



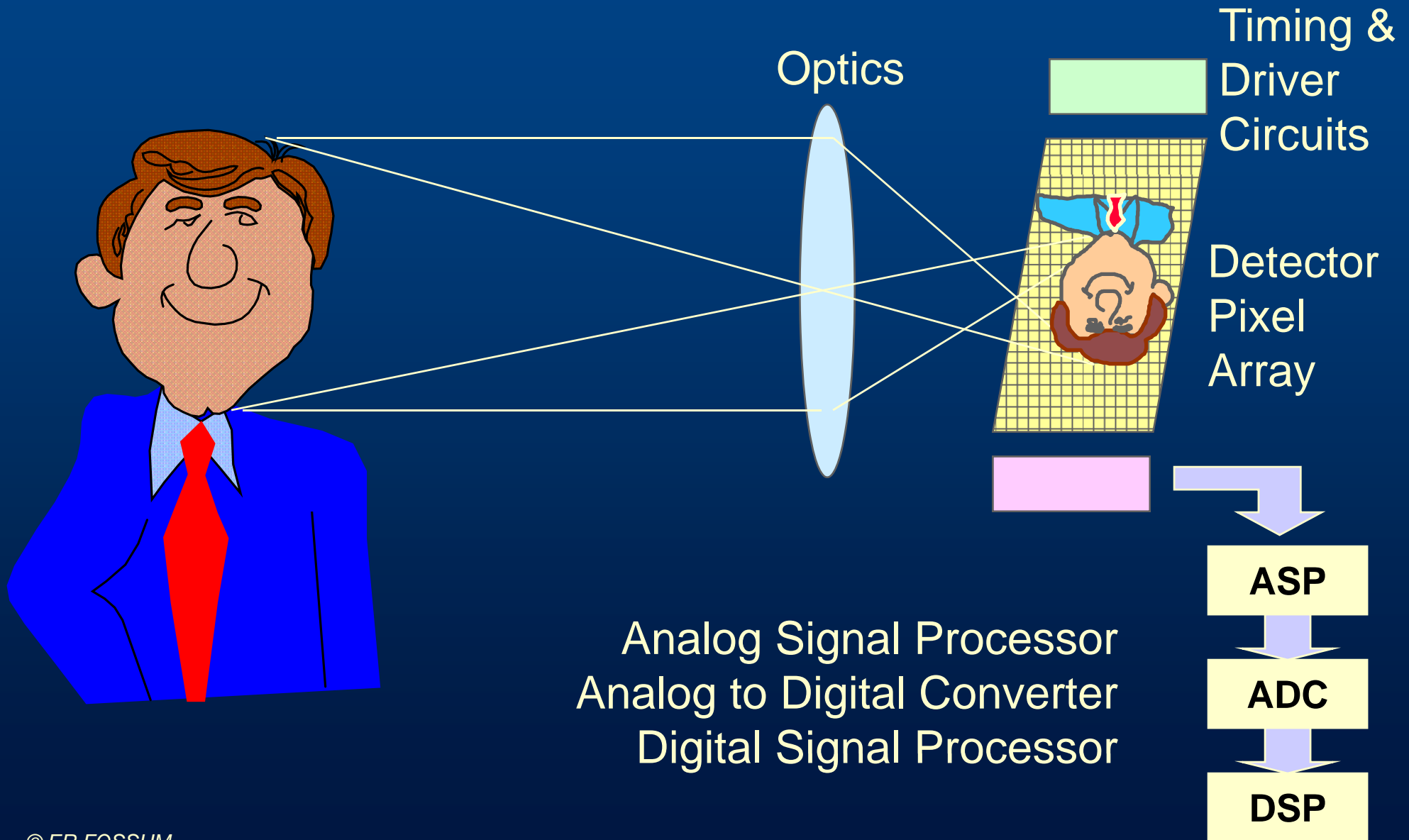
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TECHNOLOGY

