Cameras

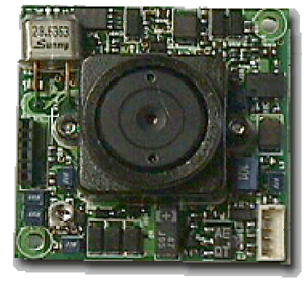
CS / ECE 181B

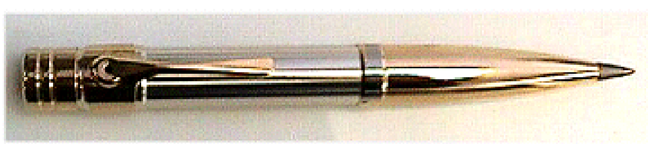
Image Formation

- Geometry of image formation
  (Camera models and calibration)
  - Where?

- Radiometry of image formation
  - How bright?
  - What color?

Examples of cameras

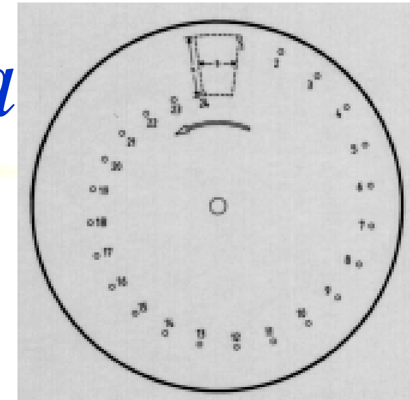




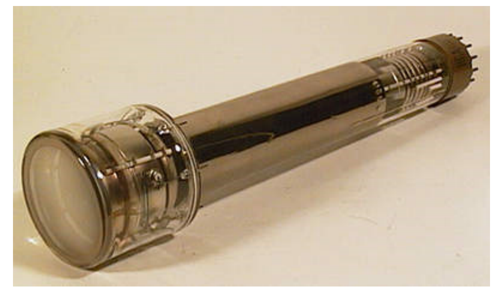
What is a Camera?

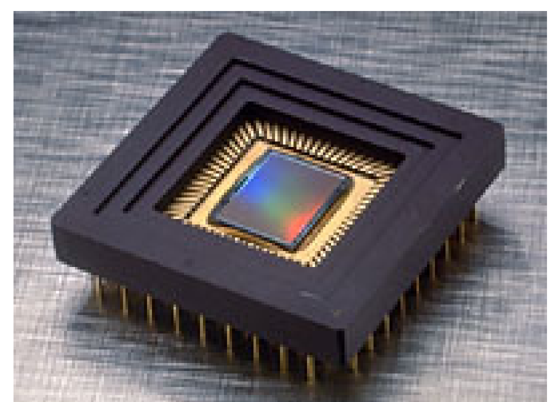
- A camera has many components
  - Optics: lens, filters, prisms, mirrors, aperture
  - Imager: array of sensing elements (1D or 2D)
  - Scanning electronics
  - Signal processing
  - ADC: sampling, quantizing, encoding, compression
    - May be done by external frame grabber (“digitizer”)
- And many descriptive features
  - Imager type: CCD or CMOS
  - Imager number
  - SNR
  - Lens mount
  - Color or B/W
  - Analog or digital (output)
  - Frame rate
  - Manual/automatic controls
  - Shutter speeds
  - Size, weight
  - Cost

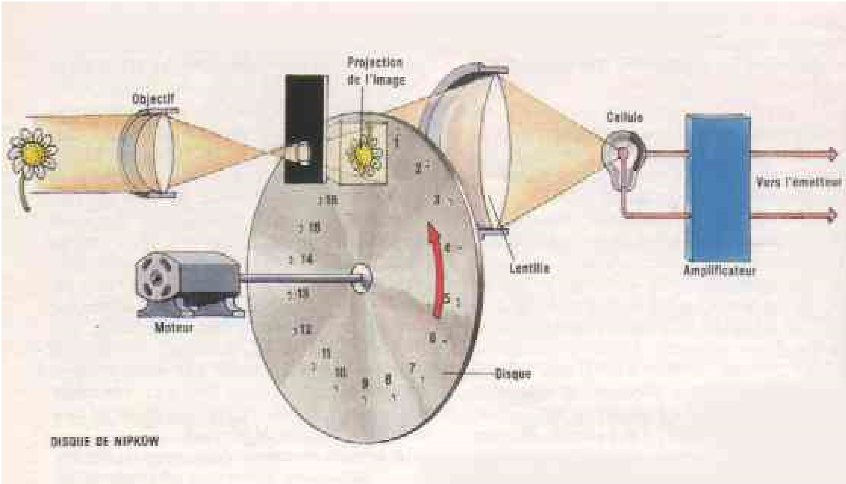
History of video camera



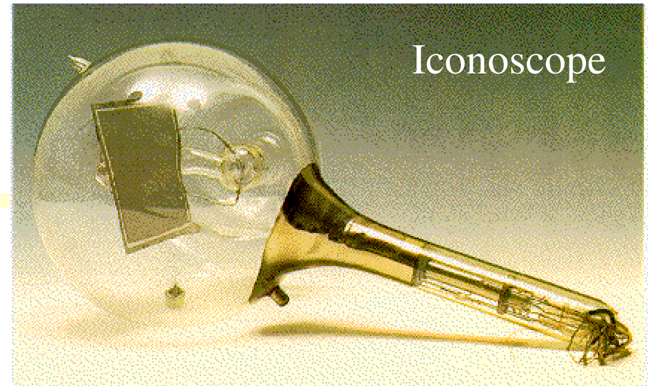
- **Mechanical scanners**
  - Nipkow disk – 1884
- **Photoelectric tubes**
  - Photoemissive, photoconductive, photovoltaic
    - Iconoscope – 1931
    - Image orthicon – 1946
    - Vidicon – 1950
- **Solid-state devices**
  - CCDs (charge-coupled devices) – 1970
    - MOS (metal-oxide-semiconductor) technology
    - Measures voltage
  - CIDs (charge injection devices) – 1971
    - MOS (metal-oxide-semiconductor) technology
    - Measures current flow
  - CMOS
    - Complementary metal-oxide-semiconductor
  - Active Pixel Sensor (APS) CMOS

