depends mainly on the size of the pixel
- too many photons causes *saturation*
  - larger capacity leads to higher *dynamic range* between the brightest scene feature that won't saturate and the darkest that isn't too noisy

Blooming

(ccd-sensor.de)

- charge spilling over to nearby pixels
  - can happen on CCD <u>and</u> CMOS sensors
  - don't confuse with glare or other image artifacts

Image artifacts can be hard to diagnose

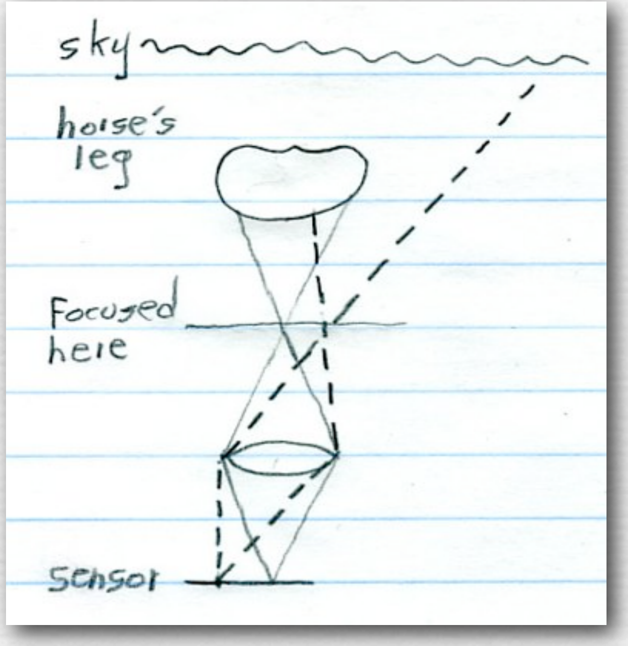


(http://farm3.static.flickr.com/2102/2248725961_540be5f9af.jpg?v=0)

Q. Is this blooming?

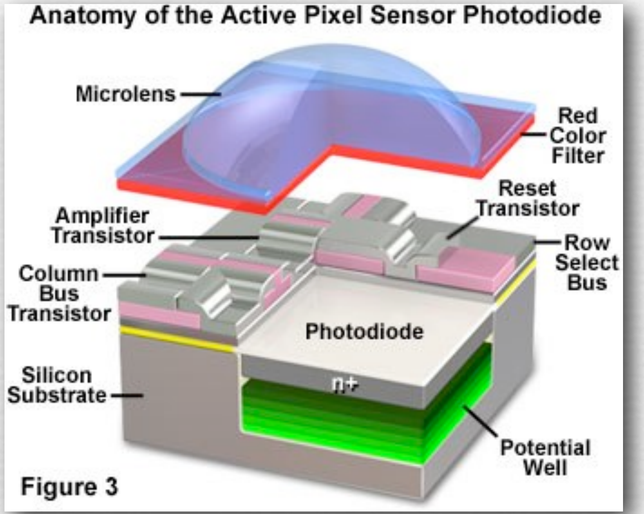
Explanation of preceding image (contents of whiteboard)

- there may be blooming in the sky, but the shrinkage of the horse's leg can be explained purely as a byproduct of misfocus
  - in the accompanying plan view diagram, the horse's leg is shown at top (in cross section)
  - the solid bundle of rays, corresponding to one sensor pixel, crossed before the leg (was misfocused), then spread out again, but saw only more leg, so its color would be dark
  - the dashed bundle of rays, corresponding to a nearby pixel, crossed at the same depth but to the side of the solid bundle, then spread out again, seeing partly leg and partly sky; its color would be lighter than the leg
  - this lightening would look like the sky was "blooming" across the leg, but it's just a natural effect produced by misfocus

