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CMOS ACTIVE PIXEL SENSOR TECHNOLOGY
- AN INTRODUCTION -

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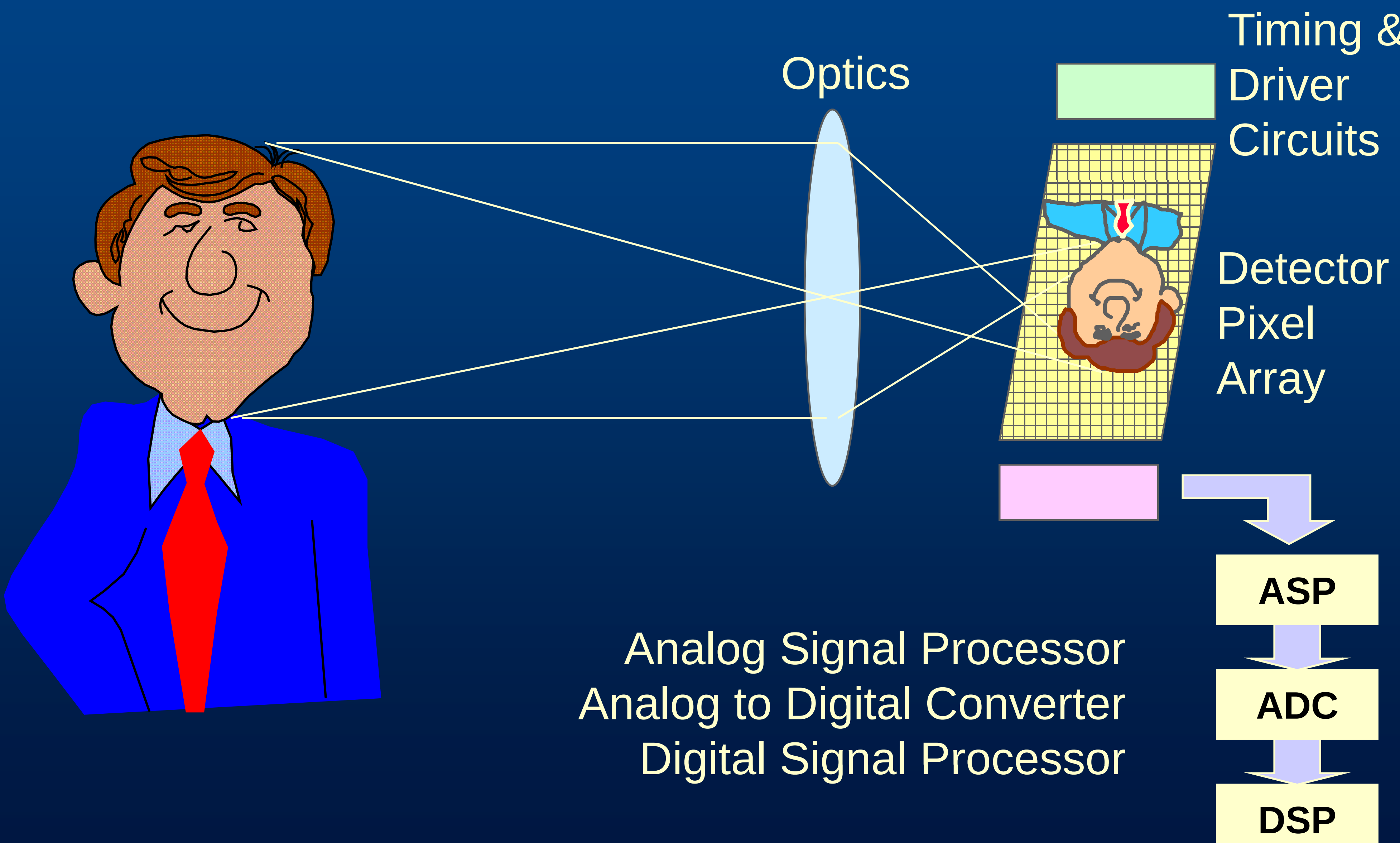
Imaging Systems



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Photons

- A photon is a “bullet” of light (quantum view of light waves)
- Energy is related to wavelength: $E = hc/\lambda$

High energy | Low energy

Ultra-violet

Infra-red

Short wavelength | Long wavelength

Your eye is sensitive from violet to dark red

450 nm - 700 nm

Silicon is sensitive from violet to the “near” infrared (not thermal)

400 nm - 1050 nm

Silicon is also sensitive to higher photon energies (e.g. x-rays)

Sources of Photons

- Three main sources
  - Solar
  - Incandescent lamp
  - Fluorescent lamp
- Typically characterized by ‘color temperature’
  - Temperature of blackbody with roughly same color distribution
  - Higher temp means more blue, less red -> looks white