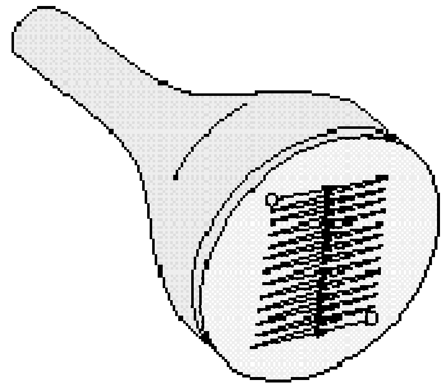






Nipkow disk





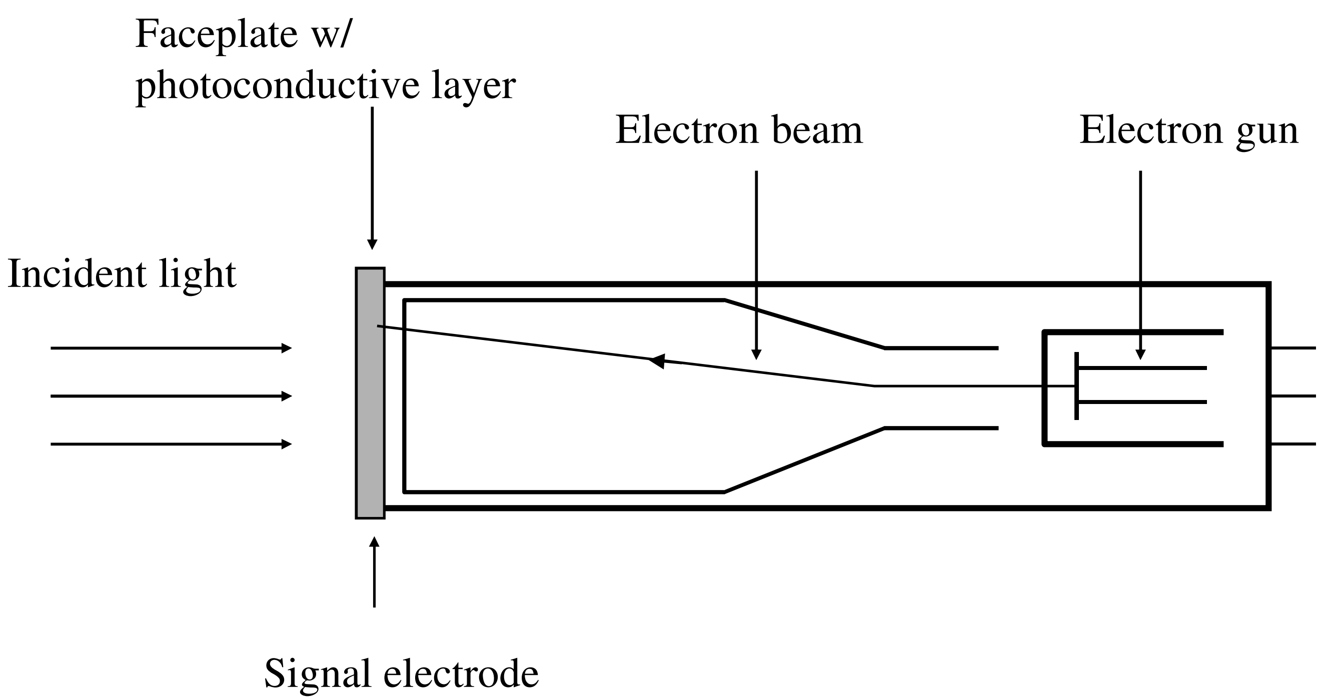
Flying Spot Scanner

Image orthicon

Vidicon

Vidicon

Photoconductive Imaging Tube



Incident light increases conductivity of the circuit

Example: Sony CXC950

Scan Type	Interlaced area scan
Frame Rate	30 Hz ← Really 29.97 fps
Camera Resolution	640 X 480
Horizontal Frequency	15.734 kHz ← 525 lines * 29.97
Interface Type	Analog
Analog Interfaces	NTSC Composite; NTSC RGB; NTSC Y/C
Video Output Level	1 Vpp @ 75 Ohms
Binning?	No
Video Color	3-CCD Color
Sensor Type	CCD
CCD Sensor Size (in.)	1/2 in.
Maximum Effective Data Rate	27.6 Mbytes/sec = 640*480*3*29.97
White Balance	Yes
Signal-to-noise ratio	60 dB ← 9-10 bits/color
Gain (user selectable)	18 dB
Spectral Sensitivity	Visible

Integration	Yes
Integration (Max Rate)	256 Frames
Exposure Time (Shutter speed)	10 µs to 8.5 s
Antiblooming	No
Asynchronous Reset	No
Camera Control	Mechanical Switches; Serial Control
Dimensions	147 mm X 65 mm X 72 mm
Weight	670 g
Power Requirements	+12V DC
Operating Temperature	-5 C to 45 C
Storage Temperature	-20 C to 60 C
Length of Warranty	1 year(s)
Included Accessories	(1) Lens Mount Cap, (1) Operating Instructions

Casio EX-FH25

File Format
Still images: RAW(DNG),JPEG (Exif Ver. 2.2), DCF1.0, DPOF
Movies: AVI format, MotionJPEG, IMA-ADPCM (Monaural)

Recording Media
Approx. 85.9MB built-in flash memory, SD Memory Card, SDHC Memory Card compatible

Number of Recorded Pixels
Still images: RAW/10M(3648x2736)/3:2(3648x2432)/ 16:9(3648x2048)/9M(3456x2592)/ 7M(3072x2304)/4M(2304x1728) 2M(1600x1200)/VGA(640x480)
Movies: HD(1280x720 30fps), HS 1000(224x64 1000fps), HS 420(224x168 420fps), HS 240 (448x336 240fps), HS 120 (640x480 120fps), HS 30-240 (448x336 30fps 240fps), HS 30-120 (640x480 30fps 120fps), STD(640x480 30fps)

Number of Effective Pixels
Approx. 10.1megapixels (/million)

Image Sensor
1/2.3-inch high-speed CMOS
Total Pixels: 10.62 megapixels (/million)

Lens
Construction: 14 lenses in 11 groups, including aspherical lens.
F-number: F2.8(W) - F4.5(T)
Focal Length: f=4.6 - 92mm
35mm Film Equivalent: Approx. 26 - 520mm equivalent to 35mm film

Zoom
Optical Zoom: 20 x optical zoom
Digital Zoom: 4x digital zoom (80 times both with optical and digital zoom)
HD Zoom: HD Zoom Maximum 114x (@VGA)

Focus
Focus Type: Contrast Detection Auto Focus, with AF assist lamp.
Focus Mode: Auto Focus, Macro Mode, Super Macro Mode, Manual focus
AF Area: Spot, Free, Tracking

Focus Range From Lens Surface
Auto Focus: Approx. 4.7" - Infinity (W)
Macro: Approx. 4.7" - 1' 8"(W)
Super Macro: Approx. 0.4" - 4.7"
Manual Focus: Approx. 4.7" inch - Infinity (W)
(Using optical zoom causes the aperture to change.)

Exposure
Exposure Metering: Multi pattern, Center Weighted, Spot by imaging element
Exposure Control: Program AE, Aperture Priority AE, Shutter Speed Priority AE, Manual Exposure
Exposure Compensation: -2EV to +2EV (in 1/3EV steps)

Aperture
F2.8(W) - F7.9(W)
(Aperture subject to change, depending on setting of optical zoom and shooting mode)

White Balance
Auto WB, Daylight, Overcast, Shade, Day white Fluorescent, Daylight Fluorescent, Tungsten, manual WB

Sensitivity (SOS/REI)
Still images: Auto/ ISO100/ ISO200/ ISO400/ ISO800/ ISO1600/ ISO3200
Movies: Auto (Hi-Speed Movie when Manual Exposure mode: ISO100, ISO200, ISO400, ISO800, ISO1600, ISO3200)
(SOS: Standard Output Sensitivity.)

Self-Timer
10 seconds, 2 seconds, Triple Self-timer

Flash Mode
Auto, Flash off, Flash on, Red eye reduction

Built-In Flash
Flash Modes: Auto, Flash off, Flash on, Red eye reduction
Wide Range: Approx. 1.3' - 23.'(W)
Tele Range: Approx. 4.3' - 14.4'(T)
Flash Continuous Shooting (when 5 shots taken): Approx. 2.0' - 7.5'(W)
Approx. 4.3' - 4.6'(T)
(Range is affected by optical zoom.)
Flash Charge Time: Approximately 5 seconds
Flash Lighting Adjustments: -2EV to +2EV (in 1/3EV steps)
Minimum Lx required when movie shooting: 18 L(STD/HDMovie Recording)

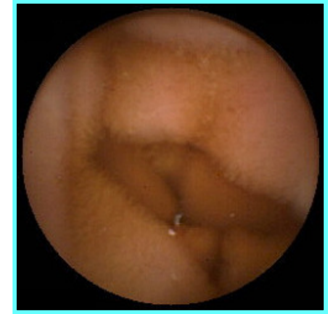
Other Recording Functions
Snapshot, High Speed Continuous shooting, Prerecord (still image), Flash Continuous shooting, Normal Speed Continuous Shooting, BEST SHOT, Face Recognition, High Speed Movie (with sound only when 30fps of HS30-120 or HS30-240), HD Movie, STD Movie, Prerecord (movie), YouTube™ Capture Mode, CMOS shift stabilization

Playback Functions
Playback Zoom, Multi-image Screen, Start-up Images, Rotate, Auto Rotate, Re-size, Trimming, Copy, BGM Slideshow, Brightness, White Balance, MOTION PRINT, Continuous Shooting Multi Print, Movie Editing, Continuous Shooting Frame Edit(DPOF Printing, Protect, Copy, Delete)