CMOS ACTIVE PIXEL SENSOR TECHNOLOGY - AN INTRODUCTION -

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Imaging Systems





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



Your eye is sensitive from violet to dark red

450 nm - 700 nm

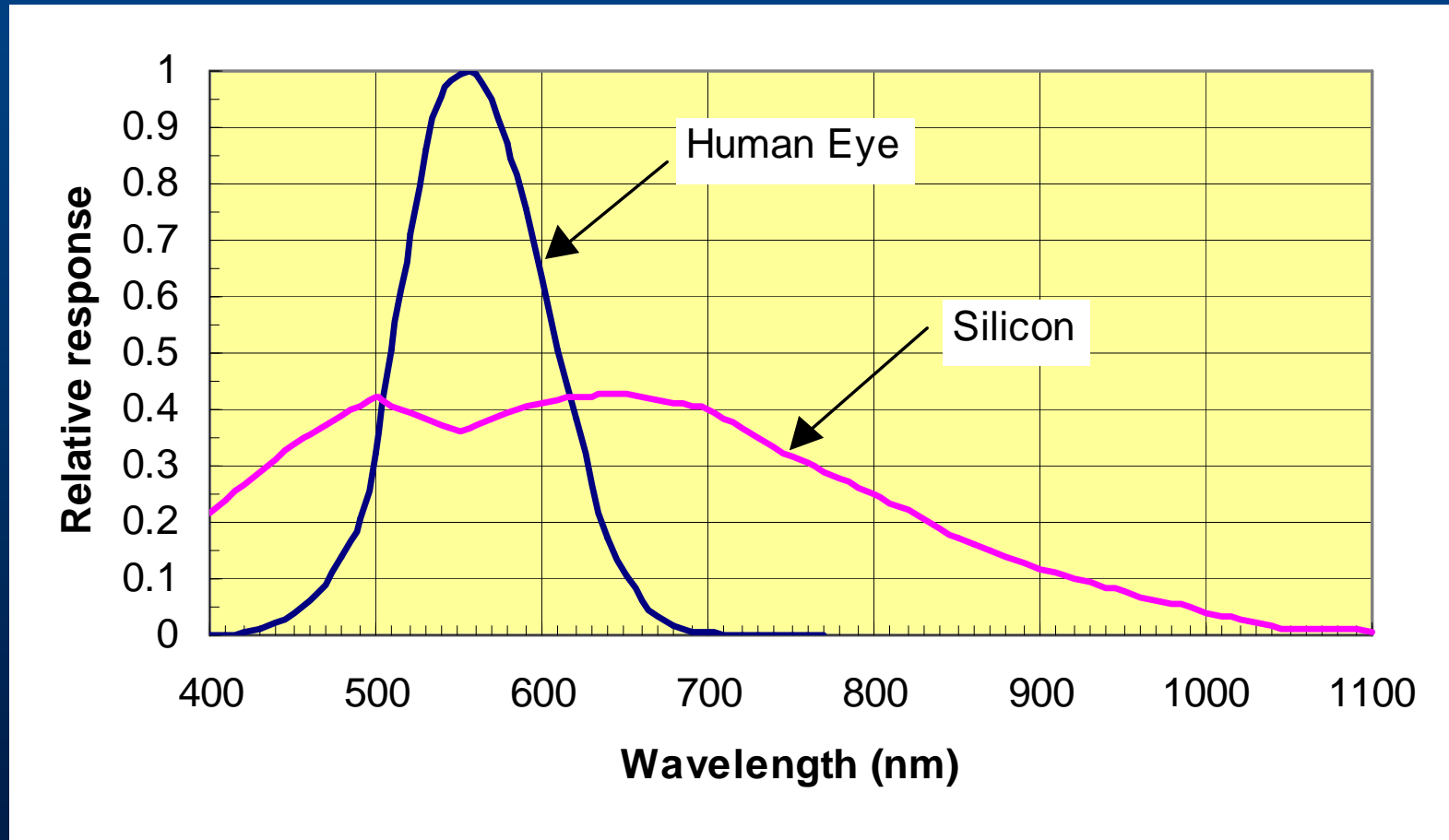
Silicon is sensitive from violet to the “near” infrared (not thermal)

400 nm - 1050 nm

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



- 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





- 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 !



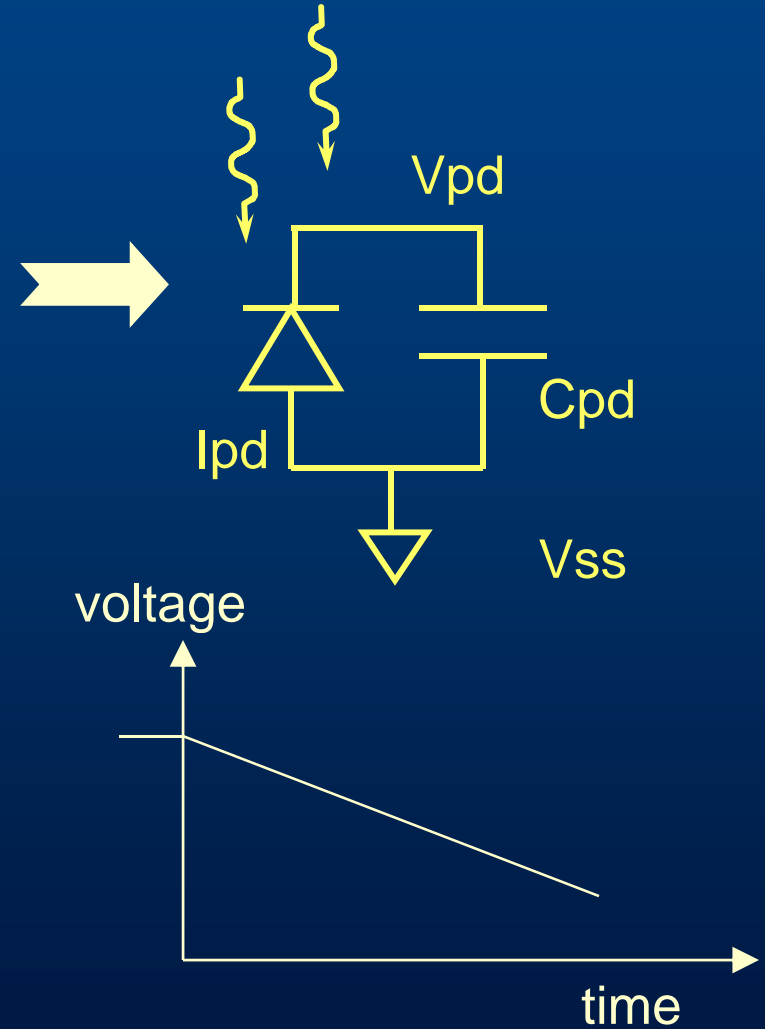
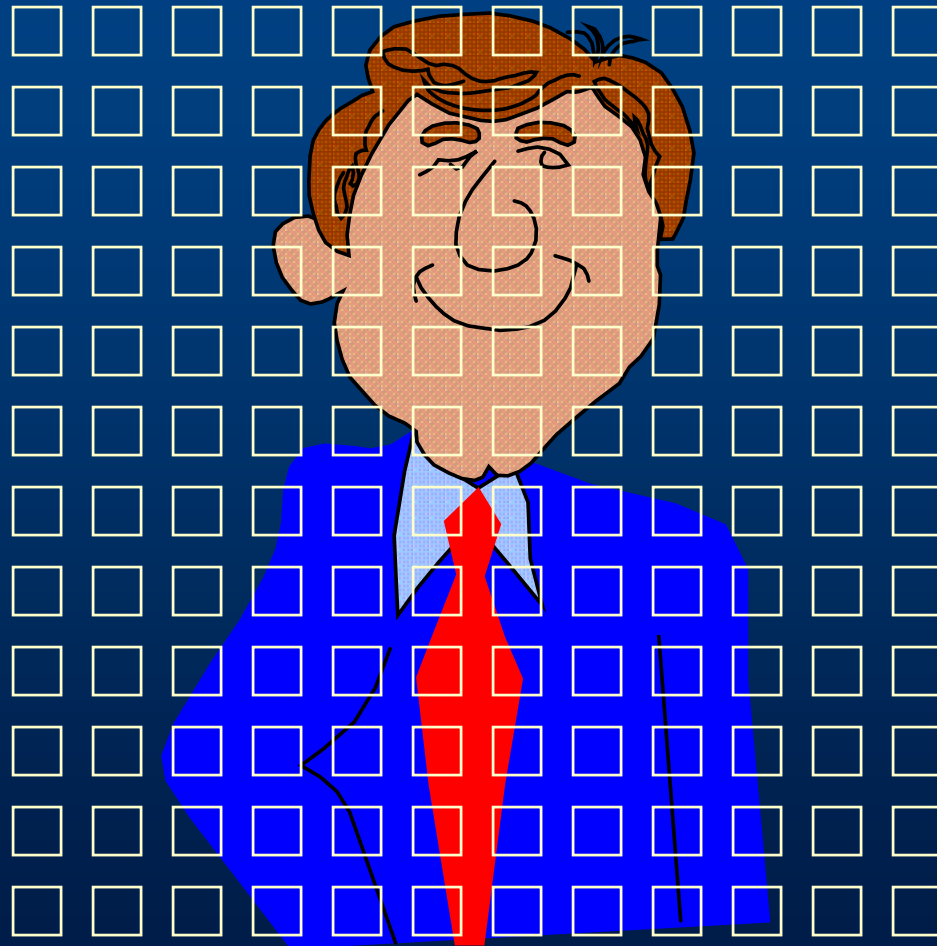
- A pixel is a “picture element”
- More pixels means more RESOLUTION
- More pixels means more DATA (could be a bad thing)
- Modern pixel sizes are between 4 and 10 microns
- Pixels are square if designed for a computer display
- Pixels have a rectangular shape for TV applications