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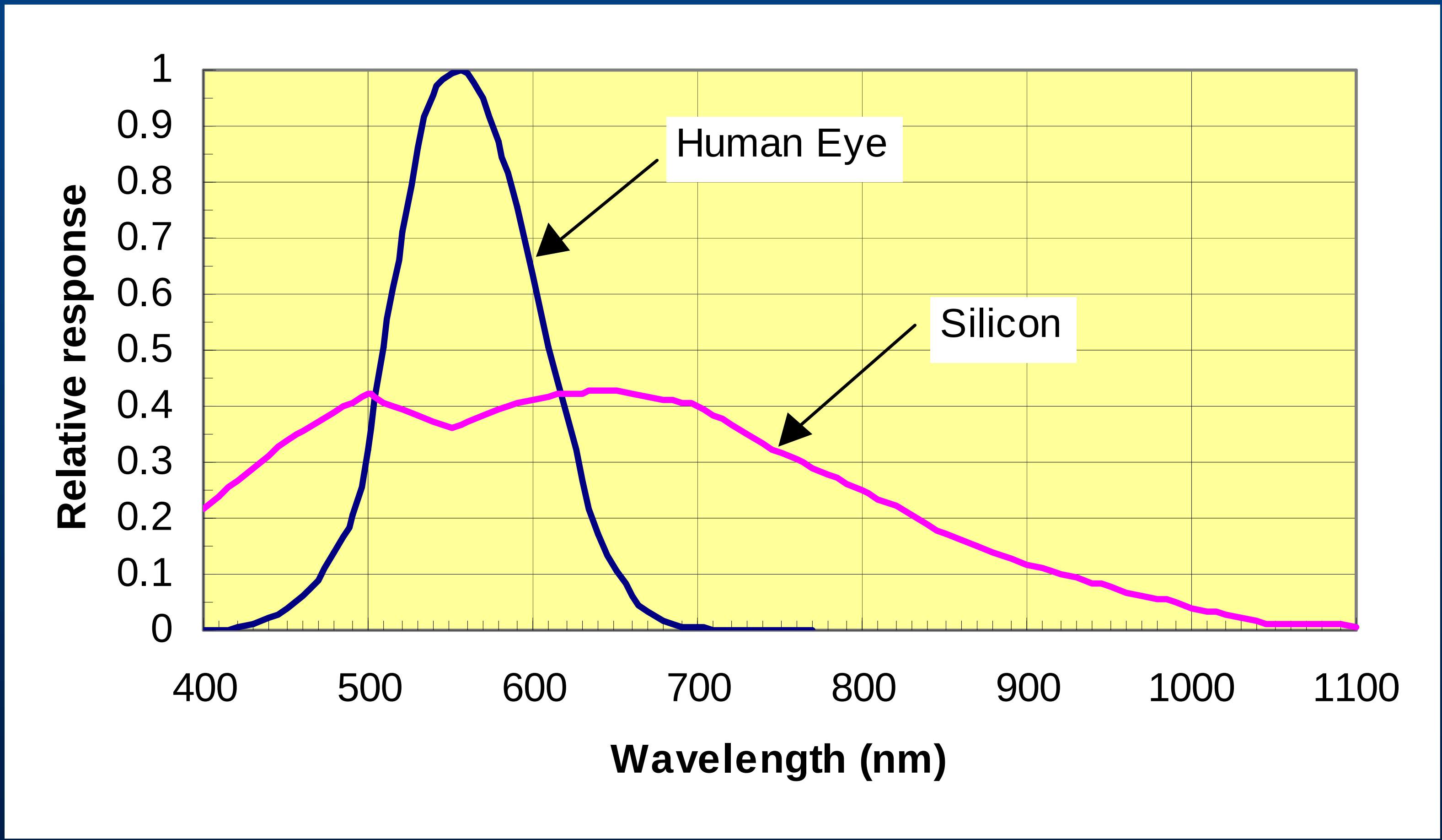
SPECTRAL RESPONSES



Optics

- Optics (lenses, mirrors) COLLECT and FOCUS light
- Optics are measured by focal length (zoom-effect)
- and by “speed” or F-number (ratio of focal length to diameter)
  - Light on sensor is $1/4F^2$ x light on scene
    - Higher F-number means less light on image sensor
    - Lower F-number mean more light
  - Iris or diaphragm adjusts F-number by changing effective lens diameter
  - Typical video cameras are F/2 (so ‘faceplate’ illuminance is 1/16 scene)
- Standard lens sizes are measured in inches (sort of lens diameter)
  - e.g. 2/3”, 1/2”, 1/3”, 1/4” etc.
  - Smaller lens sizes weigh less and cost less - important for portables
  - Smaller sizes require smaller image sensors and smaller pixel sizes (for same # of pixels) and are less sensitive to light
  - Actual image sensor diagonal is much less than lens size
  - For example, 1/3” format (8.5 mm) needs 6.1 mm diagonal !