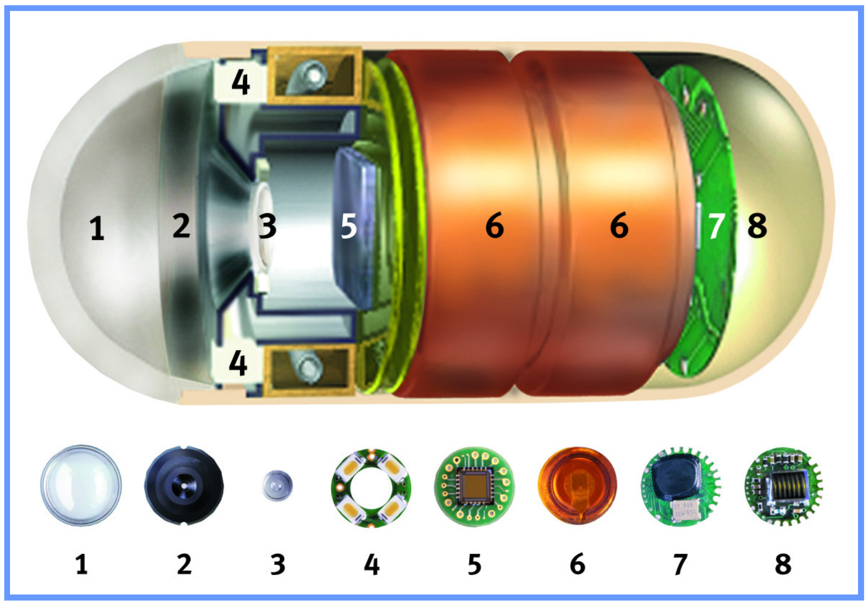
Other Functions
Monitor Screen Brightness Adjustment, EVF Brightness Adjustment, PictBridge, Video Output(NTSC/PAL), Divide Group(Dividing Up a Continuous Shutter Group), Eye-Fi Wireless Card compatible
Image Deletion: One image / All images / Deleting a Specific CS Group File / Deleting All Files in a CS Group
With memory protect function

Monitor
3.0-inch TFT color LCD (Super Clear LCD)

Examples of cameras (cont.)



- State-of-the-art example: the PillCam
  - Given Imaging (www.givenimaging.com)
    - M2A wireless video capsule (camera)
    - Small enough to swallow

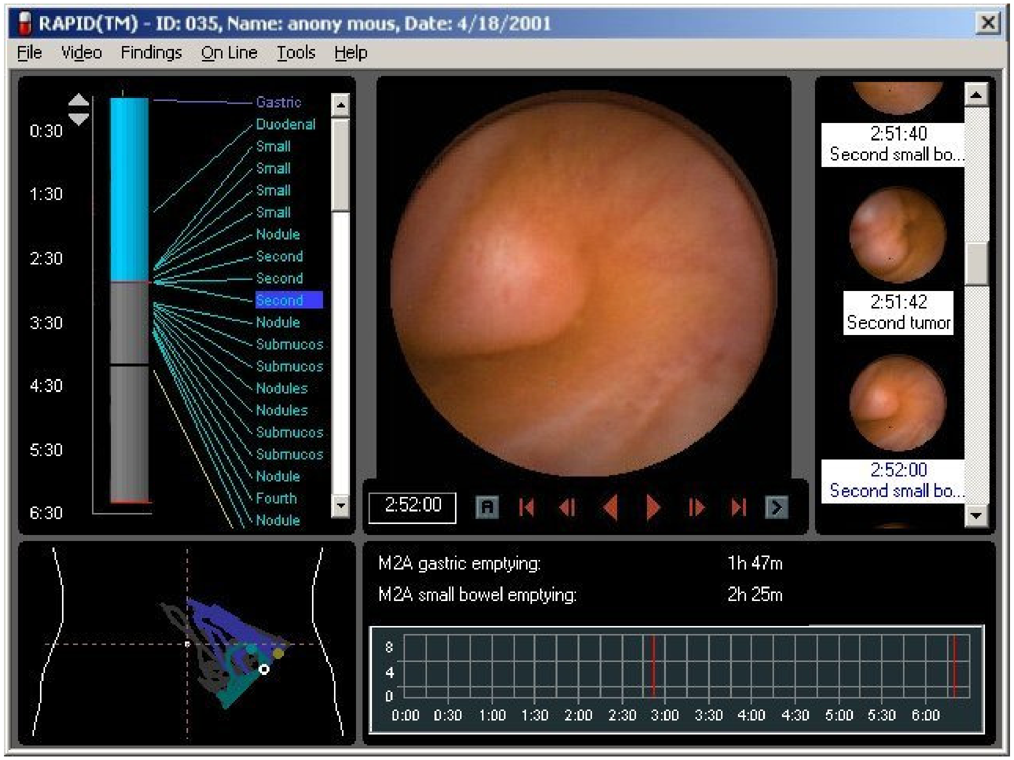


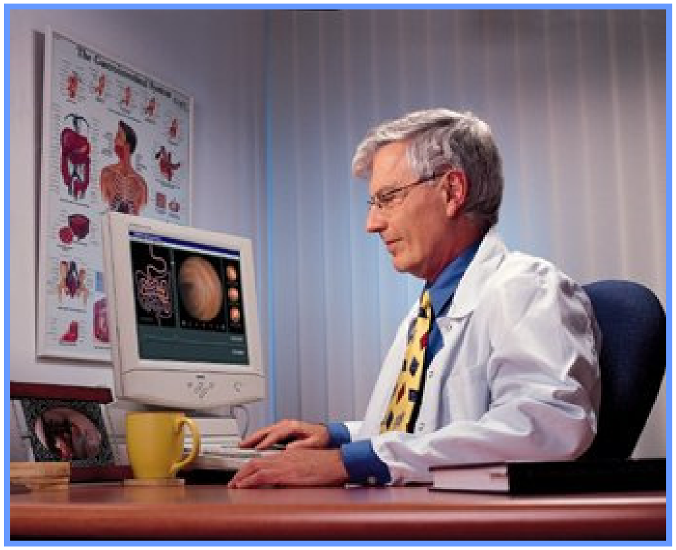
1. Optical dome
2. Lens holder
3. Lens
4. Illuminating LEDs (light emitting diodes)
5. CMOS (Complementary Metal Oxide Semiconductor) imager
6. Battery
7. ASIC (Application Specific Integrated Circuit) transmitter
8. Antenna

1. The M2A Capsule
2. SensorArray™
3. Given DataRecorder
4. RecorderBelt

RAPID application

- Visualization and control of high quality video images

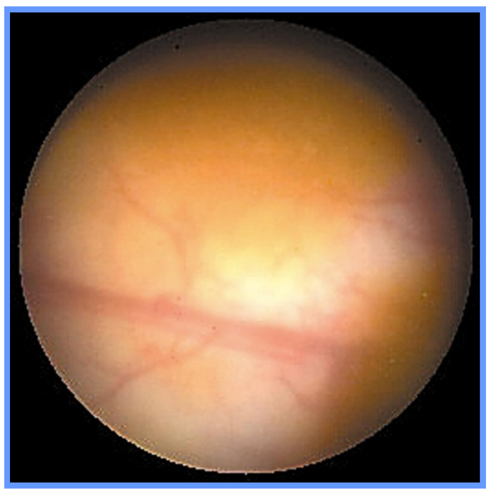




Teeth

Epiglottis

Multiple telangiectasia on a gastric fold



Wall of right colon

Ileocecal valve

Small Intestine

University of California Santa Barbara

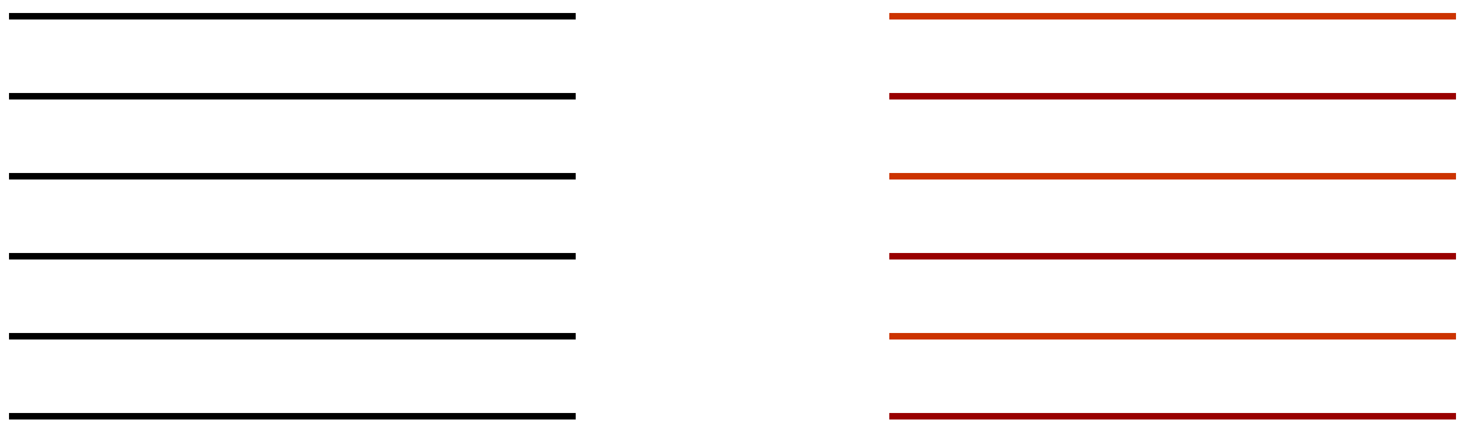
Digital images

- We're interested in digital images, which may come from
  - An image originally recorded on film
    - Digitized from negative or from print
  - Analog video camera
    - Digitized by frame grabber
  - Digital still camera or video camera
  - Sonar, radar, ladar (laser radar)
  - Various kinds of spectral or multispectral sensors
    - Infrared, X-ray, Landsat…