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



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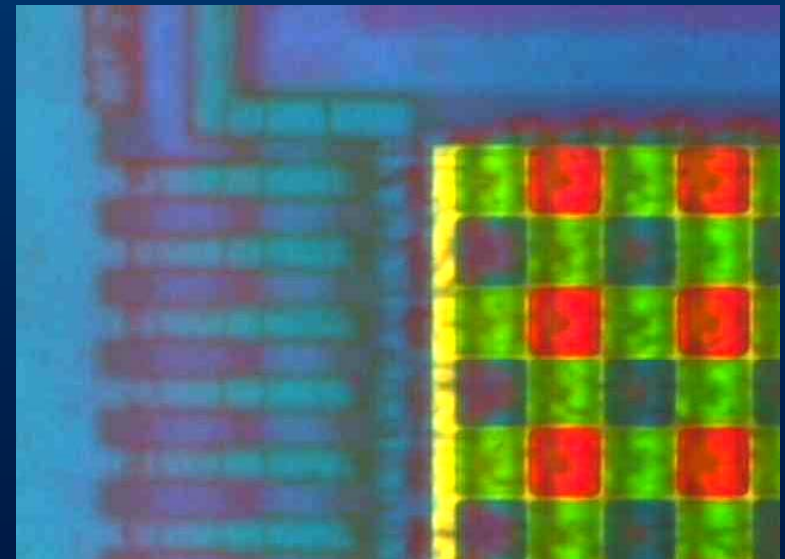
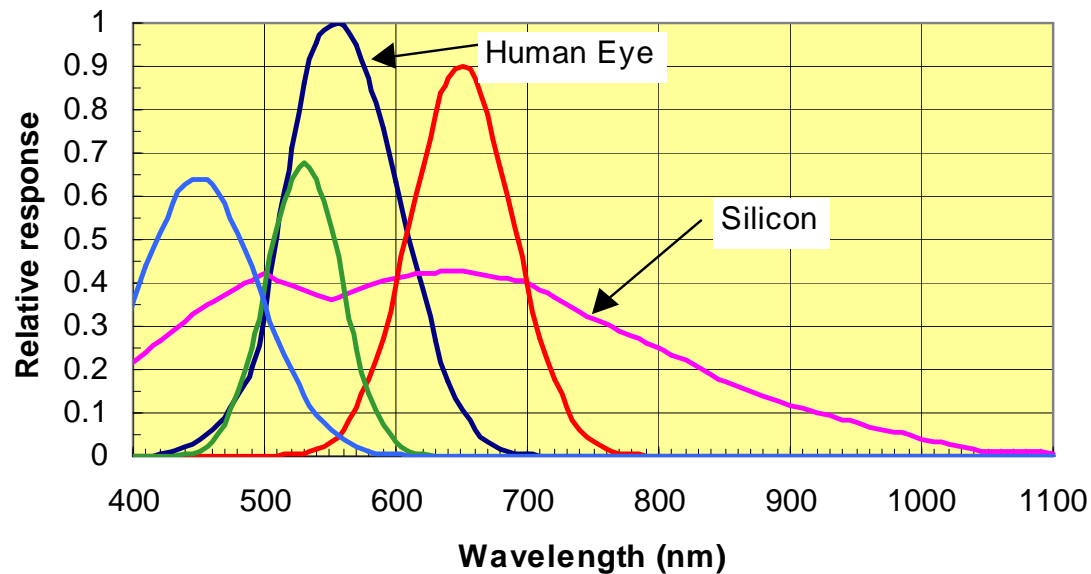
Pixels