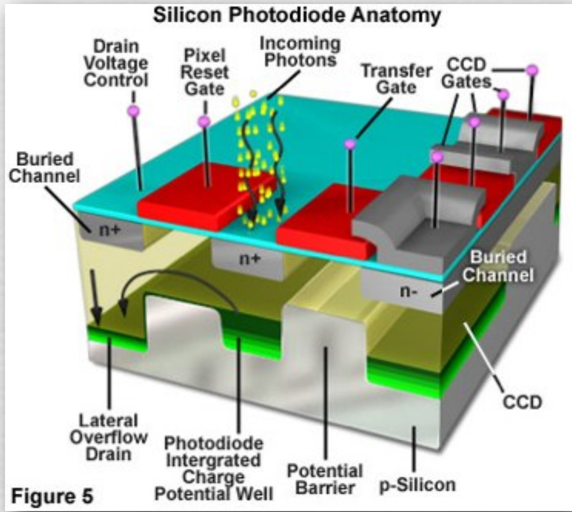


CMOS versus CCD sensors

CMOS

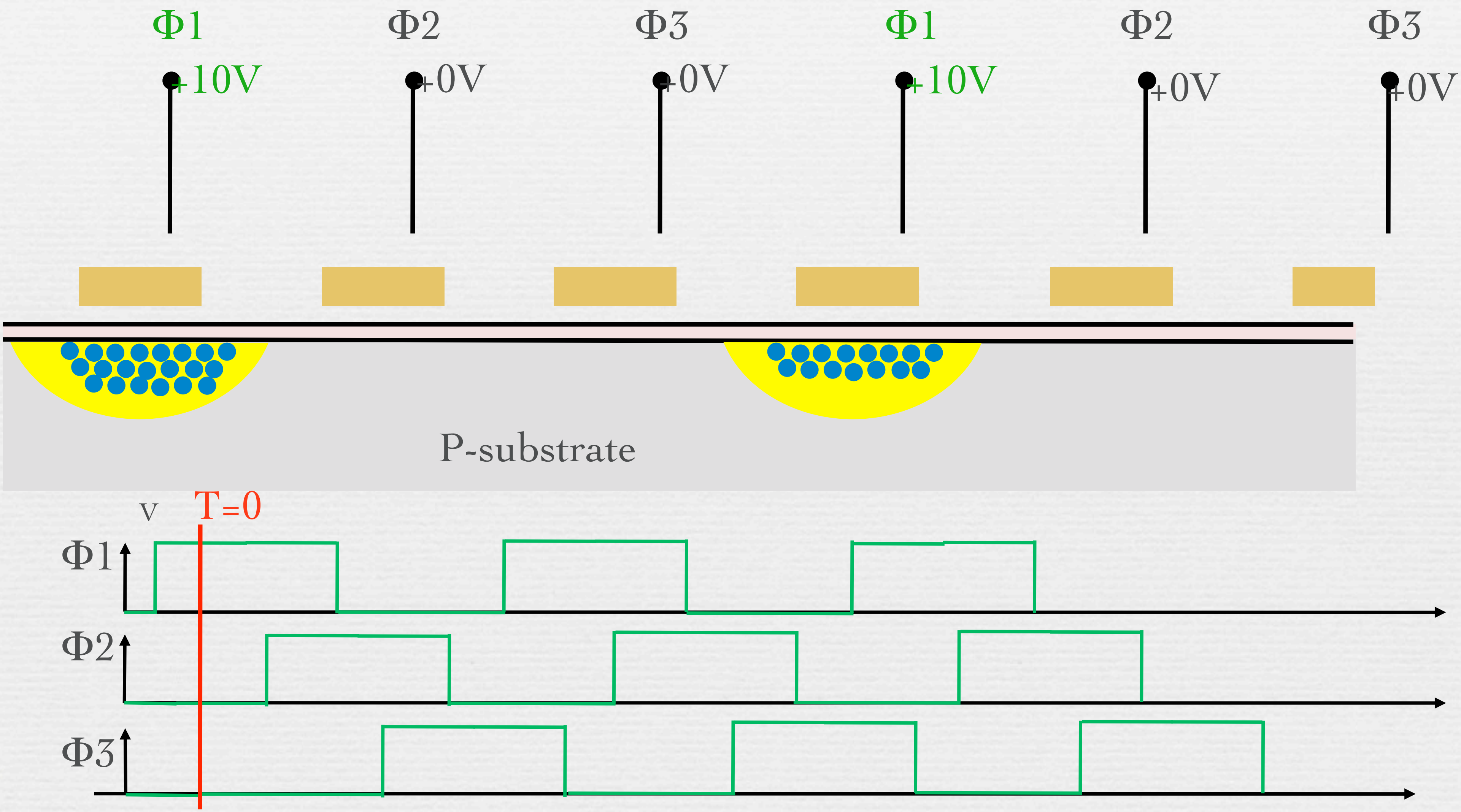


CCD

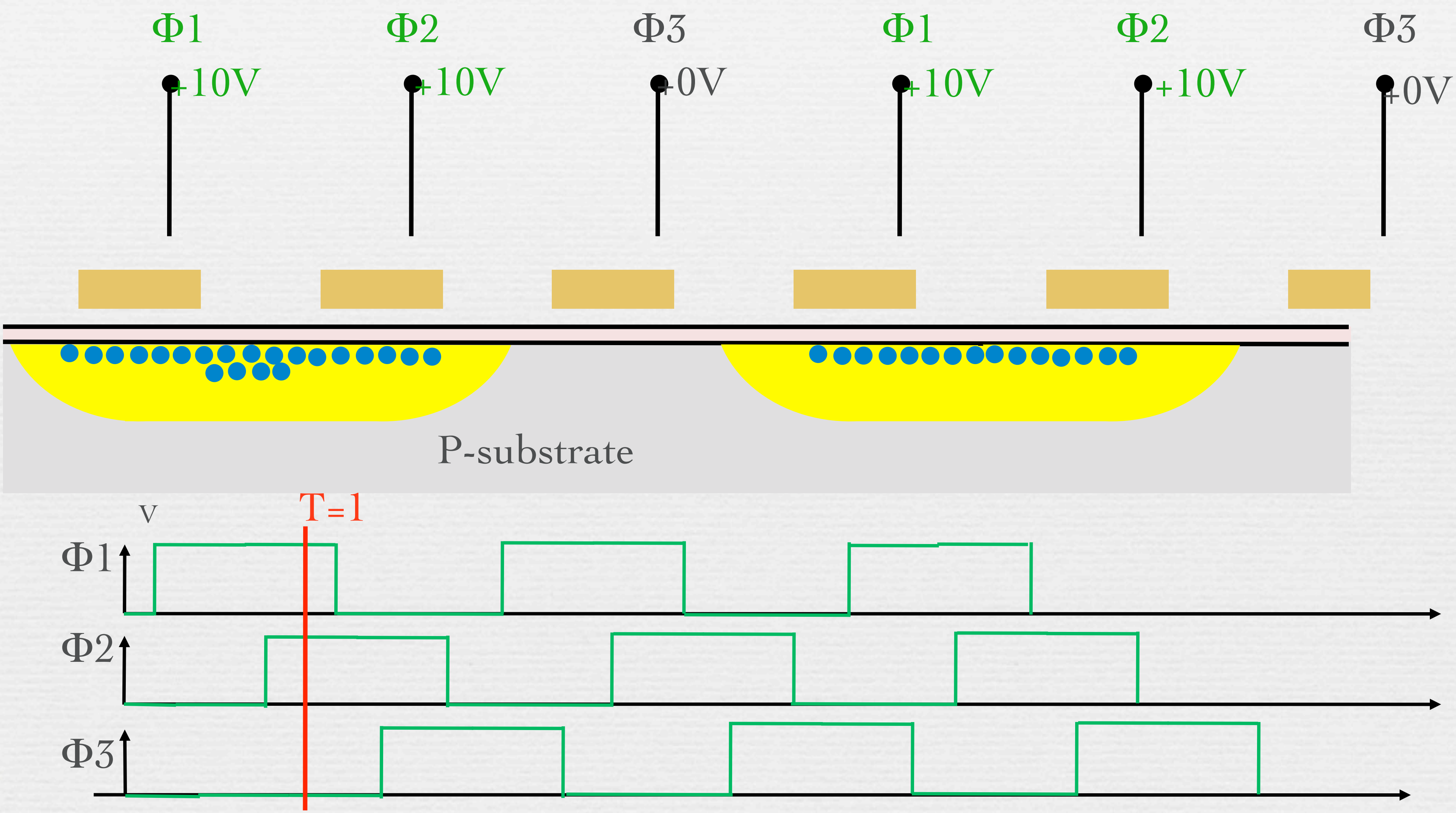


- CMOS = complementary metal-oxide semiconductor
  - an amplifier per pixel converts charge to voltage
  - low power, but noisy (but getting better)
- CCD = charge-coupled device
  - charge shifted along columns to an output amplifier
  - oldest solid-state image sensor technology
  - highest image quality, but not as flexible or cheap as CMOS

Gratuitous animation showing a CCD "bucket brigade" readout



Gratuitous animation showing a CCD "bucket brigade" readout



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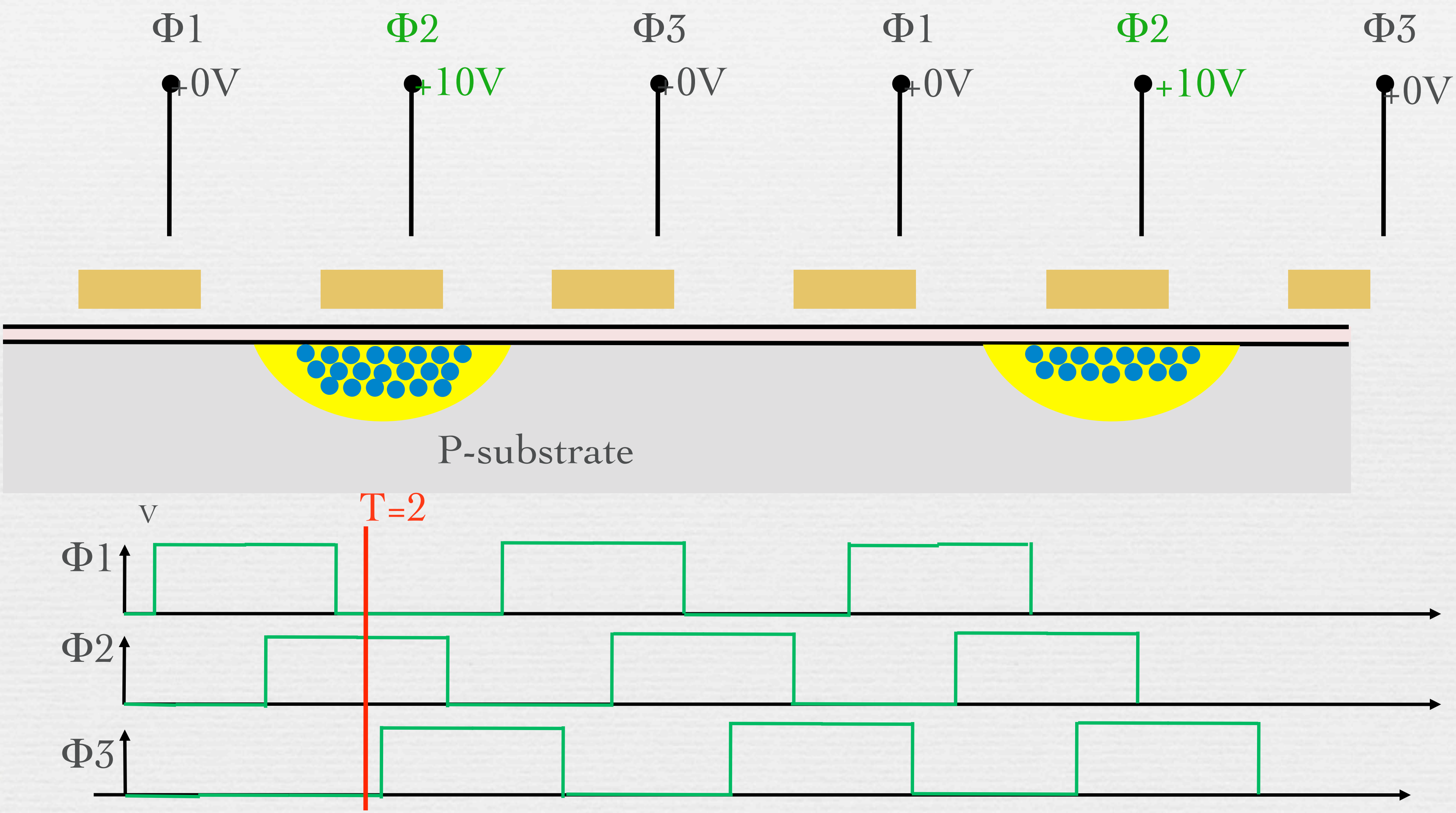