- Normally, we'll assume a digital camera (or digitized analog camera) to be our source, and most generally a video camera (spatial and temporal sampling)

Camera output: A raster image

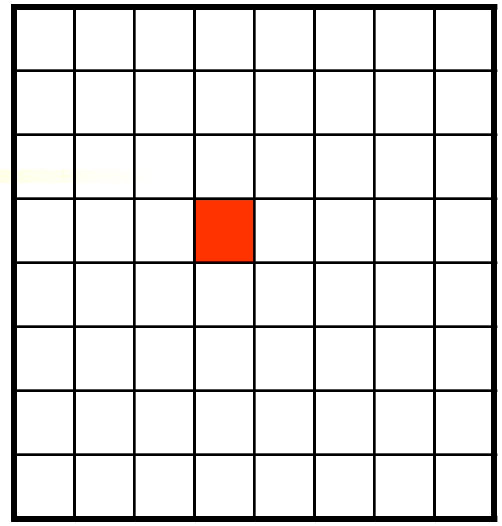
- Raster scan – A series of horizontal scan lines, top to bottom
  - Progressive scan – Line 1, then line 2, then line 3, …
  - Interlaced scan – Odd lines then even lines



Raster pattern
Progressive scan

Interlaced scan

Pixels



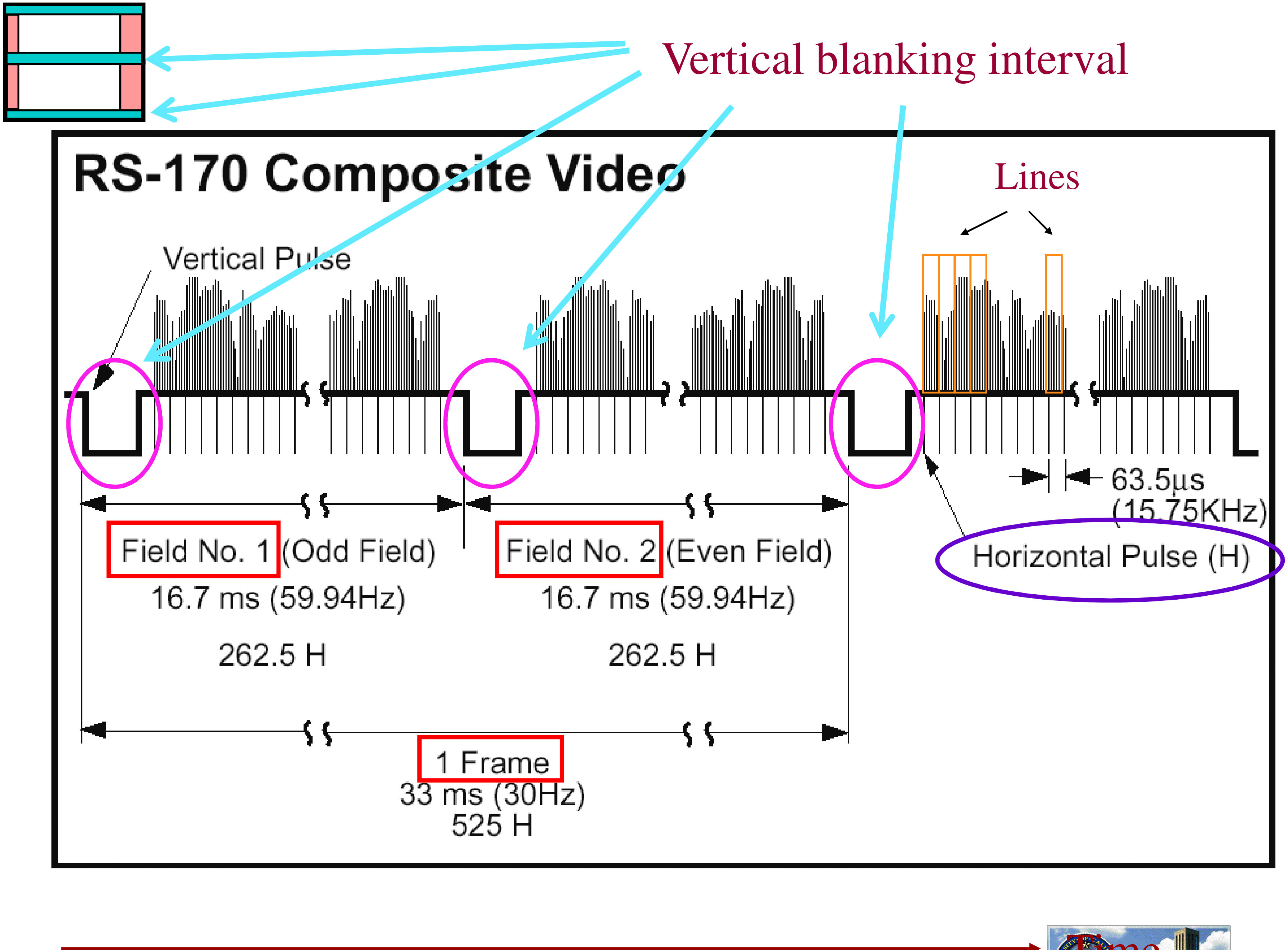
- Each line of the image comprises many picture elements, or *pixels*
  - Typically 8-12 bits (grayscale) or 24 bits (color)
- A 640x480 image:
  - 480 rows and 640 columns
  - 480 lines each with 640 pixels
  - 640x480 = 307,200 pixels
- At 8 bits per pixel, 30 images per second
  - 640x480x8x30 = 73.7 Mbps or 9.2 MBs
- At 24 bits per pixel (color)
  - 640x480x24x30 = 221 Mbps or 27.6 MBs

Aspect ratio

- Image aspect ratio – width to height ratio of the raster
  - 4:3 for TV, 16:9 for HDTV, 1.85:1 to 2.35:1 for movies
  - We also care about *pixel aspect ratio* (not the same thing)
    - Square or non-square pixels