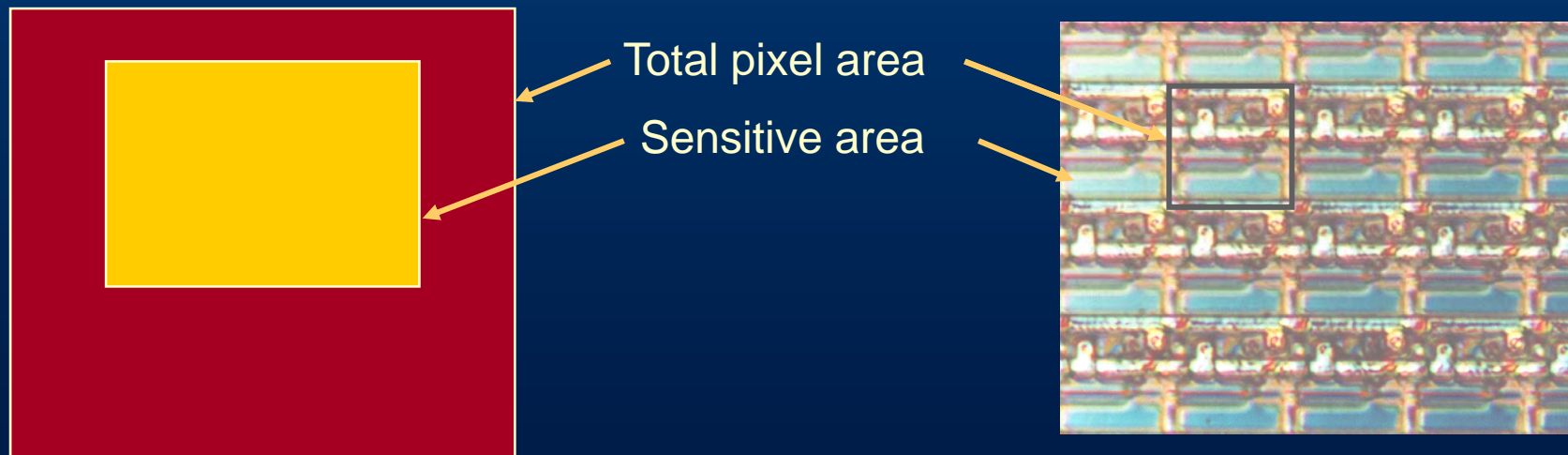
Color Filter Array (CFA)

- 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)



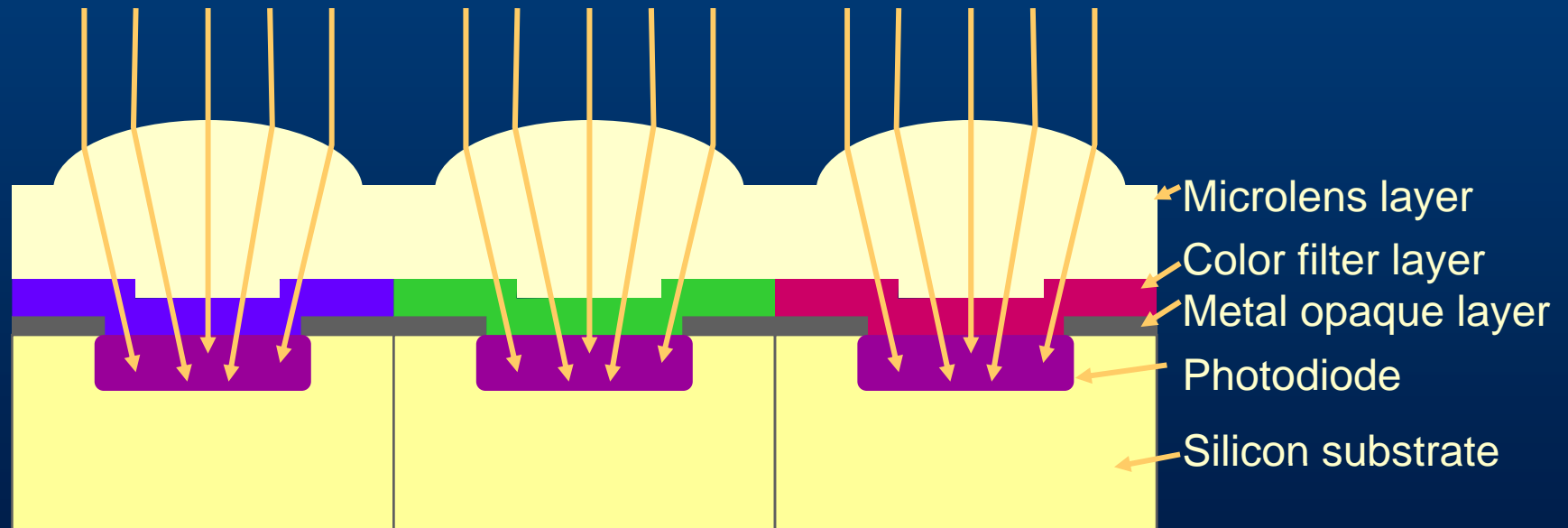


- A pixel is divided into a sensing portion and a readout portion
- Fill factor is the ratio of sensing area to total area and is typically about 20% for CCDs and CMOS APS