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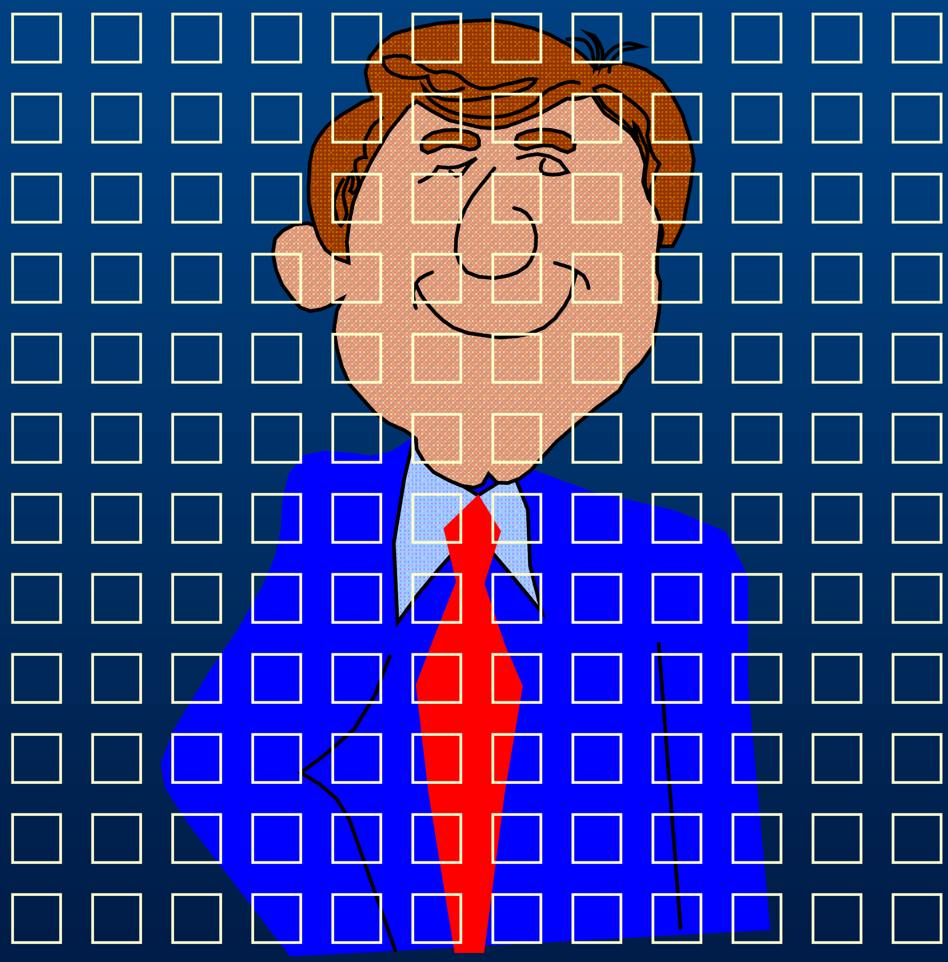
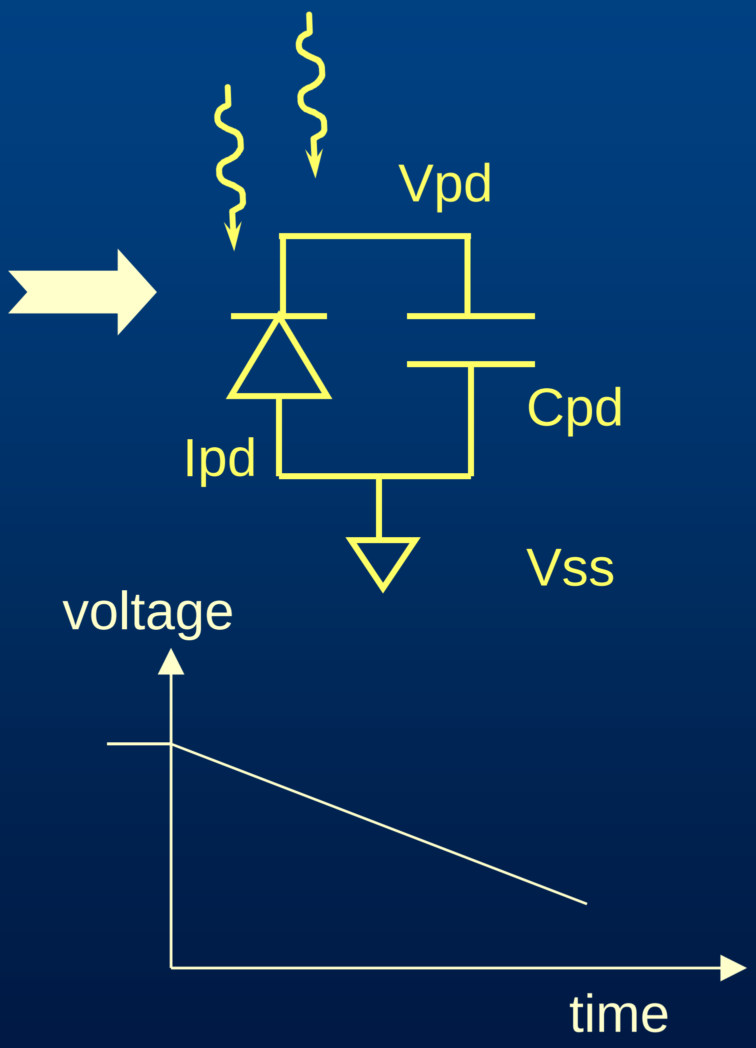
Pixel Sizes

- A pixel is a “picture element”
- More pixels means more RESOLUTION
- More pixels means more DATA (could be a bad thing)
- Modern pixel sizes are between 4 and 10 microns
- Pixels are square if designed for a computer display
- Pixels have a rectangular shape for TV applications

FORMAT	Columns	Rows	Total # Pixels
CIF	352	288	100k
VGA/TV	640	480	300k
Megapixel	1280	1024	1.3M
HDTV	1920	1120	2.0M