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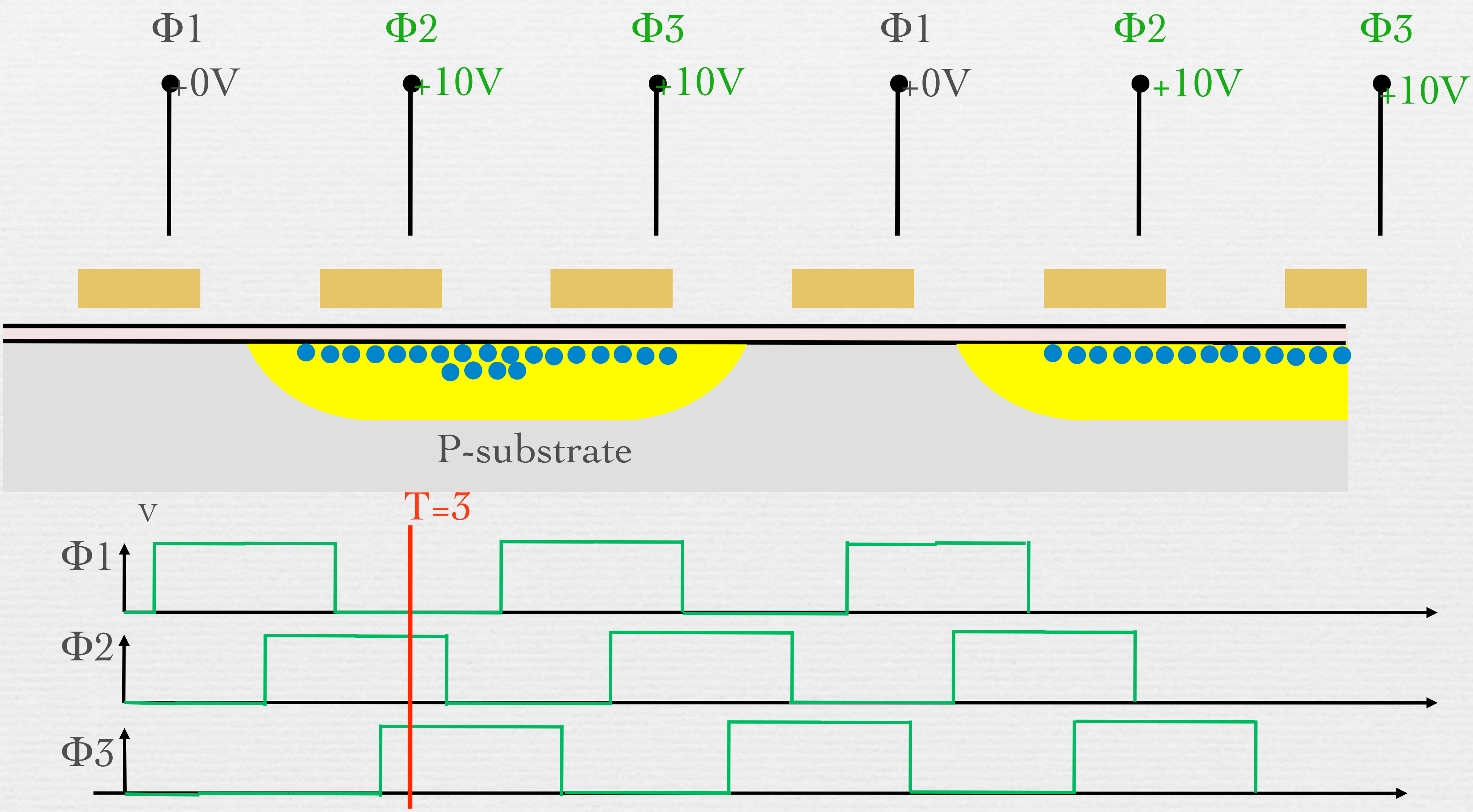

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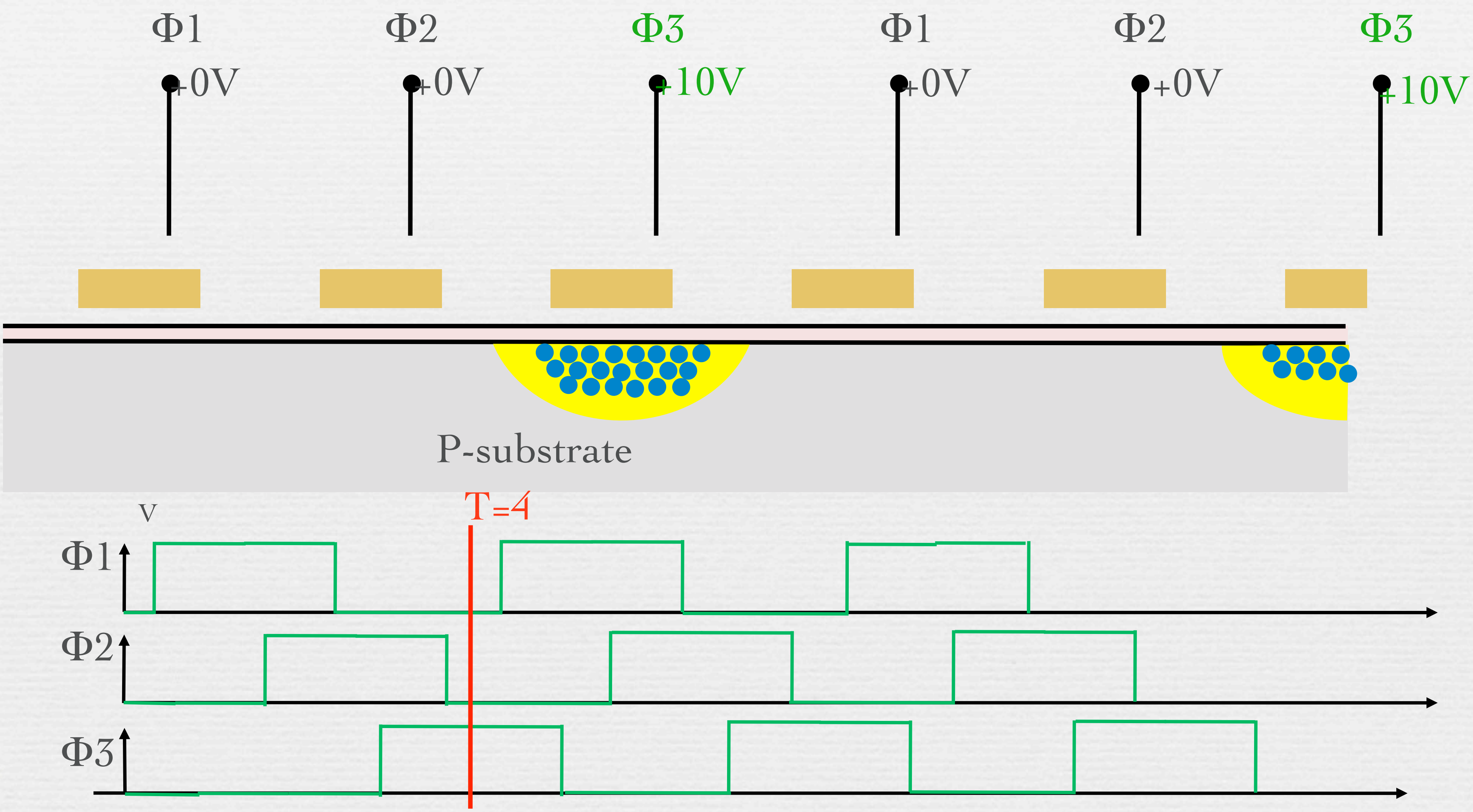