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

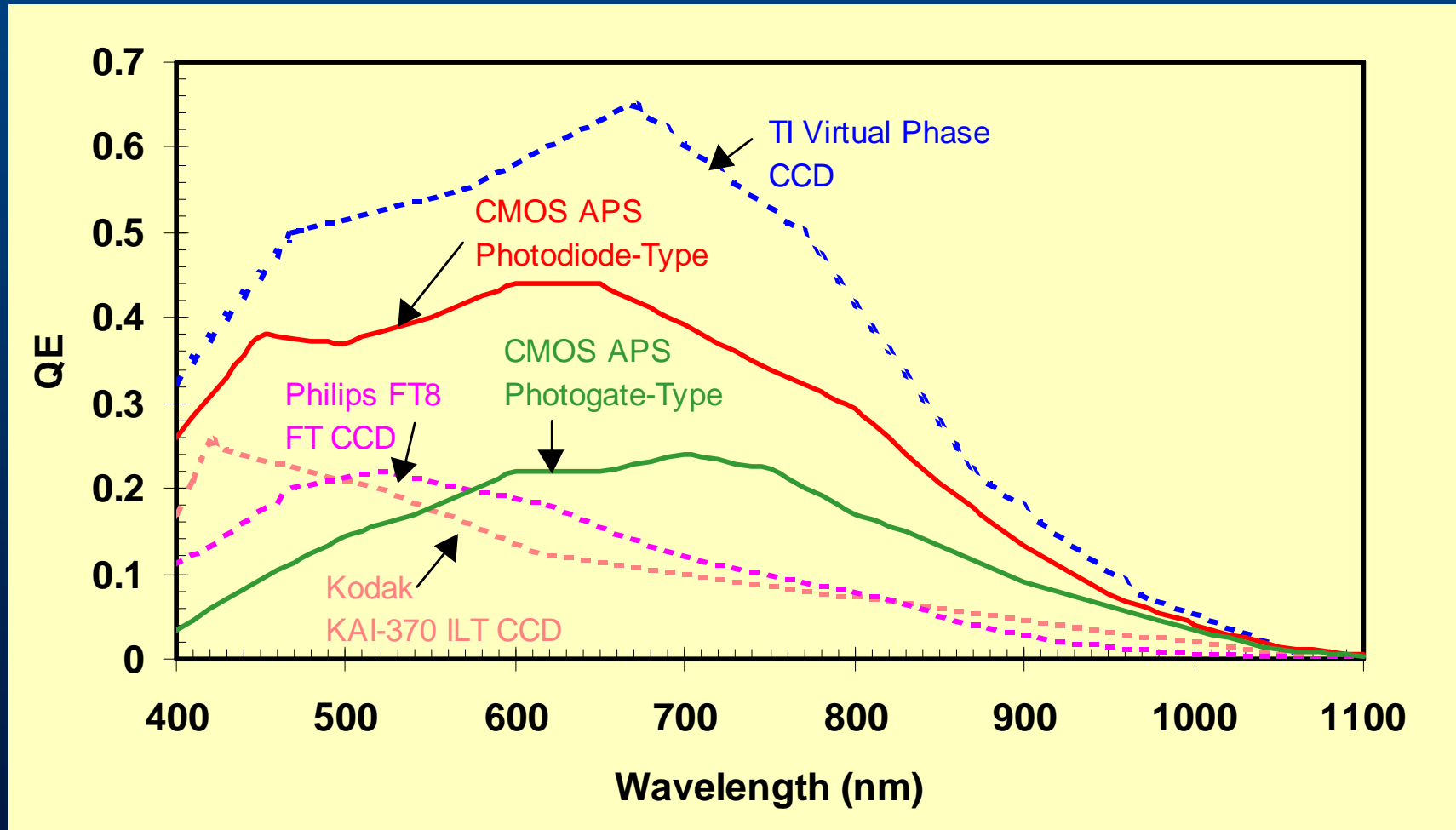




- Photon is absorbed by silicon and converted to an electron-hole pair. Typically the electrons (e^-) are collected and holes discarded.
 - Quantum efficiency (QE) is ratio of collected electrons to incident photons over whole pixel* and is always less than unity for visible light, and is wavelength 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.



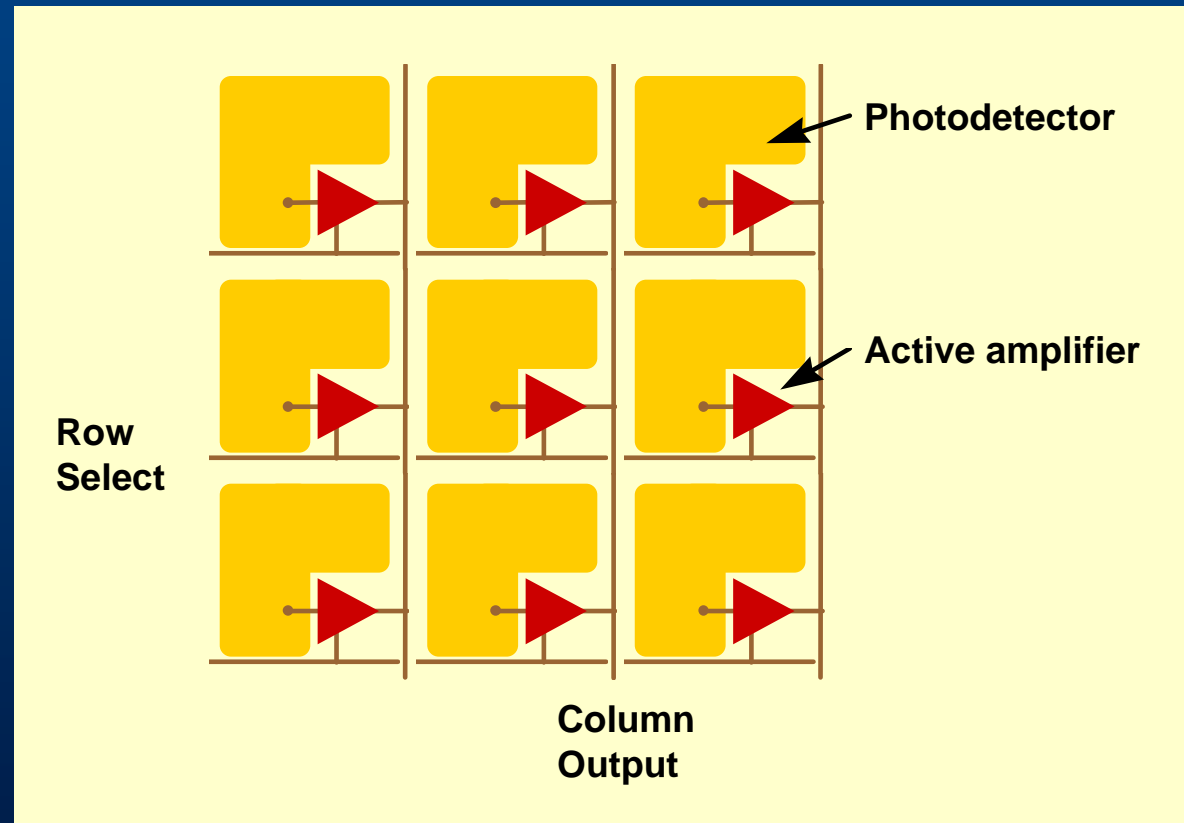
APS has quantum efficiency comparable to CCDs