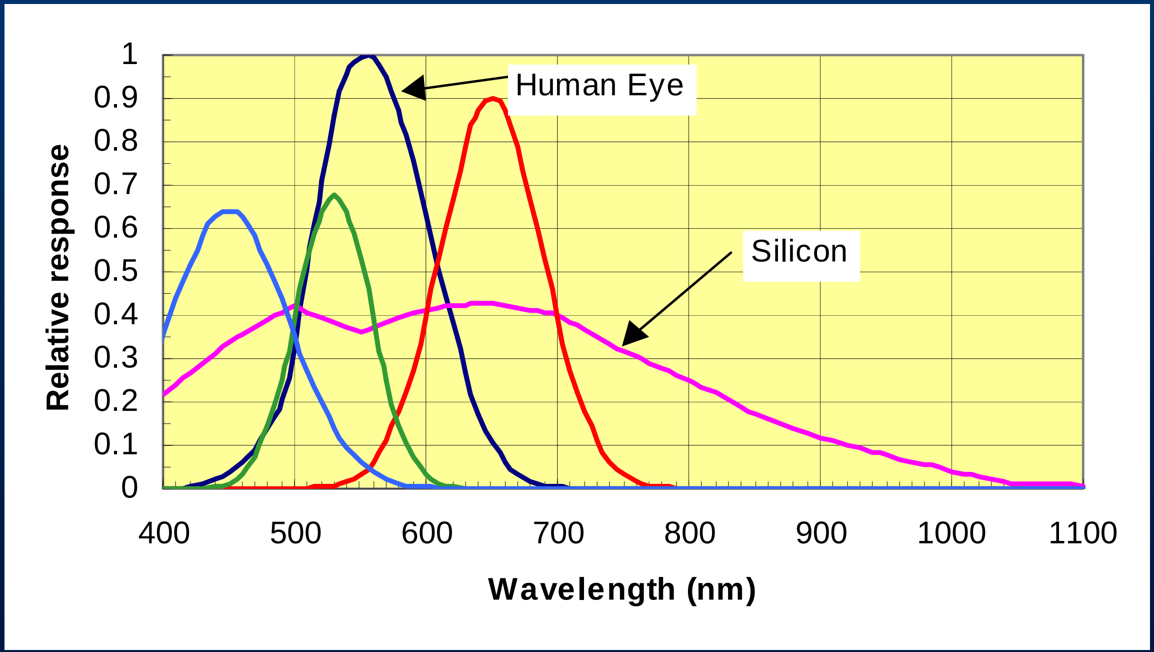
Pixels

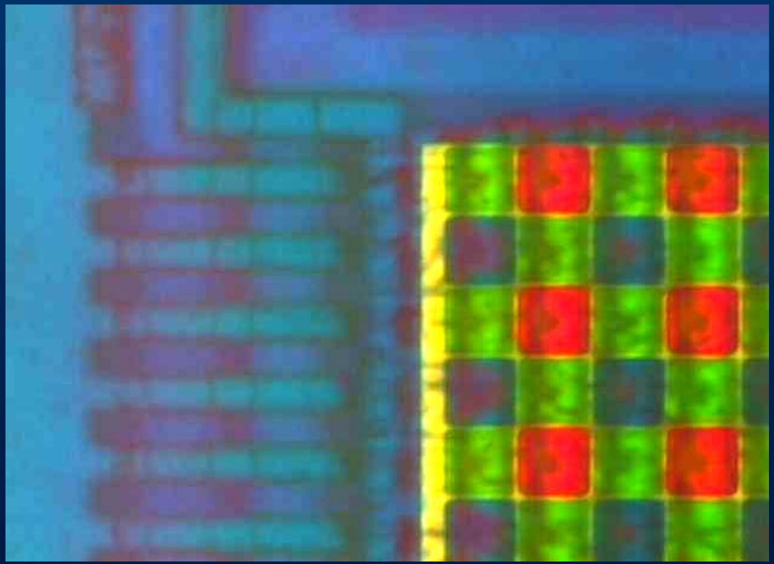




Color Filter Array (CFA)

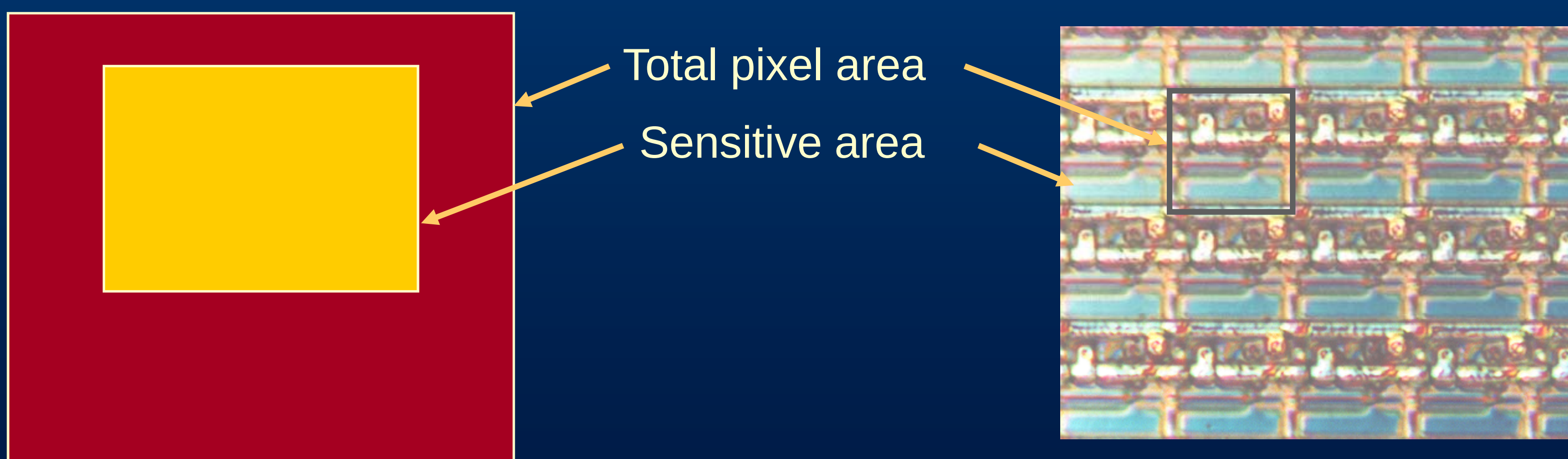
- Each pixel gets covered by a colored filter
  - We use red, green, blue (RGB) CFA - best match for RGB displays in “Bayer” pattern
  - Could use complementary colors (cyan, yellow, magenta)





Fill Factor

- A pixel is divided into a sensing portion and a readout portion
- Fill factor is the ratio of sensing area to total area and is typically about 20% for CCDs and CMOS APS