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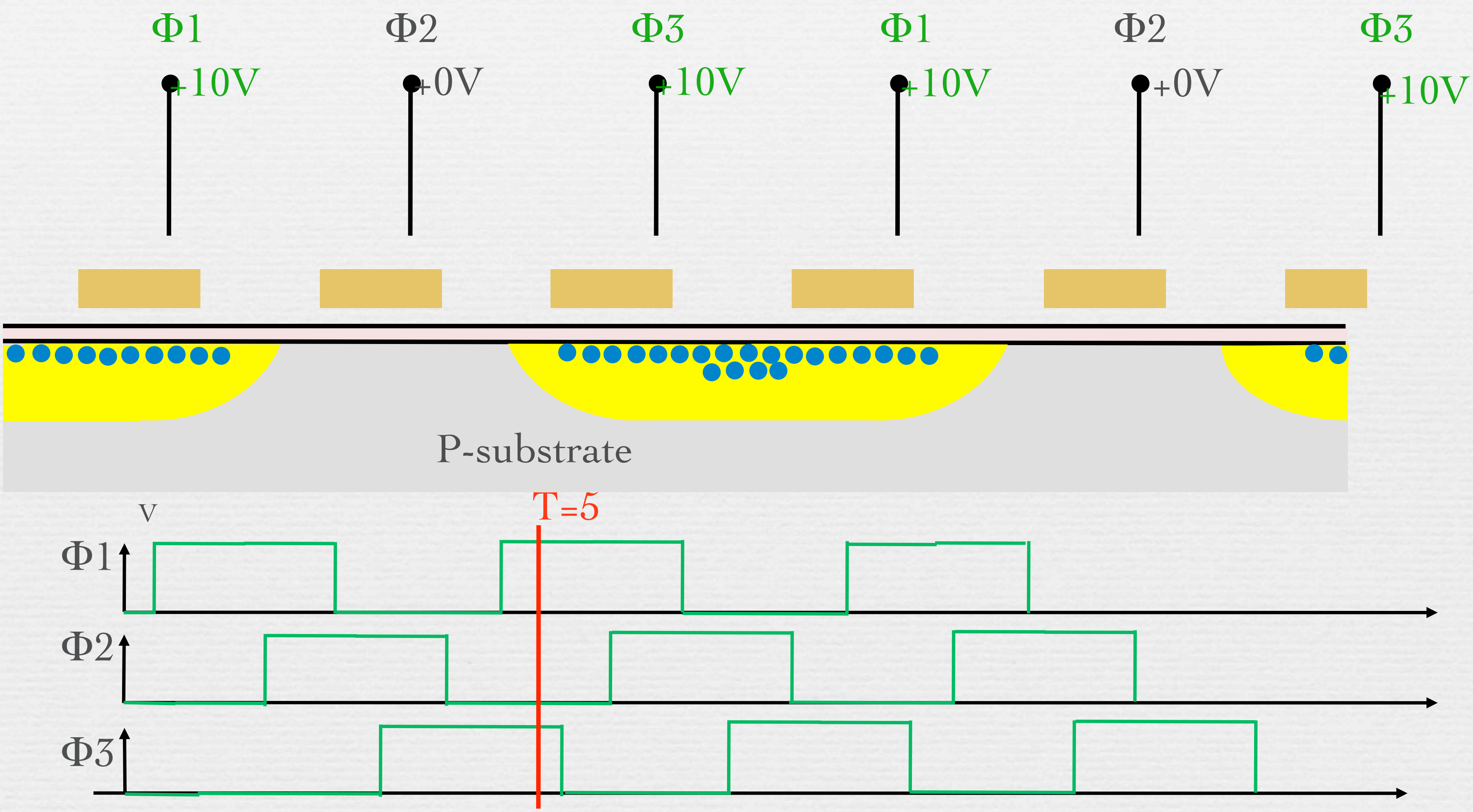
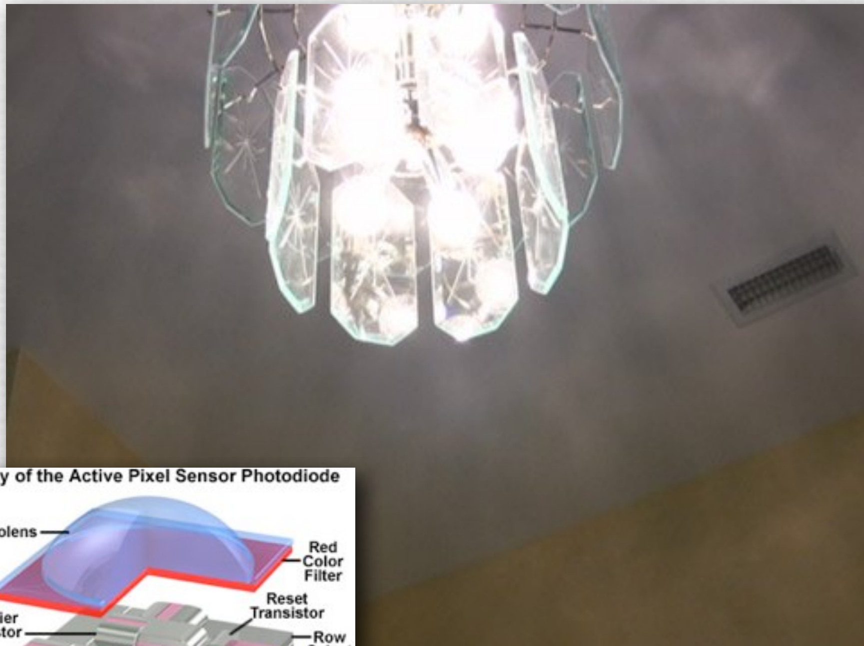
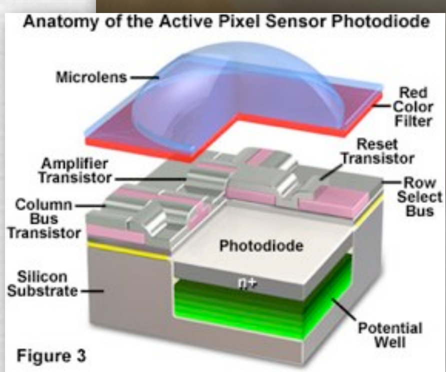


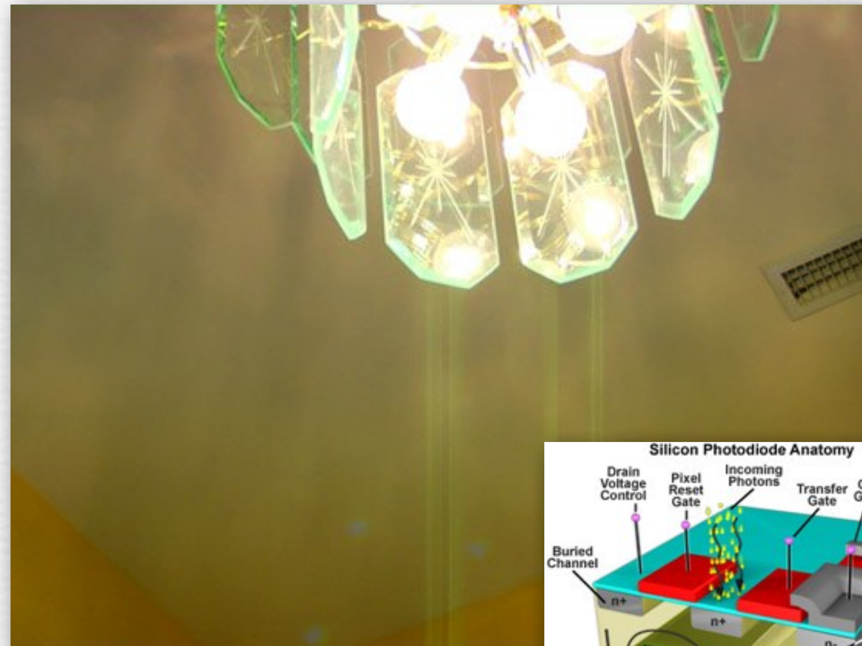
Smearing

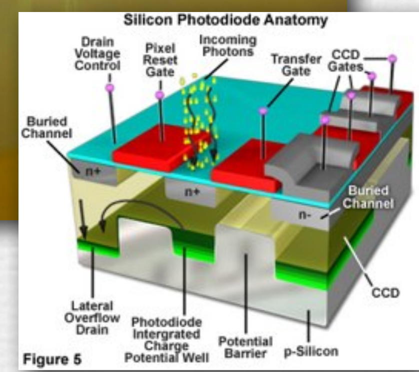
(dvxuser.com)