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

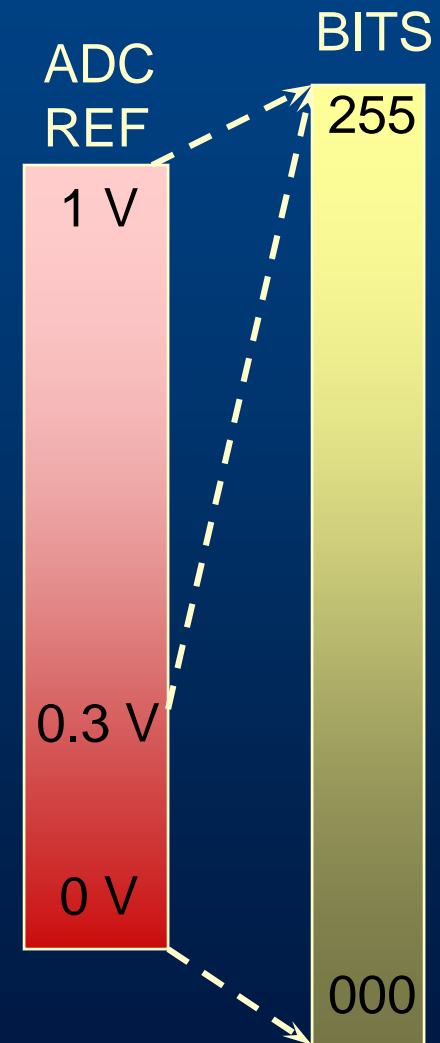




- The CONVERSION GAIN determines the amount of volts per electron for the pixels.
- Typical value range is 1-10 $\mu\text{V}/\text{e}^-$ -
- Higher value is good but limits total signal that can be handled
 - e.g. at 10 $\mu\text{V}/\text{e}^-$ -, 1 volt max = 100,000 electrons max
- Pixel amplifier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

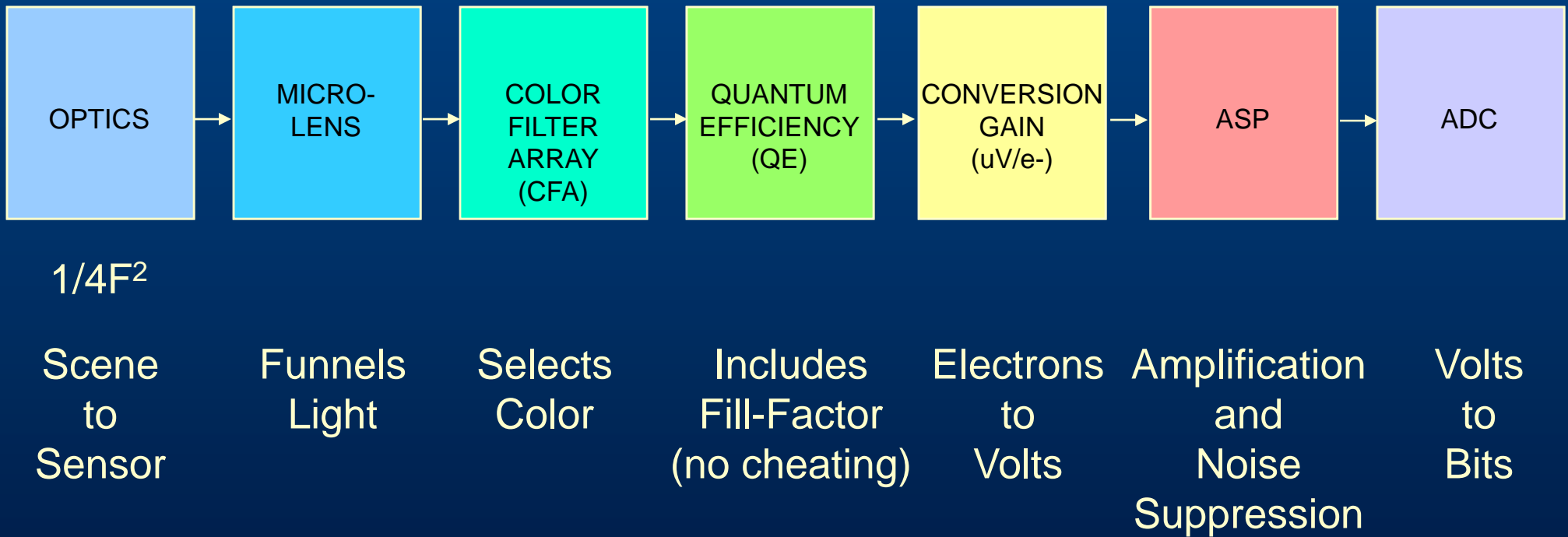


- The ANALOG-TO-DIGITAL CONVERTER (ADC) converts the voltage from the pixels to a digital word.
- The ADC may have an ANALOG SIGNAL PROCESSOR (ASP) to reduce noise and provide additional gain before conversion.
- ADC has a reference voltage, e.g. 1 Volt, so that digital word is scaled against the reference 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.