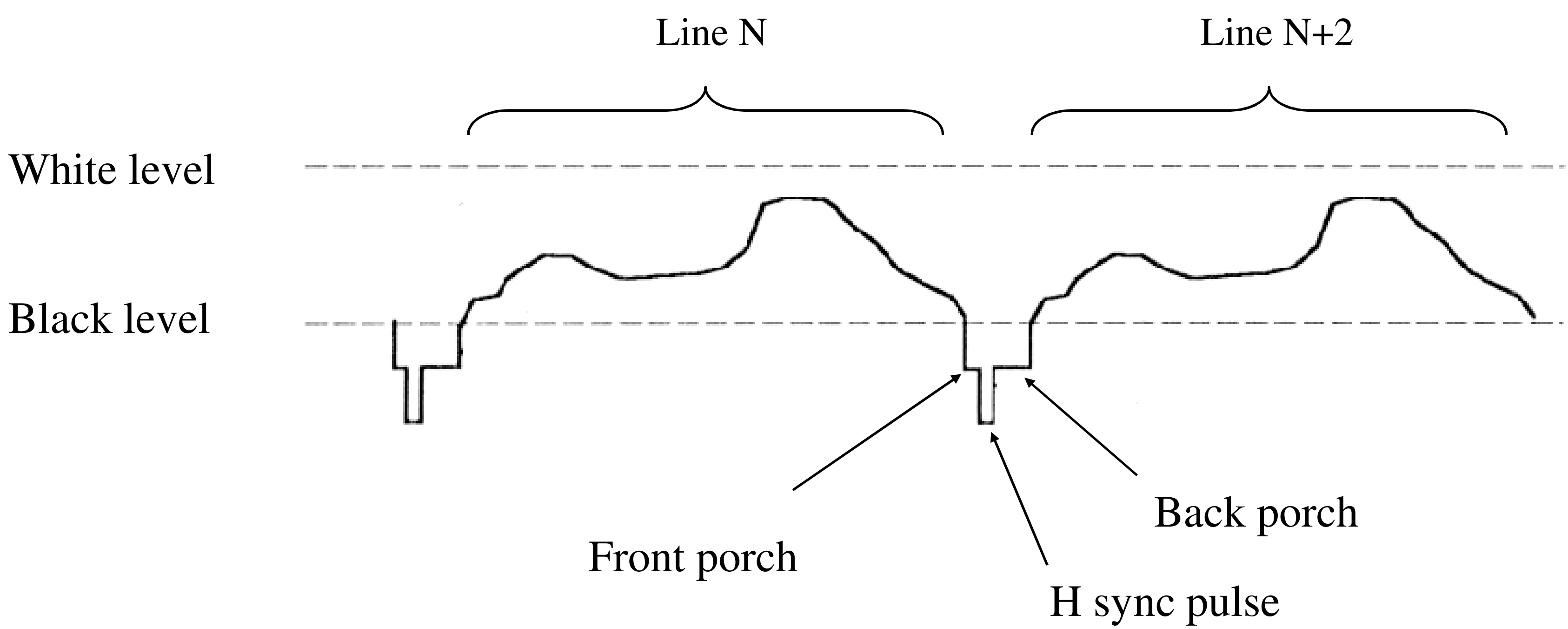
Sensor, Imager, Pixel

- An imager (sensor array) typically comprises *n* x *m* sensors
  - 320x240 to 7000x9000 or more (high end astronomy)
  - Sensor sizes range from 15x15µm down to 3x3 µm or smaller
- Each sensor contains a photodetector and devices for readout
- Technically:
  - **Imager** – a rectangular array of sensors upon which the scene is focused (photosensor array)
  - **Sensor** (photosensor) – a single photosensitive element that generates and stores an electric charge when illuminated. Usually includes the circuitry that stores and transfers it charge to a shift register
  - **Pixel** (picture element) – atomic component of the image (technically not the sensor, but…)
- However, these are often intermingled



Vertical blanking interval
RS-170 Composite Video
Lines
Vertical Pulse
63.5µs
(15.75KHz)
Horizontal Pulse (H)
Field No. 1 (Odd Field)
16.7 ms (59.94Hz)
262.5 H
Field No. 2 (Even Field)
16.7 ms (59.94Hz)
262.5 H
1 Frame
33 ms (30Hz)
525 H
Time
University of California
Santa Barbara

Horizontal Blanking



H blanking signal
(blanking pulse)

Imagers

- Some imager characteristics:
  - Scanning: Progressive or interlaced
  - Aspect ratio: Width to height ratio
  - Resolution: Spatial, color, depth
  - Signal-to-noise ratio (SNR) in dB
    - SNR = 20 log (S/N)
  - Sensitivity
  - Dynamic range
  - Spectral response
  - Aliasing
  - Smear and other defects
  - Highlight control

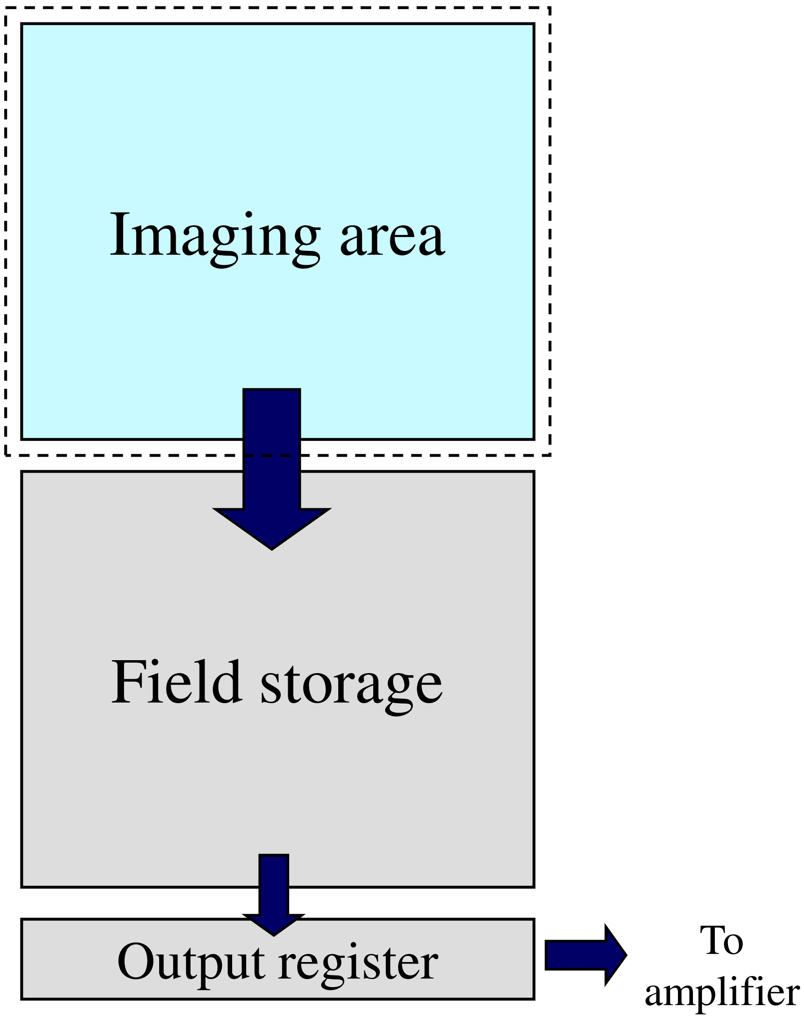
CCD and CMOS

- The market today for image acquisition devices is dominated by CCD (charge-coupled device) chips
- We will focus on CCD and CMOS imagers
  - Not tubes, film, etc.
- These solid-state sensors convert incident radiant power into *photocurrent* that is proportional to the radiant power
  - Incident photons generate electron-hole pairs in the silicon
  - Some of these are converted into photocurrent
  - These are collected in a *potential well* and converted to voltage when read out

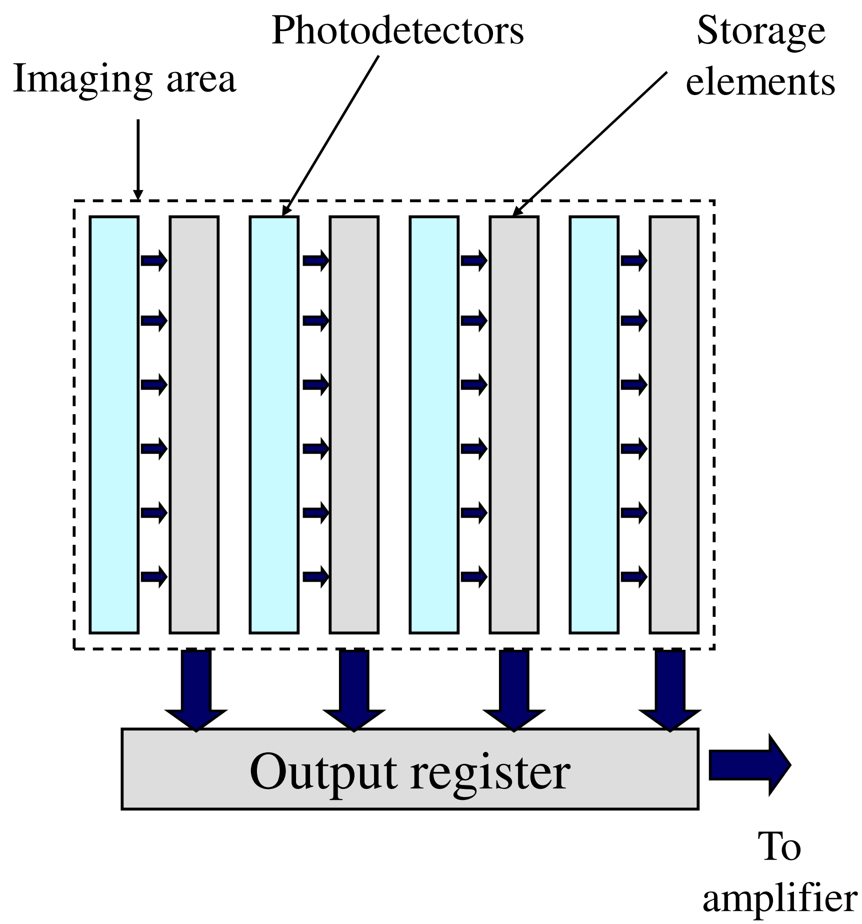
Charge-Coupled Devices (CCDs)