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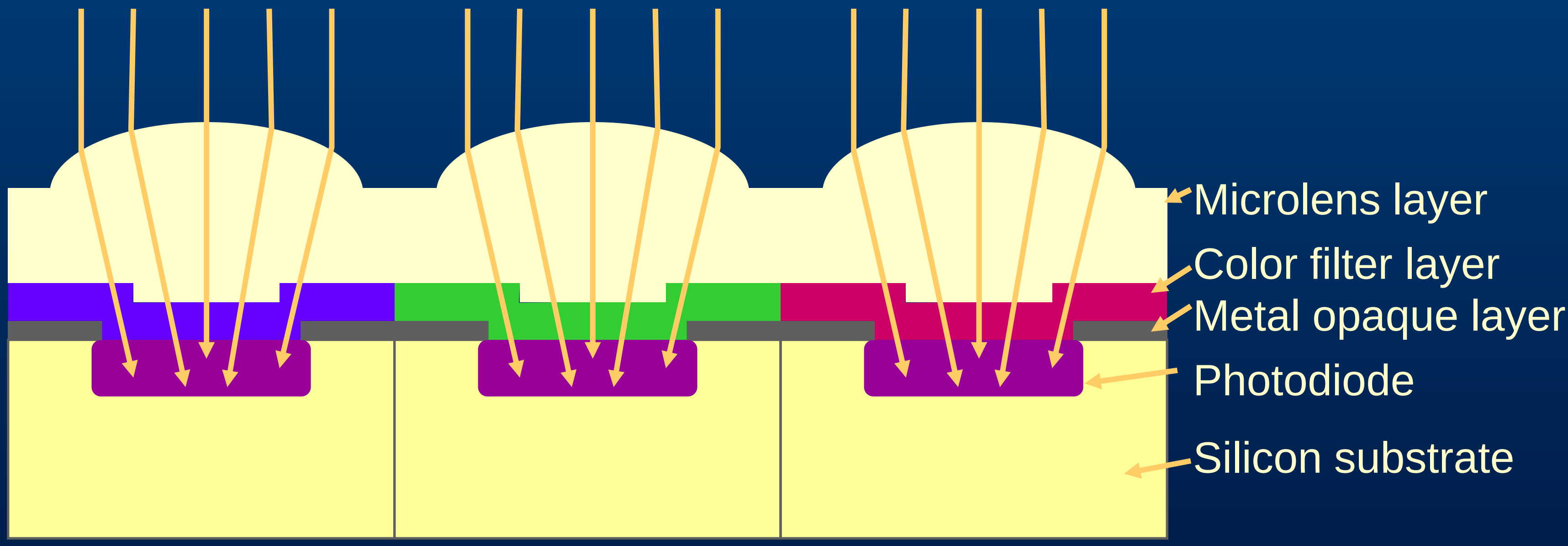
Microlenses

- Microlenses funnel light away from non-sensitive portions of pixel



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Photons to Electrons

- Photon is absorbed by silicon and converted to an electron-hole pair. Typically the electrons (e -) are collected and holes discarded.
- Quantum efficiency (QE) is ratio of collected electrons to incident photons over whole pixel* and is always less than unity for visible light, and is wavelength dependent.
- Depends on:
  - fill factor
  - microlenses
  - design
  - vertical photosensor structure
  - fundamental physics of silicon

* some people just use the defined sensitive area to get a higher value but we consider this cheating. One always needs to check how it is defined.

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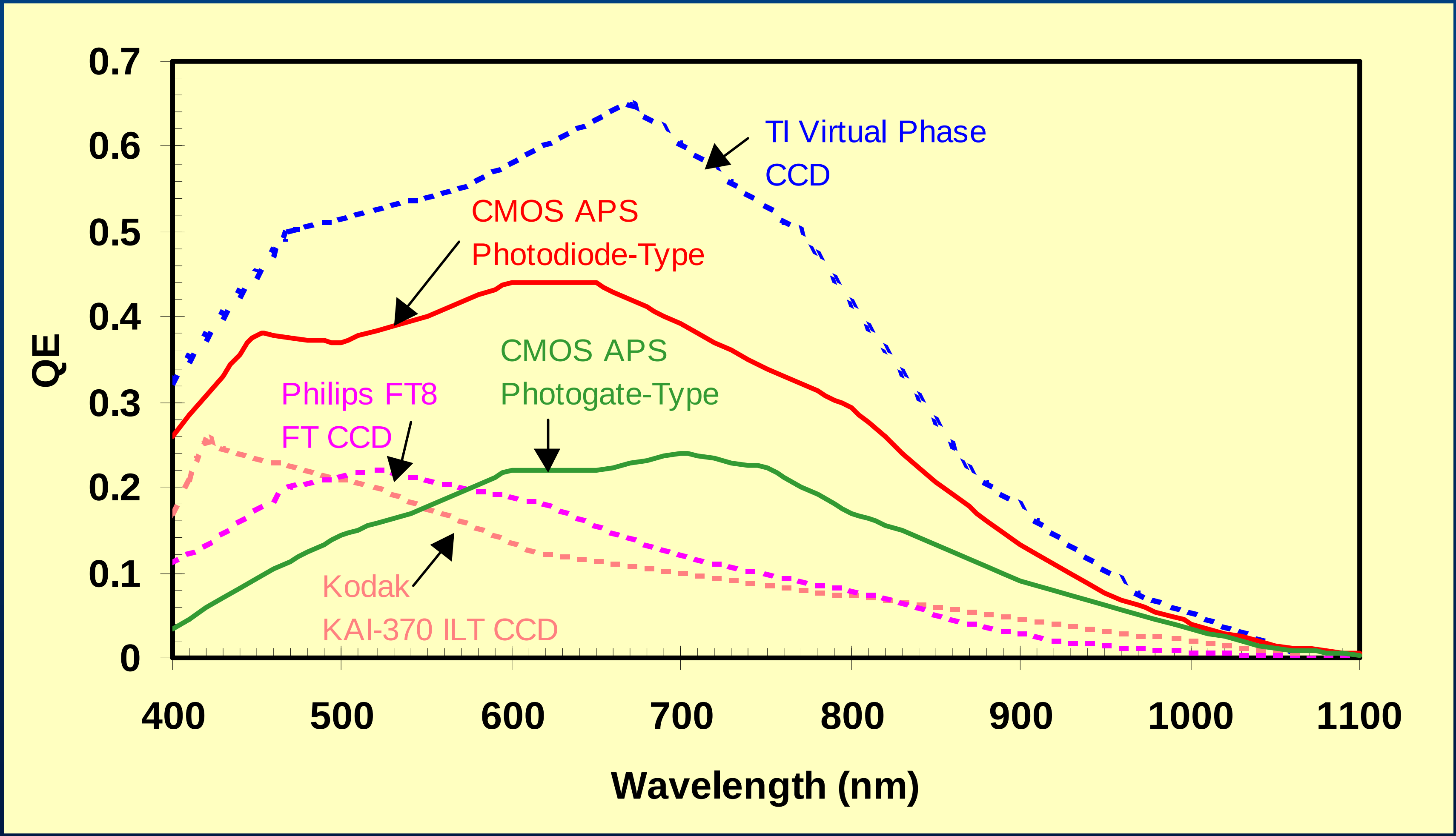
Quantum Efficiency