Photons to Bits

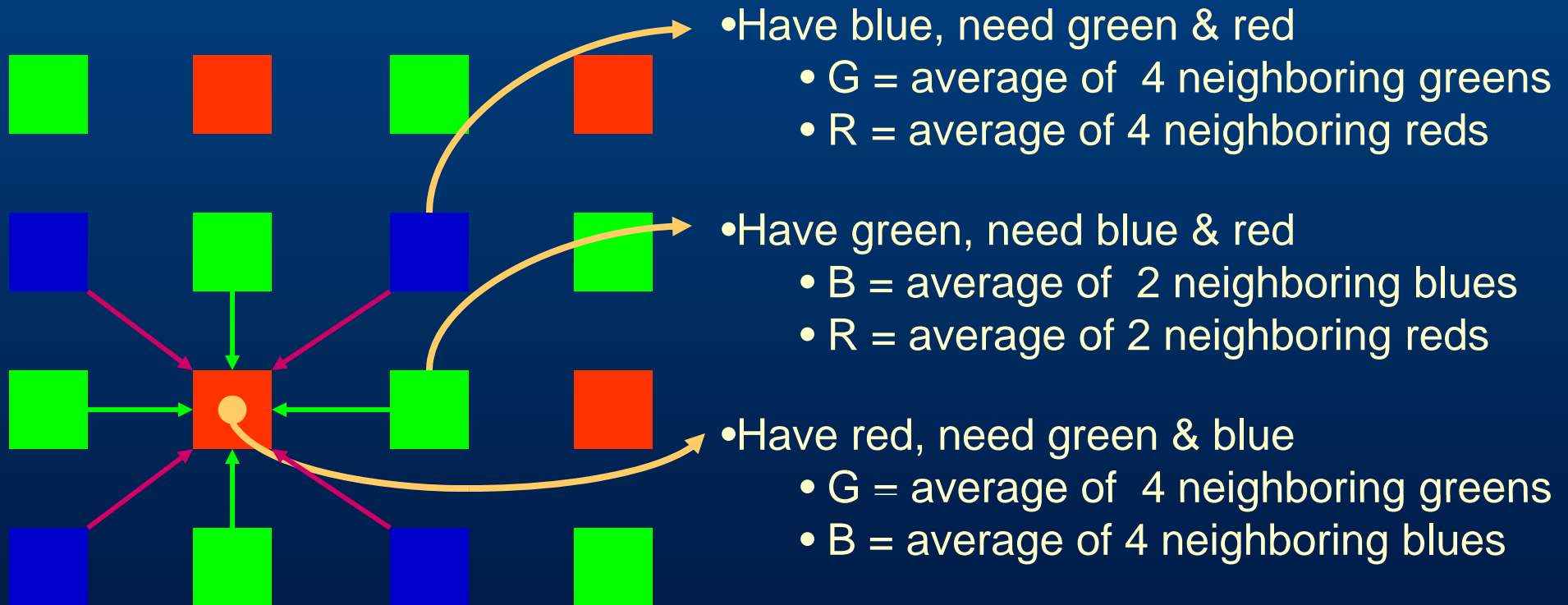




- Sensor produces 8b (or more) for each pixel
- System eventually wants 24b (RGB) for each pixel
 - Color interpolation required
 - Color balancing (“white balance”) required
- Additional processing used for aperture correction, etc.
- Communication is usually bandwidth limited
 - Compression often required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