CMOS

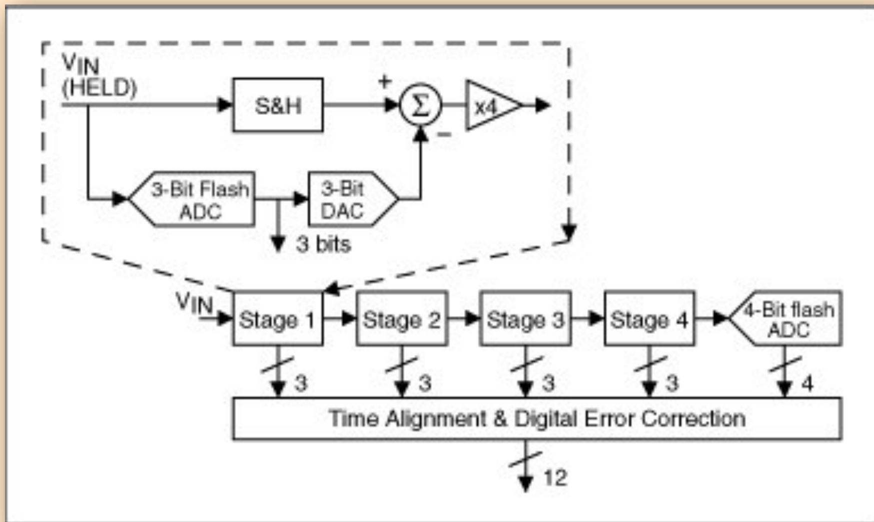


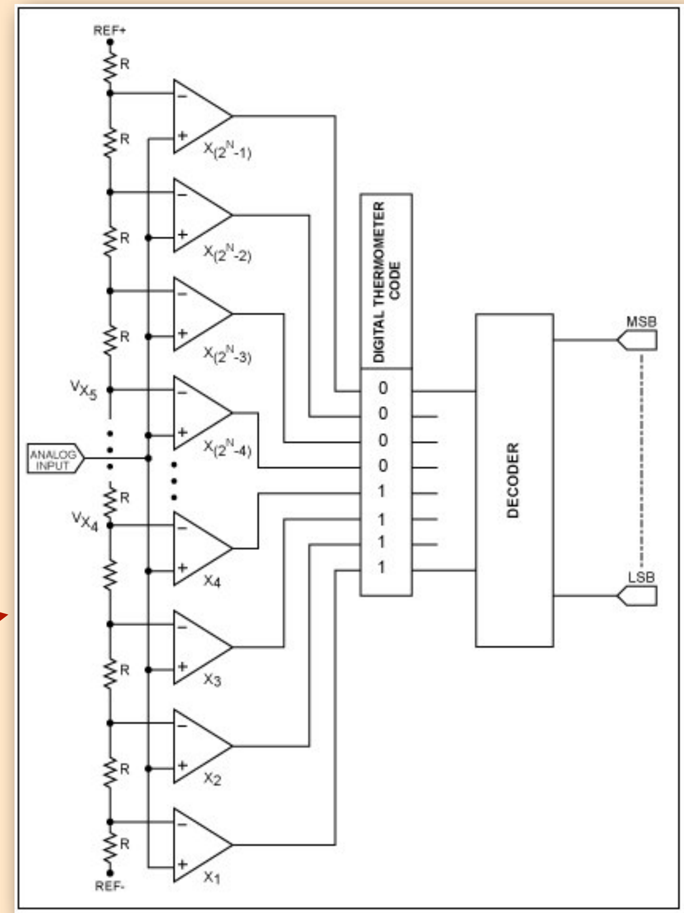


CCD

- side effect of bucket-brigade readout on CCD sensors
  - only happens if pixels saturate
  - doesn't happen on CMOS sensors

Analog to digital conversion (ADC)

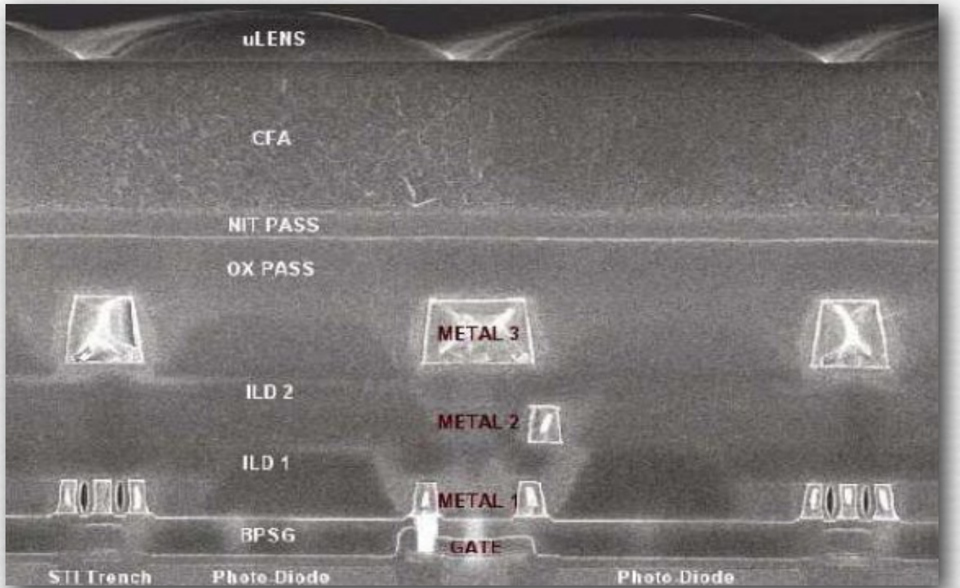




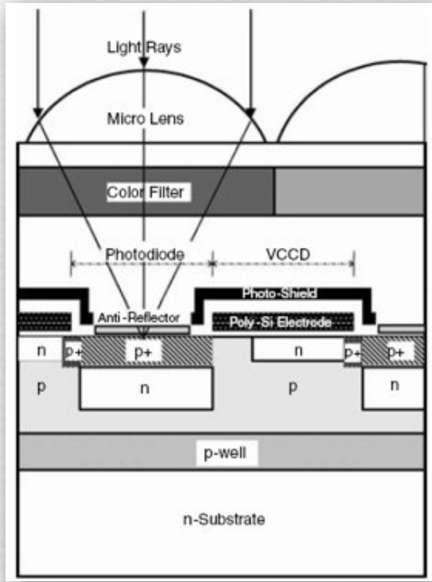
(maxim-ic.com)

- flash ADC
  - voltage divider → comparators → decoder
  - for n bits requires 2^n comparators
- pipelined ADC
  - 3-bit ADC → 3-bit DAC → compute residual → 4× → repeat
  - longer latency, but high throughput
  - some new sensors use an ADC per column

Fill factor



on a CMOS sensor



on a CCD sensor

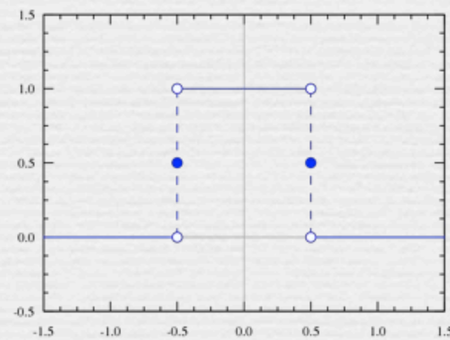
- fraction of sensor surface available to collect photons
  - can be improved using per-pixel microlenses

Q. An image sensor performs 2D sampling.
What is the prefilter, with and without microlenses?

What per-pixel microlenses do

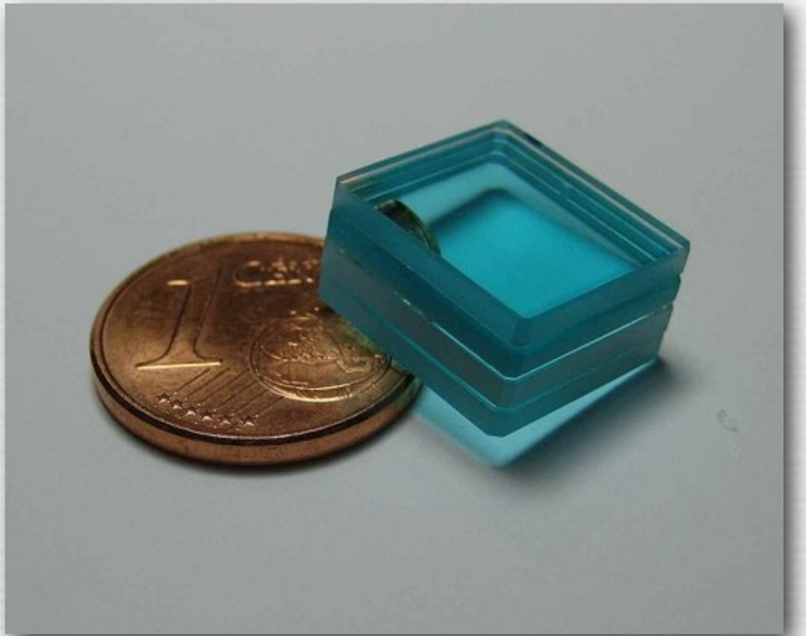
- integrating light over an area at each pixel site instead of point sampling serves two functions
  - capturing more photons, to improve *dynamic range*
  - convolving the image with a prefilter, to avoid *aliasing*
- if the pixel is a rectangle, then this prefilter is a 2D rect

$$rect(x) = \Pi(x) = \begin{cases} 0 & if\ |x| > \frac{1}{2} \\ \frac{1}{2} & if\ |x| = \frac{1}{2} \\ 1 & if\ |x| < \frac{1}{2} \end{cases}$$

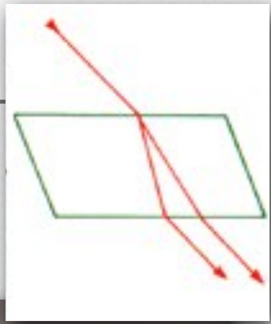


  - if only a portion of each pixel site is photo-sensitive, this rect doesn't span the spacing between pixels, so the prefilter is poor
- microlenses both gather more light and improve the prefilter
  - with microlenses, prefilter width roughly equals pixel spacing

Antialiasing filters



antialiasing filter



birefringence in a calcite crystal

- ✦ improves on non-ideal prefilter, even with microlenses
- ✦ typically two layers of birefringent material
  - splits 1 ray into 4 rays
  - operates like a 4-tap discrete convolution filter kernel!