APS has quantum efficiency comparable to CCDs



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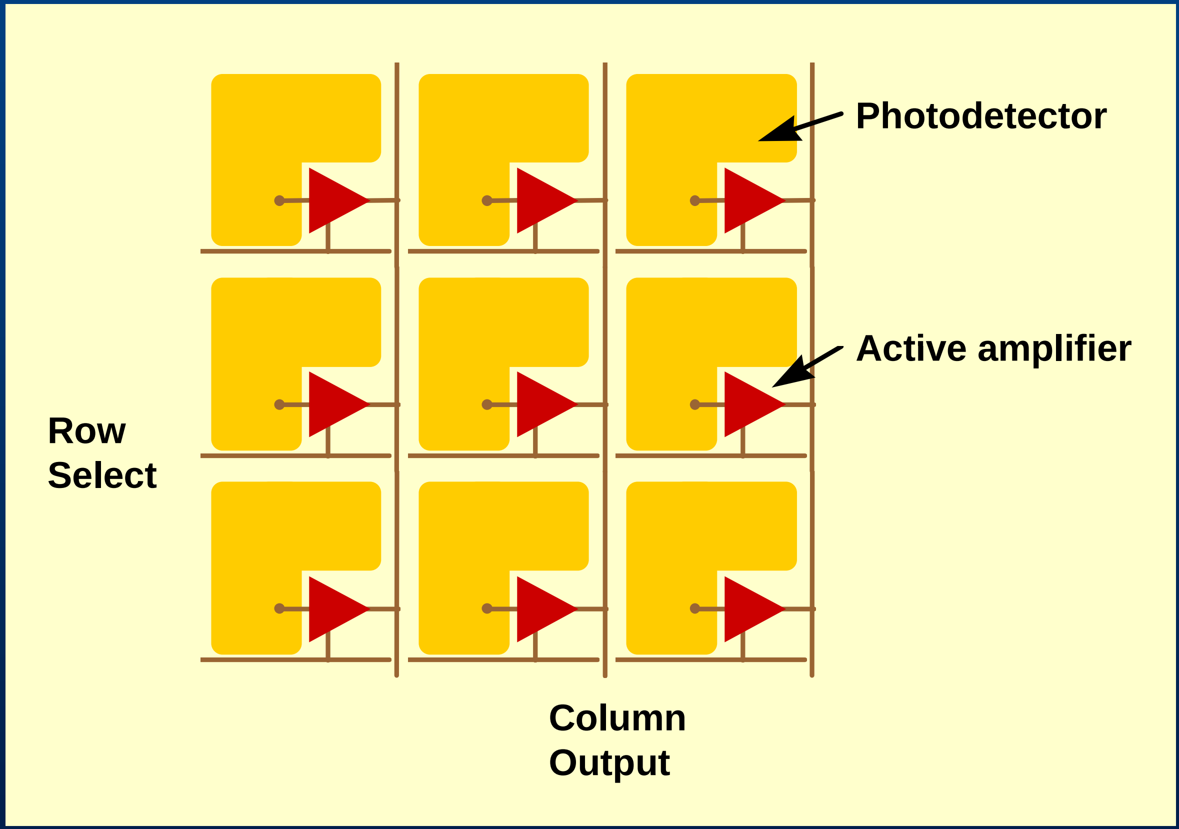
CMOS Active Pixel

- Each pixel has its own output amplifier
- Pixels are X-Y addressed
- Key is low noise readout circuit
- Best of CCD detection/readout and CMOS integration



Electrons to Volts

- The CONVERSION GAIN determines the amount of volts per electron for the pixels.
- Typical value range is 1-10 μV/e -
- Higher value is good but limits total signal that can be handled
  – e.g. at 10 μV/e -, 1 volt max = 100,000 electrons max
- Pixel amplifier should introduce minimum noise
- Noise is measured in equivalent number of electrons
  – e.g. 200 μV rms @ 10 μV/e - = 20 e - rms noise

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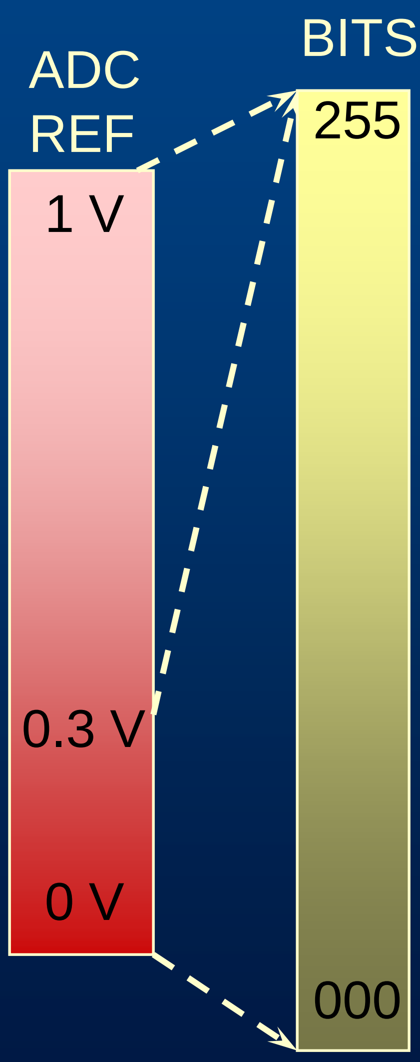
Volts to Bits

- The ANALOG-TO-DIGITAL CONVERTER (ADC) converts the voltage from the pixels to a digital word.
- The ADC may have an ANALOG SIGNAL PROCESSOR (ASP) to reduce noise and provide additional gain before conversion.
- ADC has a reference voltage, e.g. 1 Volt, so that digital word is scaled against the reference voltage. A lower reference voltage is similar to adding gain.
- On-chip ADCs trade power for resolution (number of bits)
- 8 bits is enough for teleconferencing. 10-12 bits is desired for digital still cameras.