- Invented in the 1970s, initially used as memory devices
  - Then their light sensitive properties became important
  - CCDs convert light energy into electrical charge on a silicon chip
- CCDs perform four main functions:
  - spatial sampling
  - photosensing
  - charge storage
  - charge transfer
- Photons release electrons – CCDs measure electrons
  - Photoelectric effect!
- Semiconductor circuit elements control the storage and read-out of the electric charges generated by the photosensor

Frame transfer

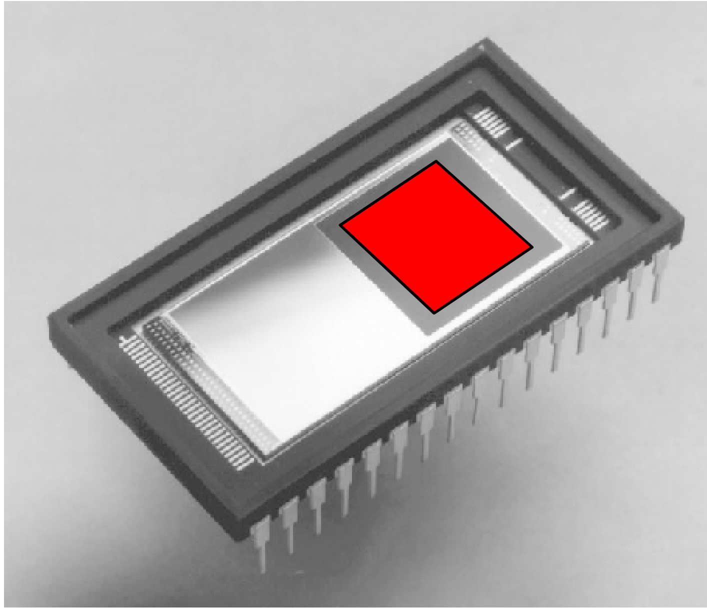


Interline transfer

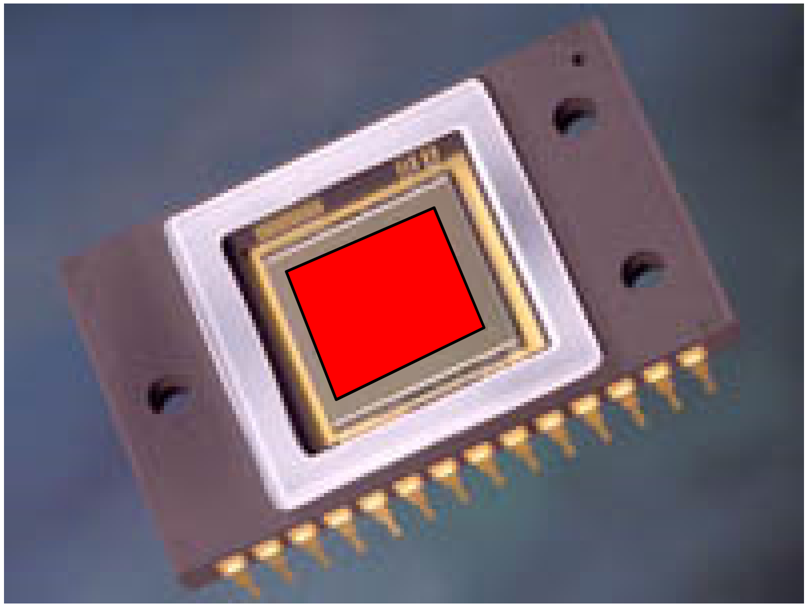


CCD chips

Frame Transfer Chip



Interline Transfer Chip



Noise

- In addition to “good” electrons, additional “bad” electrons are generated
- Noise reduces the SNR
- With photoconductive storage tubes, most of the noise is from the preamplifier (in the external circuitry)
- With CCDs, most of the noise is generated within the device
  - Coherent, fixed-pattern noise caused by imperfections in design or manufacture (can be greatly reduced)
  - Thermally-generated random noise (this predominates especially in the darkest areas)
- The SNR of CCD imagers has steadily improved in recent years, and typically exceeds that of storage tube imagers

Noise types

- **Photon noise**
  - Random variations in number of photons that reach the sensor during exposure (longer integration time reduces this)
- **Fixed pattern noise**
  - Spatial variation under uniform illumination
  - More visible at low illumination
  - Worse for CMOS than CCD
- **Dark current (thermal noise)**
  - Photodetector leakage current (caused by electrons, not photons)
  - “Dark” image still produces electrons
    - One minute at room temperature complete fills the potential well
  - Increases exponentially with temperature (doubles every ~7 deg K)
  - Limits dynamic range
- **Readout noise**
  - Amplifier voltage as a function of electron charge
- **Spatial sampling and low-pass filtering**
  - Spatial and temporal sampling introduces quantization noise, aliasing

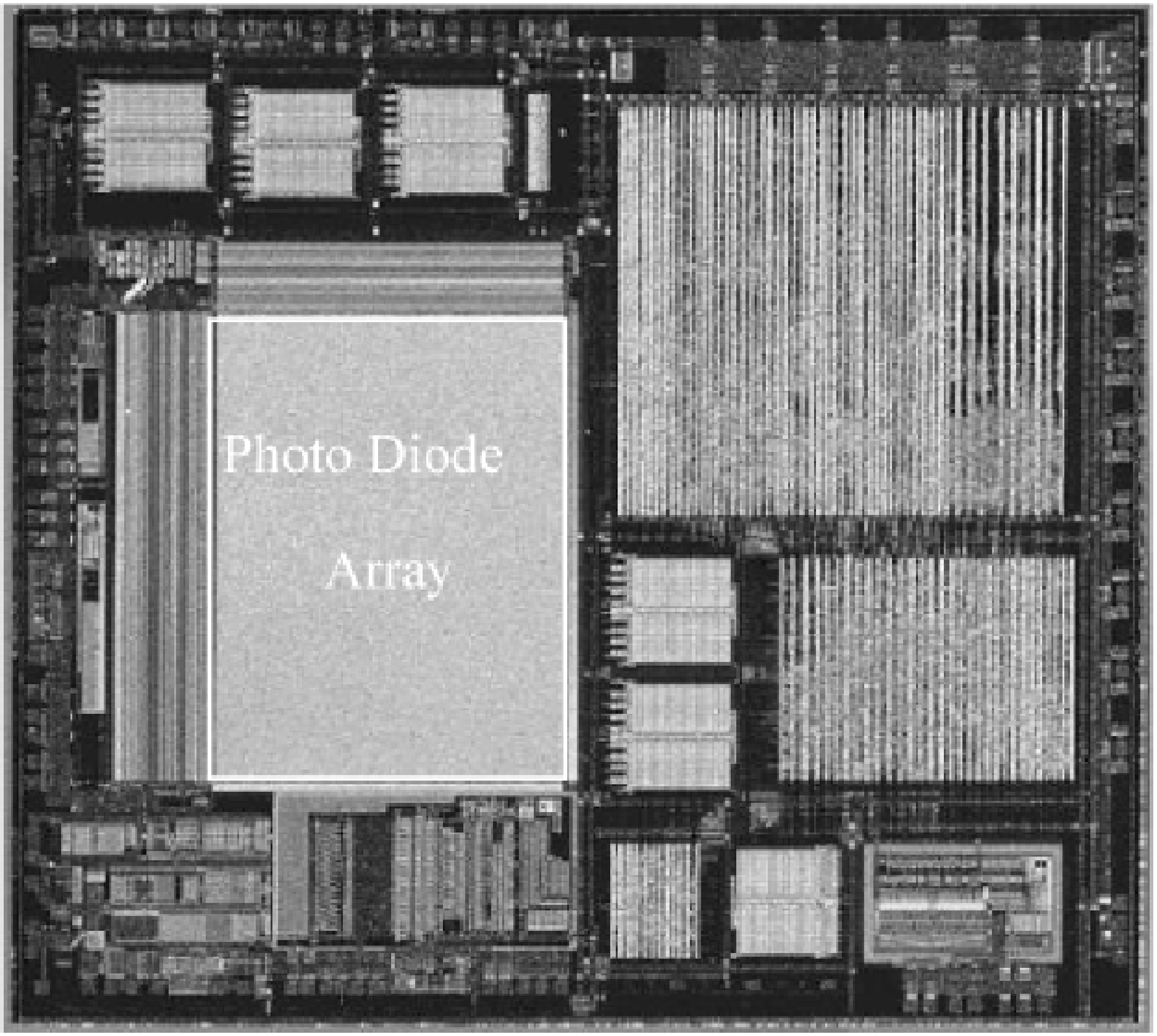
CMOS sensor technology

- CCDs are fabricated in foundries using specialized and expensive processes

- **CMOS** fabs, used for processor and memory chips, can also be used to make imagers, at lower cost than CCDs
  - Uses standard silicon processes in high-volume foundries