Removing the antialiasing filter

- "hot rodding" your digital camera
  - $450 + shipping

(maxmax.com)

anti-aliasing filter removed

normal

Removing the antialiasing filter

- "hot rodding" your digital camera
  - $450 + shipping

(maxmax.com)

anti-aliasing filter removed

normal

Recap

- photons strike a sensor and are converted to electrons
  - performance factors include *quantum efficiency* and *pixel size*

- sensors are typically CCD or CMOS
  - both can suffer *blooming*; only CCDs can suffer *smearing*

- integrating light over an area serves <u>two</u> functions
  - capturing more photons, to improve *dynamic range*
  - convolving the image with a prefilter, to avoid *aliasing*
  - to ensure that the area spans pixel spacing, use *microlenses*

Questions?

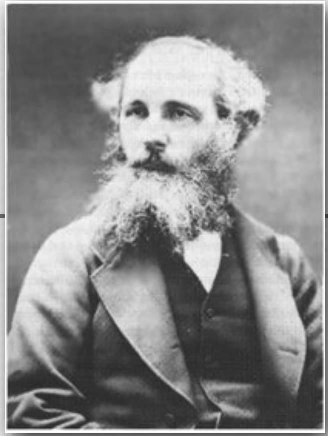
Color

- silicon detects all visible frequencies well
- can't differentiate wavelengths after photon knocks an electron loose
  - all electrons look alike
- must select desired frequencies before light reaches photodetector
  - block using a filter, or separate using a prism or grating
- 3 spectral responses is enough
  - a few consumer cameras record 4
- silicon is also sensitive to near infrared (NIR)
  - most sensors have an IR filter to block it
  - to make a NIR camera, remove this filter

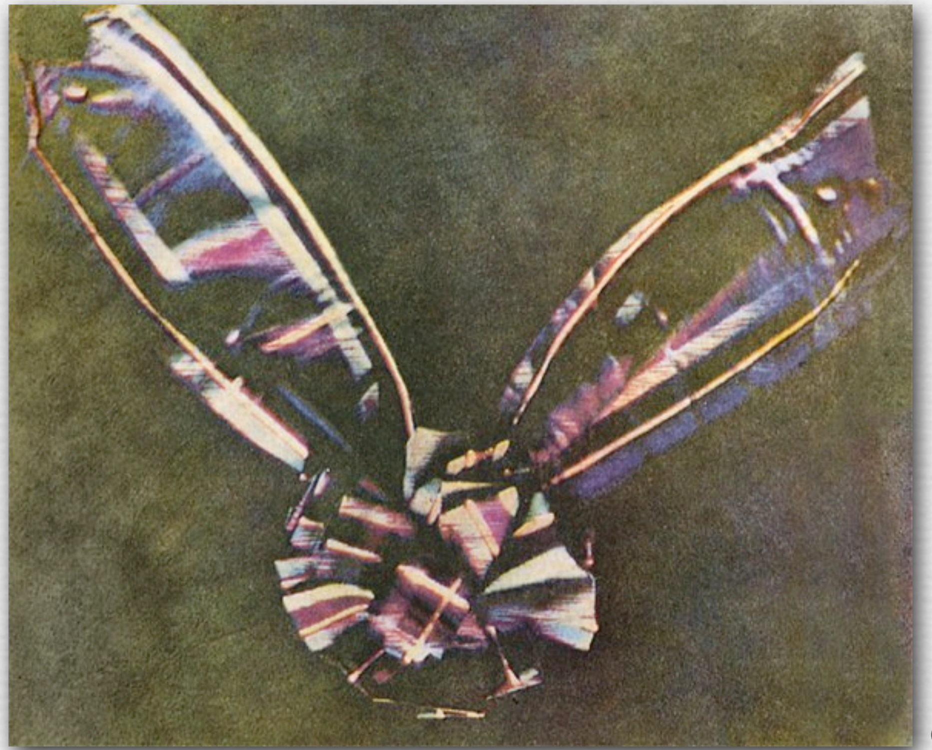
Color sensing technologies

- field-sequential
- 3-sensor
- vertically stacked
- spatial mosaic

Historical interlude



Q. Who made the first color photograph?



(wikipedia)

- ✦ James Clerk Maxwell, 1861
  - of Maxwell's equations
  - 3 images, shot through filters, then simultaneously projected

Historical interlude

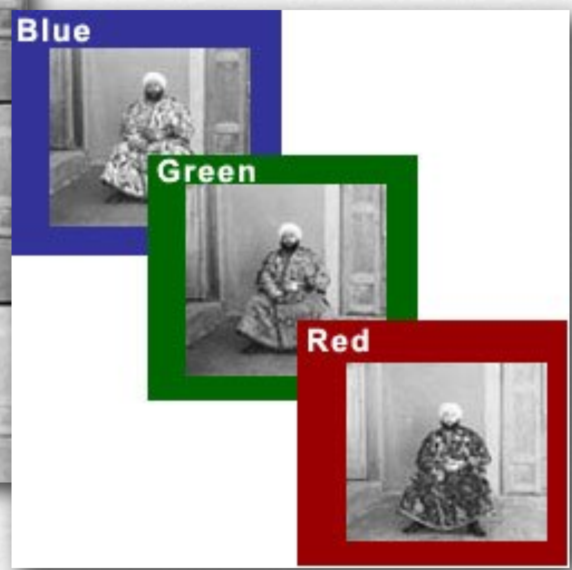
Q. Who made the first color print?


Fig. 16. — Louis Ducos du Hauron (1).

(wikipedia)

- Louis Arthur Ducos du Hauron, 1877
  - 3 images, shot through filters, printed with color inks
  - he experimented with RGB and CMY

Sergey Prokudin-Gorsky



- shot sequentially through R, G, B filters
- simultaneous projection provided good saturation, but available printing technology did not
- digital restoration lets us see them in full glory...

Sergey Prokudin-Gorsky, Alim Khan, emir of Bukhara (1911)

Sergey Prokudin-Gorsky,
Pinkhus Karlinskii, Supervisor of the Chernigov Floodgate (1919)

First color movie technology?

(wikipedia)

A Visit to the Seaside (1908)

- George Albert Smith's Kinemacolor, 1906
  - alternating red and green filters, total of 32 fps
  - projected through alternating red and green filters

Technicolor

Toll of the Sea (1922)

Phantom of the Opera (1925)

- beam splitter leading through 2 filters to two cameras
- 2 strips of film, cemented together for projection

Technicolor

Disney's Flowers and Trees (1932)

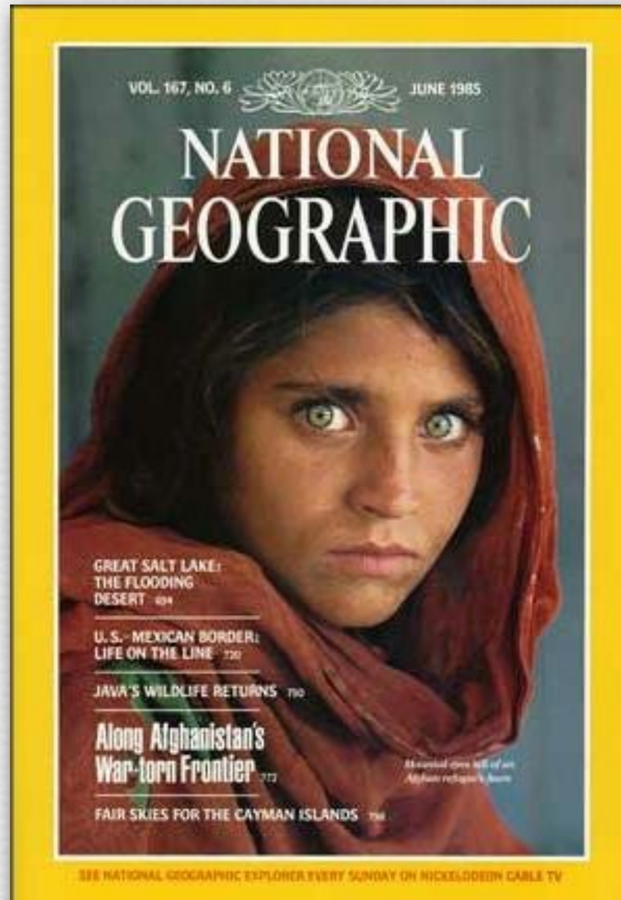
Wizard of Oz (1939)

- 3 filters, 3 cameras, 3 strips of film
- better preserved than single-strip color movies of 1960s!

First consumer color film?