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Photons to Bits

OPTICS	→	MICRO-LENS	→	COLOR FILTER ARRAY (CFA)	→	QUANTUM EFFICIENCY (QE)	→	CONVERSION GAIN (uV/e-)	→	ASP	→	ADC
$1/4F^2$												
Scene to Sensor		Funnels Light		Selects Color		Includes Fill-Factor (no cheating)		Electrons to Volts		Amplification and Noise Suppression		Volts to Bits

Post-Capture Processing

- Sensor produces 8b (or more) for each pixel
- System eventually wants 24b (RGB) for each pixel
  - Color interpolation required
  - Color balancing (“white balance”) required
- Additional processing used for aperture correction, etc.
- Communication is usually bandwidth limited
  - Compression often required
- Interfaces need to have data format and output according to interface specification
  - Interface controller/data formatter required e.g., USB, NTSC

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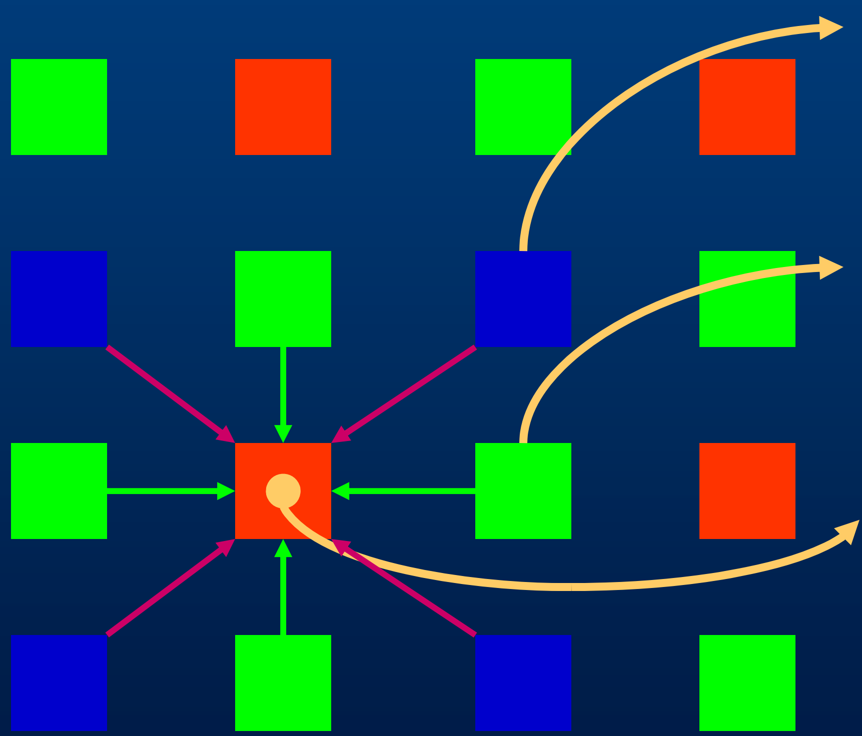
Color Interpolation

- Goal is to get best approximation for RGB at each pixel site
- Many possible approaches, e.g.:



•Have blue, need green & red
  - G = average of 4 neighboring greens
  - R = average of 4 neighboring reds

•Have green, need blue & red
  - B = average of 2 neighboring blues
  - R = average of 2 neighboring reds

•Have red, need green & blue
  - G = average of 4 neighboring greens
  - B = average of 4 neighboring blues

Color Correction

- Need to correct colors
  - relative intensities (white balance)
  - remove mixtures (off-diagonal elements)

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

No perfect solution due to filter overlaps and eye response
Best-fit by weights to standard color chart

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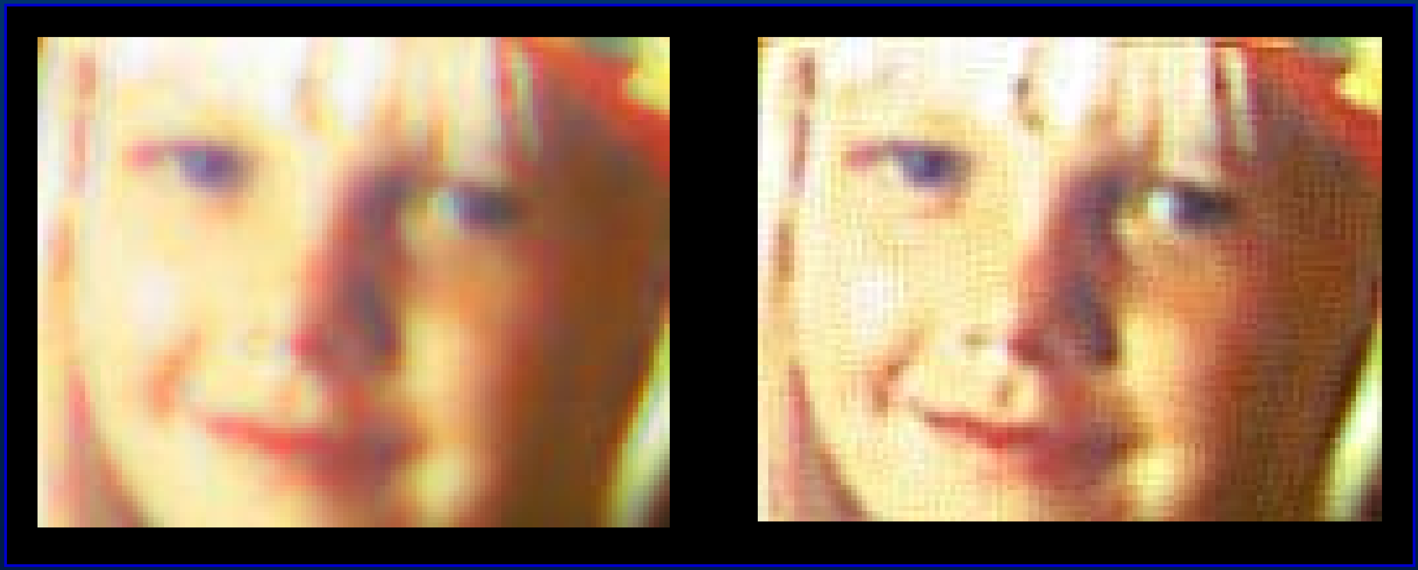
Aperture Correction