- **CMOS** imagers can incorporate other circuits on the same chip, eliminating the many separate chips required for a CCD (e.g., image stabilization, image compression)
  - Integration enables new functionality, smaller size, lower power…

CMOS chip



The bottom line

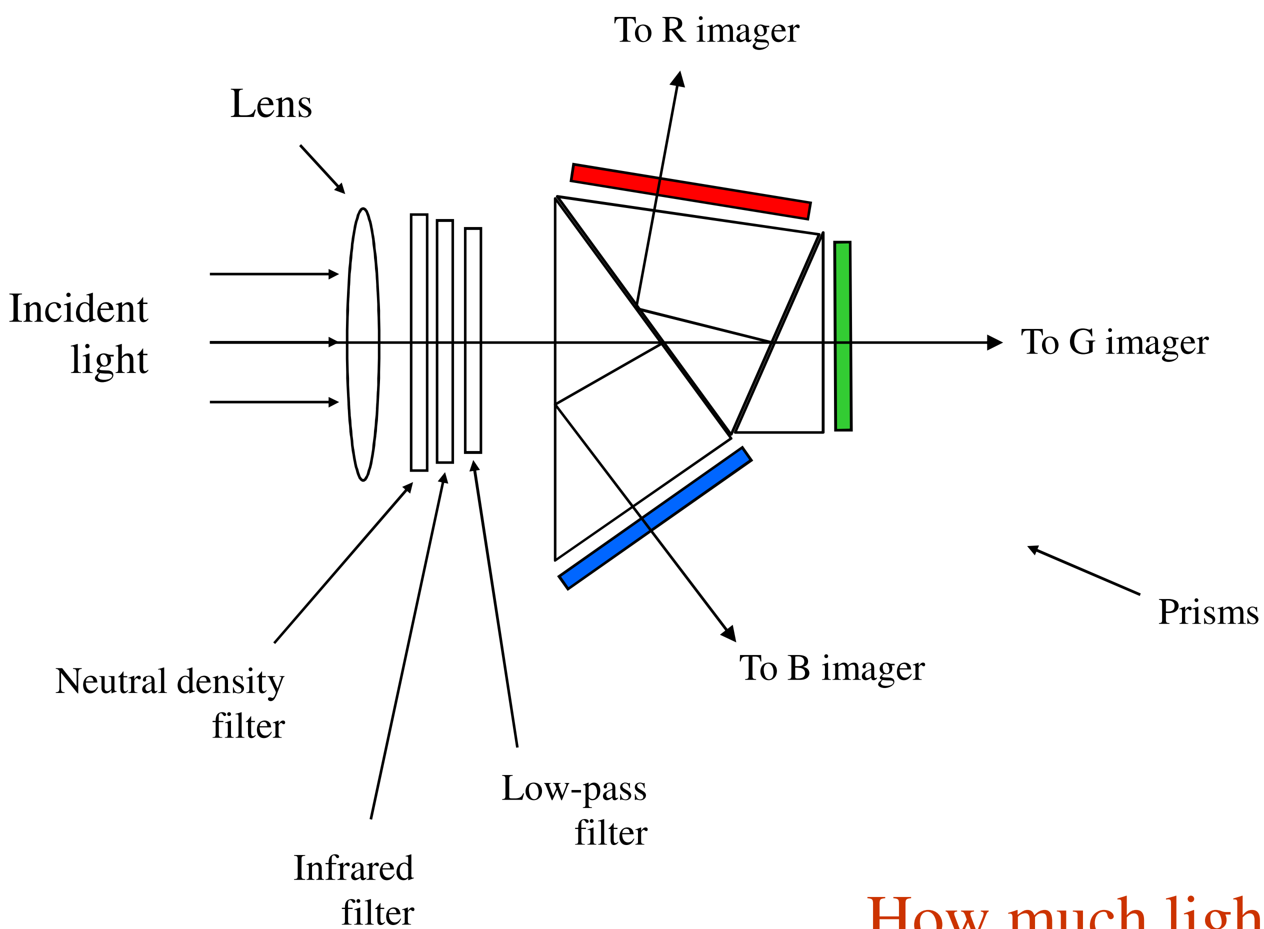
- CCD and CMOS imagers will both have a role in imaging systems in the foreseeable future
  - They are complementary technologies in many ways
  - Choice depends on the particular problem

- Current conventional wisdom:
  - CMOS – low-end
    - Consumer imaging
  - CCD – high-end
    - Scientific imaging (e.g., astronomy)
  - Both good enough for electronic display applications, but still fall short of print capability (where film rules)
    - Esp. dynamic range and sensitivity

Color sensors

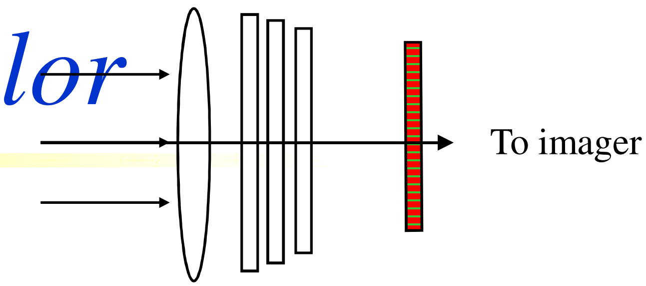
- CCD and CMOS chips do not have any inherent ability to discriminate color (i.e., photon wavelength/energy)
  - They sense "number of photons", not wavelengths
  - Essentially grayscale sensors – need filters to discriminate colors!
- Approaches to sensing color
  - 3-chip color: Split the incident light into its primary colors (usually red, green and blue) by filters and prisms
    - Three separate imagers
  - Single-chip color: Use filters on the imager, then reconstruct color in the camera electronics
    - Filters absorb light (2/3 or more), so sensitivity is low

3-chip color

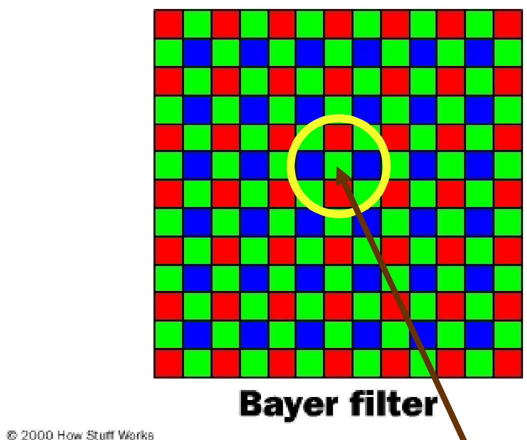


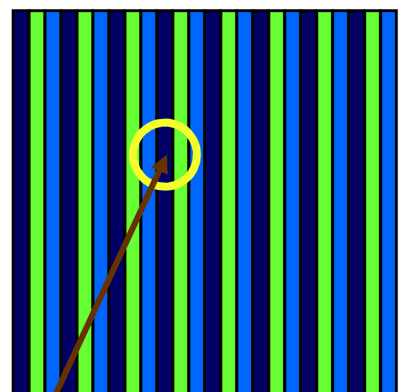
How much light energy
reaches each sensor?