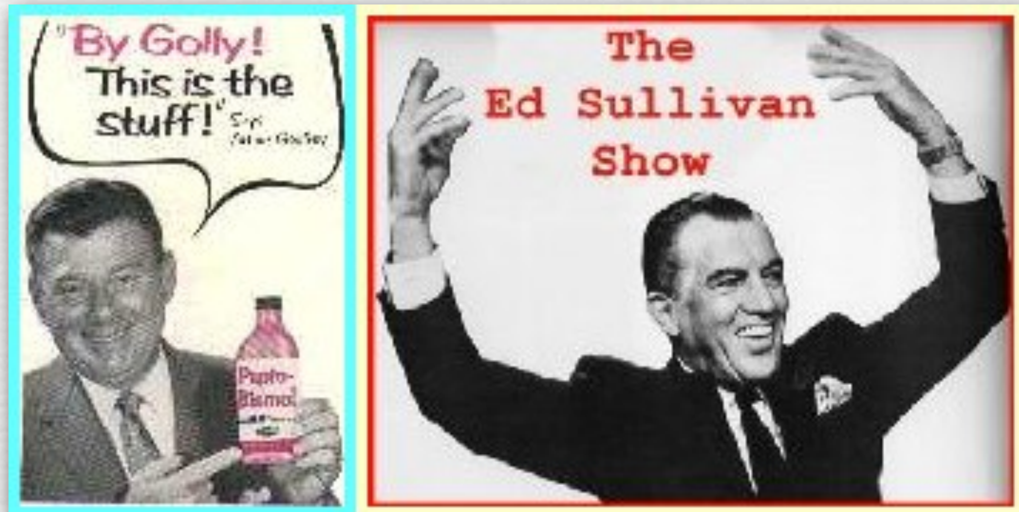
(wikipedia)

Picadilly Circus, 1949



- Kodachrome, 1935
  - no longer available

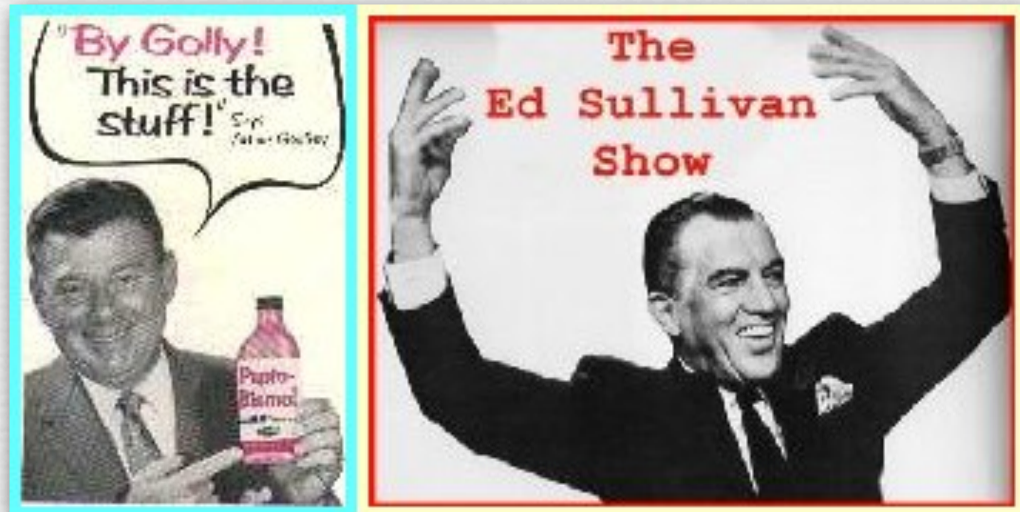
First color television broadcast?



1951

- competing standards
  - U.S. NTSC 525-line, 30fps, interlaced
  - Europe PAL 625-line, 25fps, interlaced
  - France SECAM 625-line, 25fps, interlaced

First color television broadcast?



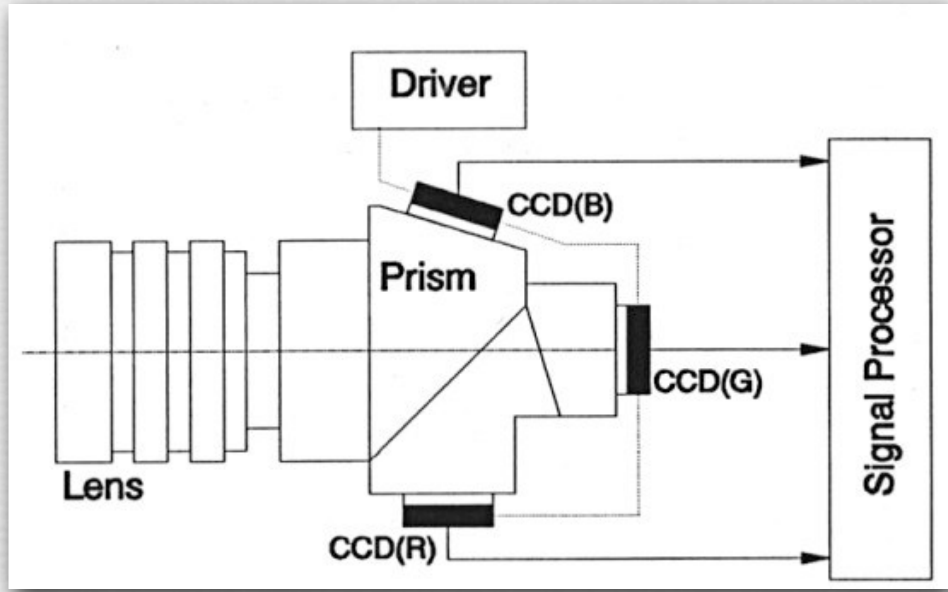
1951

- competing standards
  - U.S. NTSC Never Twice the Same Color
  - Europe PAL Pale and Lurid
  - France SECAM Système Electronique Contre les Americains

Color sensing technologies

- field-sequential - just covered
- 3-chip
- vertically stacked
- color filter arrays

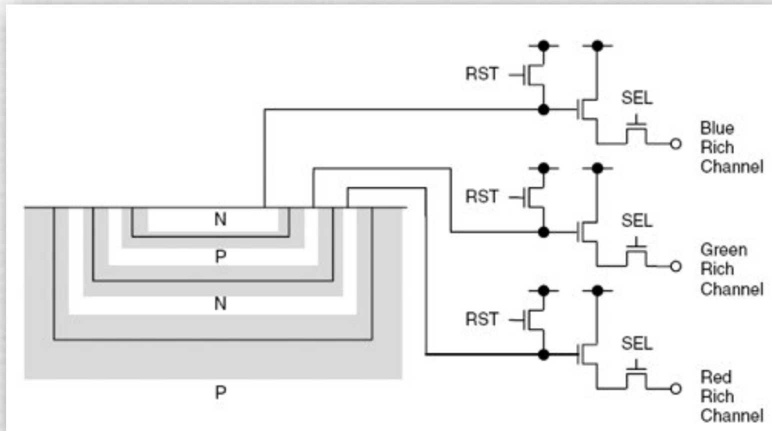
3-chip cameras



(Theuwissen)

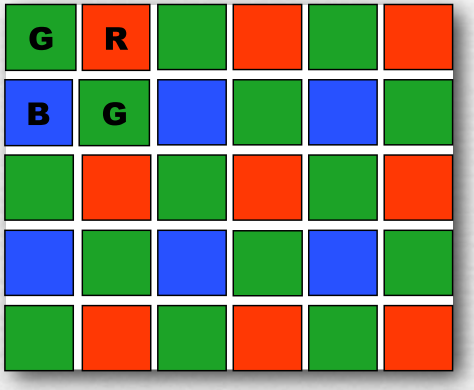
- high-quality video cameras
- prism & dichroic mirrors split the image into 3 colors, each routed to a separate sensor (typically CCD)
- no light loss, as compared to filters
- expensive, and complicates lens design

Foveon stacked sensor

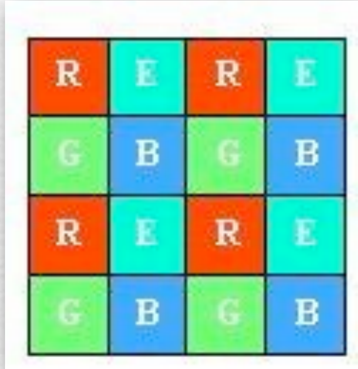


- longer wavelengths penetrate deeper into silicon, so arrange a set of vertically stacked detectors
  - top gets mostly blue, middle gets green, bottom gets red
  - no control over spectral responses, so requires processing
- fewer color artifacts than color filter arrays
  - but possibly worse noise performance, especially in red