- Interpolation and color correction leads to ‘blurring’ of image since averaging over a neighborhood
- Want to restore apparent sharpness to image
- Apply simple image sharpening algorithm to ‘green’ image
- Apply green correction to red and blue



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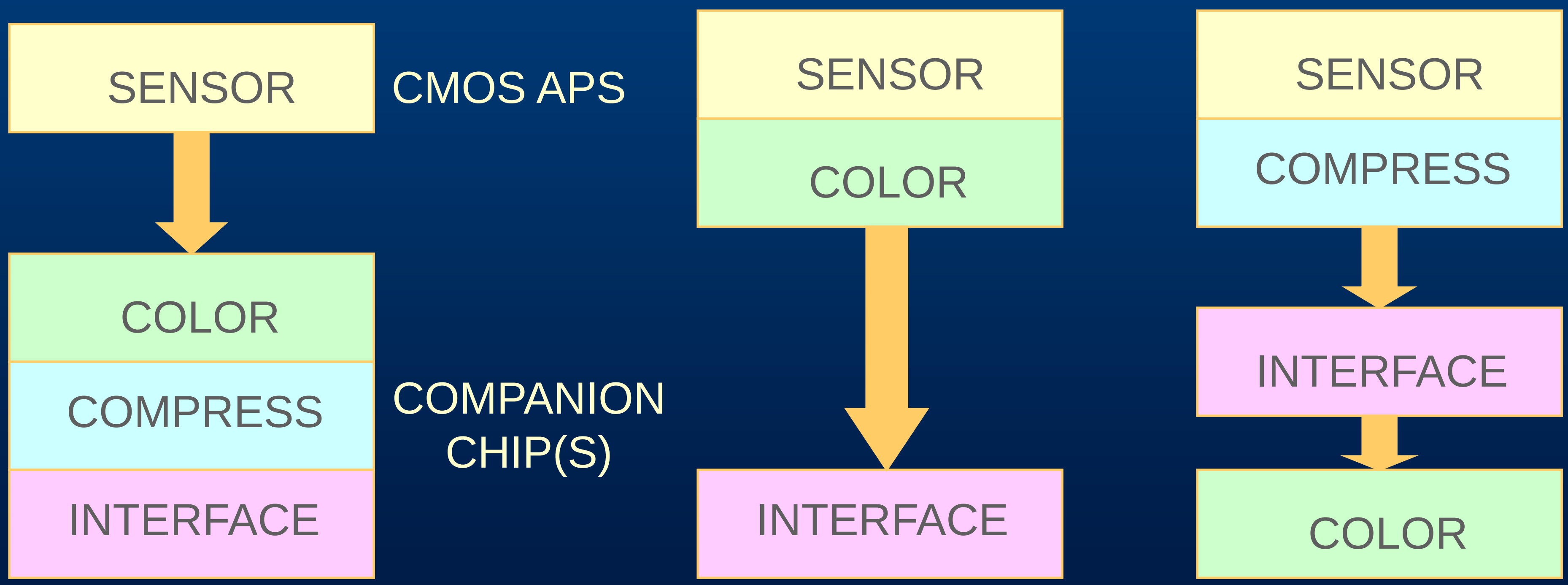
Compression

- Communications typically limited in bandwidth (bits/sec)
- USB, Firewire, POTS, Internet….
- Many different compression techniques
  - JPEG - still pictures
  - MPEG - moving pictures (e.g. video)
  - wavelet
  - fractal
  - vector quantization
- Few lossless approaches - image quality ALWAYS degrades -- but is it acceptable?
- Poor sensor plus poor compression = very poor image

Camera System

- How design and partition system? Many options.
- Jury is out on ASIC vs. PC-based processing.



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Imaging System-on-a-Chip

PROS

- Possibly lower cost
  - single package
  - single-pass testing
- Smaller footprint / form factor
- Lower total power dissipation
- Easier system assembly
- Increased reliability

CONS

- Possibly higher cost
  - Color filters and microlenses deposited on digital logic
  - Use of larger than optimal design rules
  - Lower yield due to large die size
- Noise corruption due to on-chip digital clocking
- Power dissipation leads to increase in dark current level

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Cameras and the Internet

- 1 Gb/s ~ 335 TeraBytes/month
- Total Worldwide Internet Traffic 2000*
  - 20,000 TeraBytes/month, or 60 Gb/s average load
  - increasing 100%/yr, and about 10% total capacity
- A single CIF resolution image sensor PC video camera with 3:1 compression produces about 10 Mb/s.
  - 6,000 households with live cameras are equivalent to the total worldwide internet traffic
- A 1.3 Mpixel sensor at 1000 fps with 10b output produces about 13 Gb/s
  - 5 High speed high resolution cameras are equivalent to total worldwide internet traffic

* "The size and growth rate of the internet", K.G. Coffman and A. Odlyzko, http://www.firstmonday.dk/issues/issue3_10/coffman/