Single-chip color



- Uses a mosaic color filter
  - Each photosensor is covered by a single filter
  - Must reconstruct (R, G, B) values via interpolation

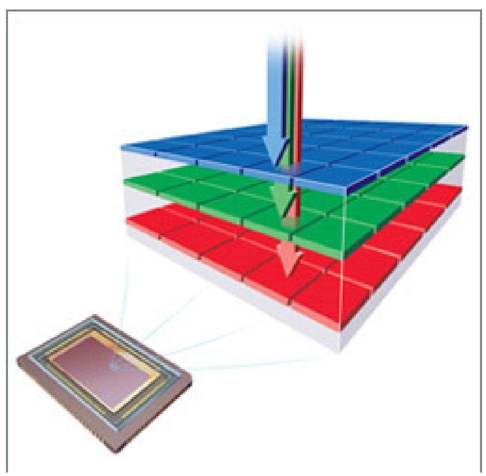




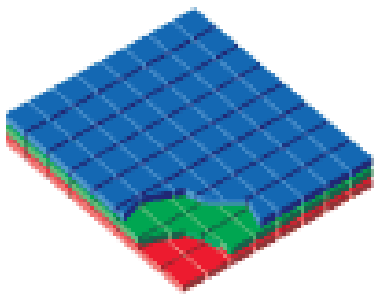
$$R(x, y) = f_R(I(x \pm dx, y \pm dy))$$
$$G(x, y) = f_G(I(x \pm dx, y \pm dy))$$
$$B(x, y) = f_B(I(x \pm dx, y \pm dy))$$

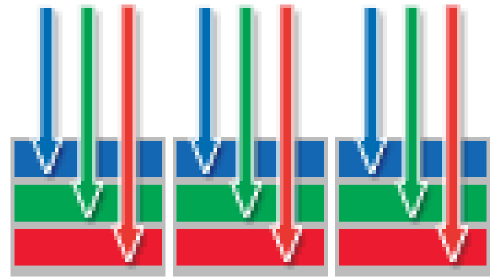
Newer X3 technology

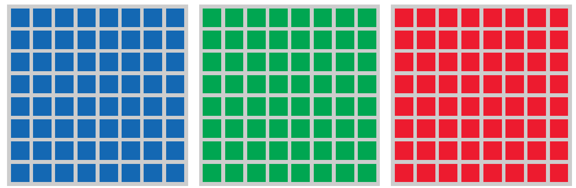
- Single chip, R, G, and B at every pixel (www.foveon.com)
  - Uses three layers of photodetectors embedded in the silicon
    - First layer absorbs “blue” (and passes remaining light)
    - Second layer absorbs “green” (and passes remaining light)
    - Third layer absorbs “red”
  - No color mosaic filter and interpolation required



Foveon X3 Capture





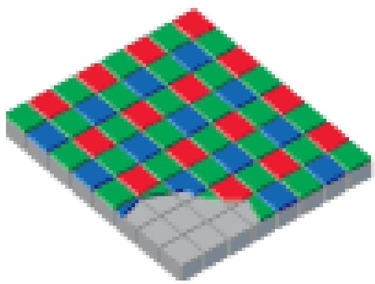


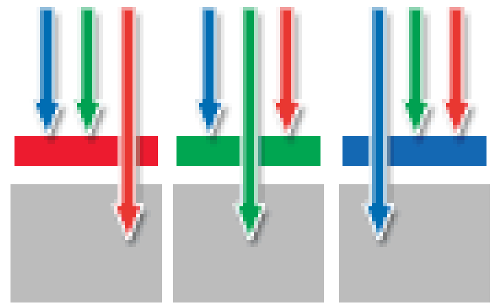
A Foveon X3 image sensor features three separate layers of photo-detectors embedded in silicon

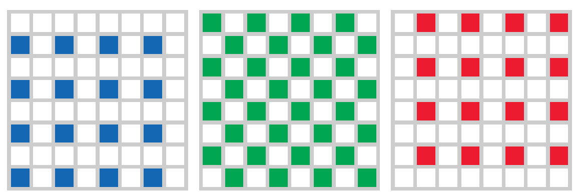
Since silicon absorbs different wave-lengths of light at different depths, each layer captures a different color.

As a result, only Foveon X3 image sensors capture red, green and blue light at every pixel location.

Mosaic Capture







In conventional systems, color filters are applied to a single layer of photo-detectors in a titled mosaic pattern.

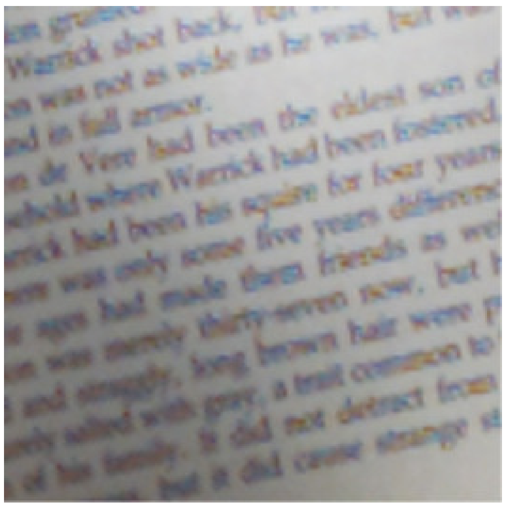
The filters let only one wavelength of light—red, green or blue—pass through to any given pixel, allowing it to record only one color.

As a result, typical mosaic sensors capture 50% of the green and only 25% of the red and blue light.

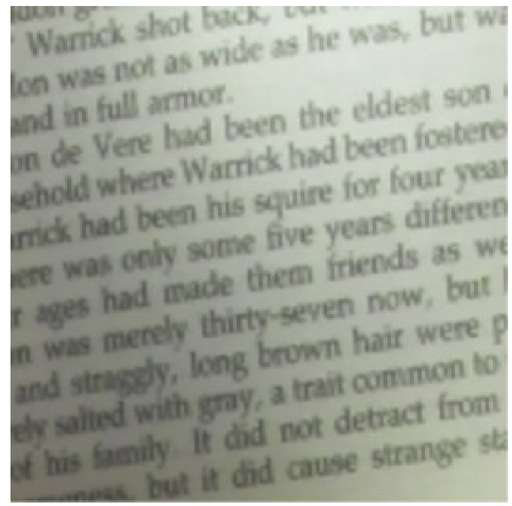
X3 vs. mosaic

Sharpness

Mosaic



Foveon X3

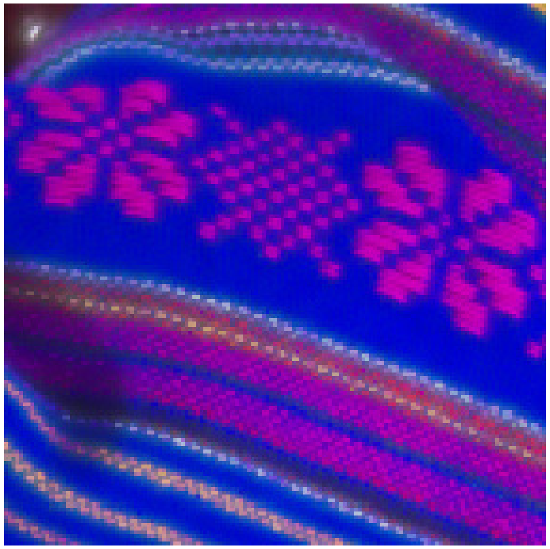


X3 vs. mosaic

Color Detail

Mosaic

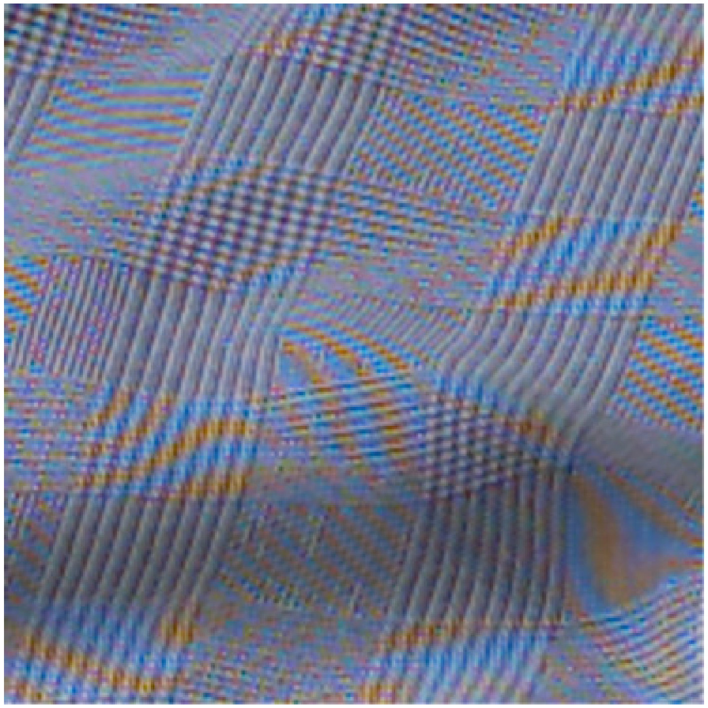
Foveon X3



X3 vs. mosaic

Artifacts

Mosaic



Foveon X3