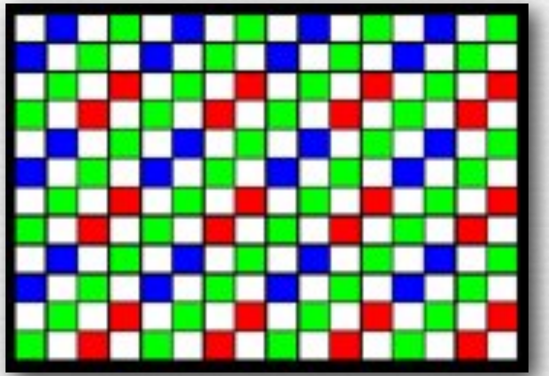
Color filter arrays



Bayer pattern



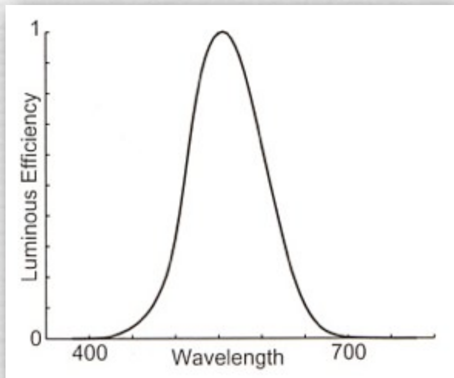
Sony RGB+E
better color



Kodak RGB+C
less noise

- Why more green pixels than red or blue?
  - because humans are most sensitive in the middle of the visible spectrum
  - sensitivity given by the human luminous efficiency curve

(Stone)



Example of Bayer mosaic image

Small fan at Stanford women's soccer game

(Canon 1D III)

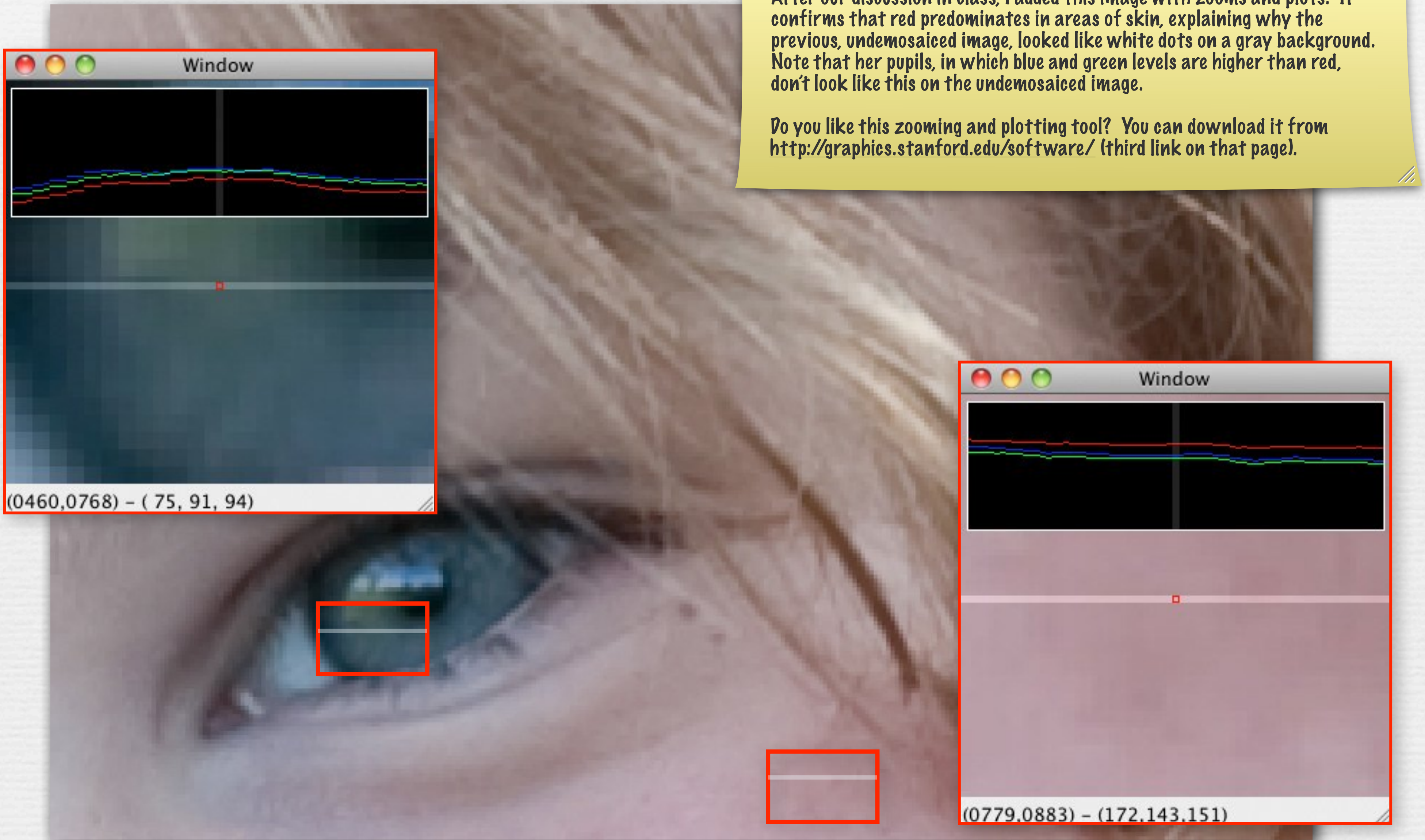
Example of Bayer mosaic image

Before demosaicing (`dcraw -d`)

Example of Bayer mosaic image

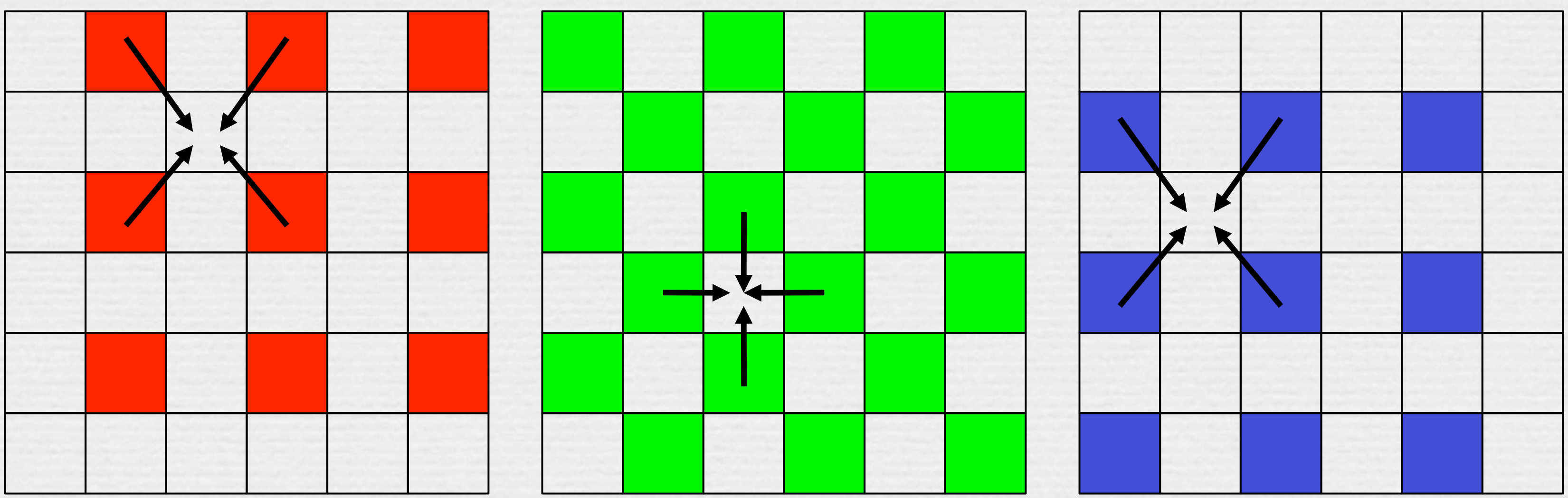
After our discussion in class, I added this image with zooms and plots. It confirms that red predominates in areas of skin, explaining why the previous, undemosaiced image, looked like white dots on a gray background. Note that her pupils, in which blue and green levels are higher than red, don't look like this on the undemosaiced image.

Do you like this zooming and plotting tool? You can download it from http://graphics.stanford.edu/software/ (third link on that page).



Demosaicing

- linear interpolation
  - average of the 4 nearest neighbors of the same color
- cameras typically use more complicated scheme
  - try to avoid interpolating across feature boundaries
  - demosaicing is often combined with denoising, sharpening...
- due to demosaicing, 2/3 of your data is "made up"!



Recap

- color can only be measured by selecting certain light frequencies to reach certain sensor sites or layers
  - selection can employ *filters* or *gratings* or *penetration depth*

- measuring color requires making a tradeoff
  - *field sequential* cameras trade off capture duration
  - *3-chip* cameras trade off weight and expense
  - *vertically stacked* sensors (Foveon) trade off noise (in red)
  - *color filter array* (e.g. Bayer) trades off spatial resolution

Questions?

Not yet covered

- sensors
  - dynamic range
  - noise and ISO
- color
  - spectral characteristics of color filters
  - practical demosaicing methods

Slide credits

- Brian Curless
- Eddy Talvala
- Abbas El Gamal

- Theuwissen A., *Solid-State Imaging with Charge-Coupled Devices,* Kluwer Academic Publishers, 1995.