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

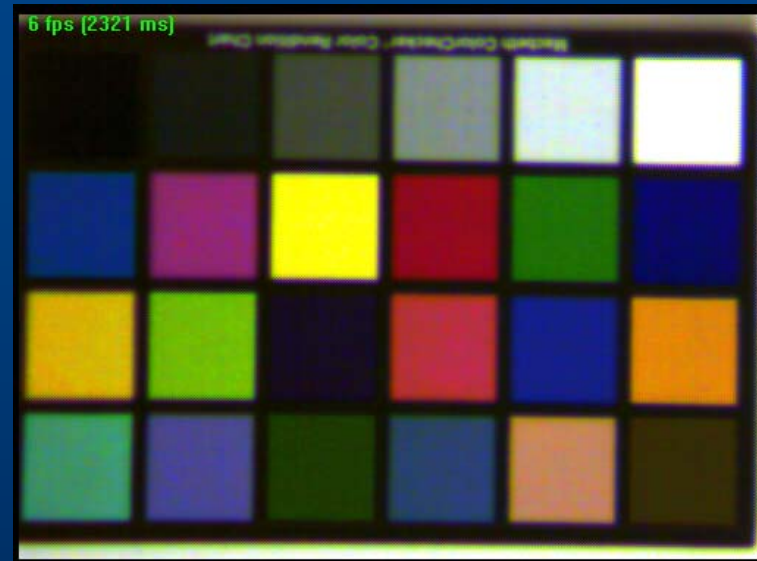




Color Correction

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

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

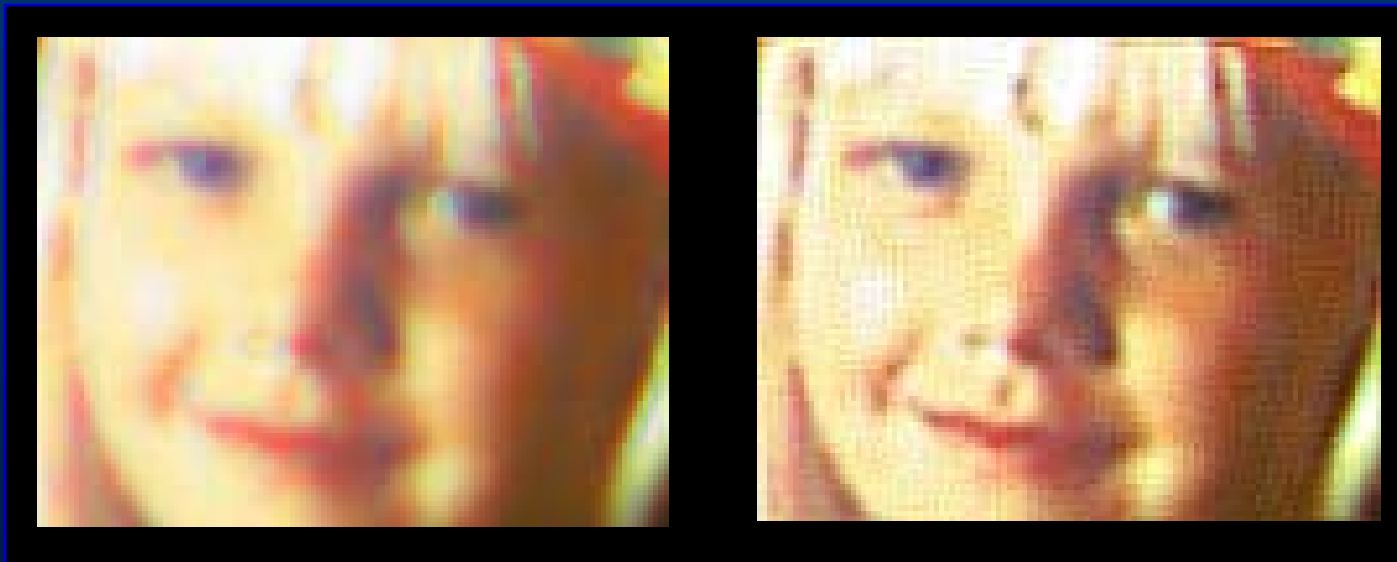


No perfect solution due to filter overlaps and eye response
Best-fit by weights to standard color chart



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

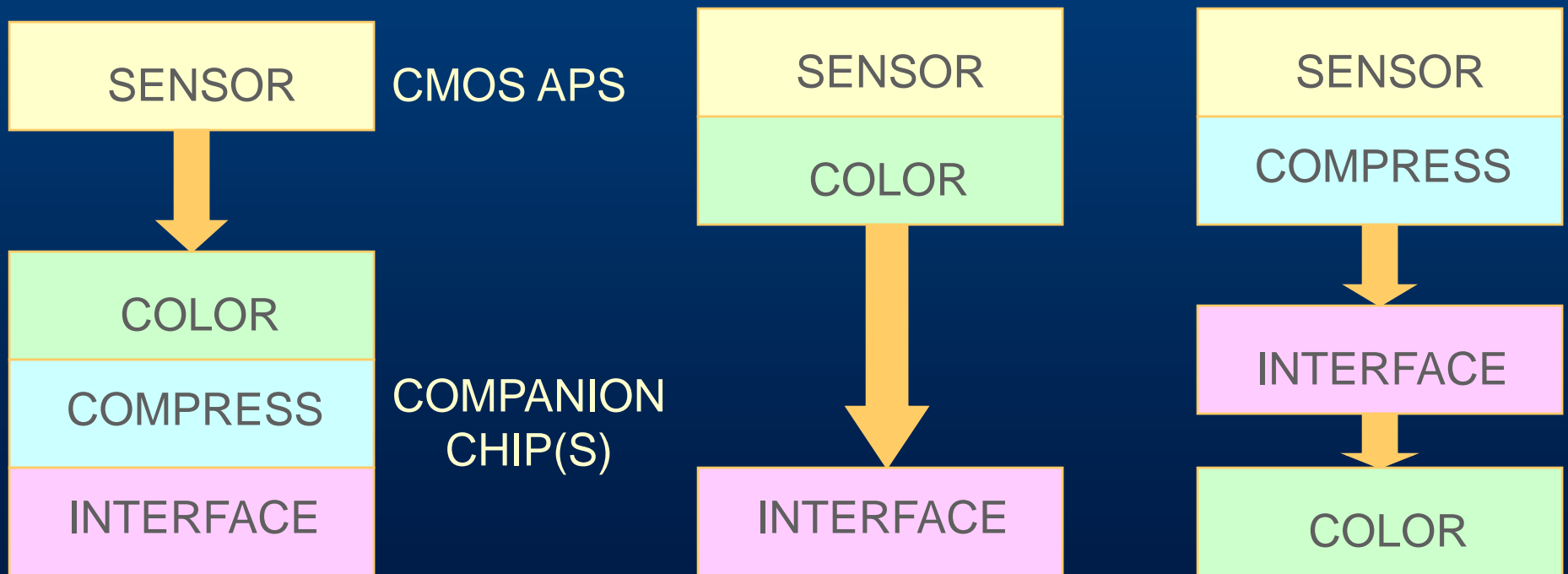




- Communications typically limited in bandwidth (bits/sec)
- USB, Firewire, POTS, Internet....
- Many different compression techniques
 - JPEG - still pictures
 - MPEG - moving pictures (e.g. video)
 - wavelet
 - fractal
 - vector quantization
- Few lossless approaches - image quality ALWAYS degrades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



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





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

Cameras and the Internet



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- 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/