Lecture 4
Image Sensors

ECE 325
OPTOELECTRONICS

Menoufia University

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CCD Image Sensor

The inventors of the CCD (charge coupled device) image sensor at AT&T Bell Labs: Willard Boyle (left) and George Smith (right). The CCD was invented in **1969**, the first CCD solid state camera was demonstrated in **1970**, and a broadcast quality TV camera by **1975**. (W. S. Boyle and G. E. Smith, "Charge Coupled Semiconductor Devices", *Bell Systems Technical Journal*, *49*, 587, 1970. (Courtesy of Alcatel-Lucent Bell Labs.)

INTRODUCTION

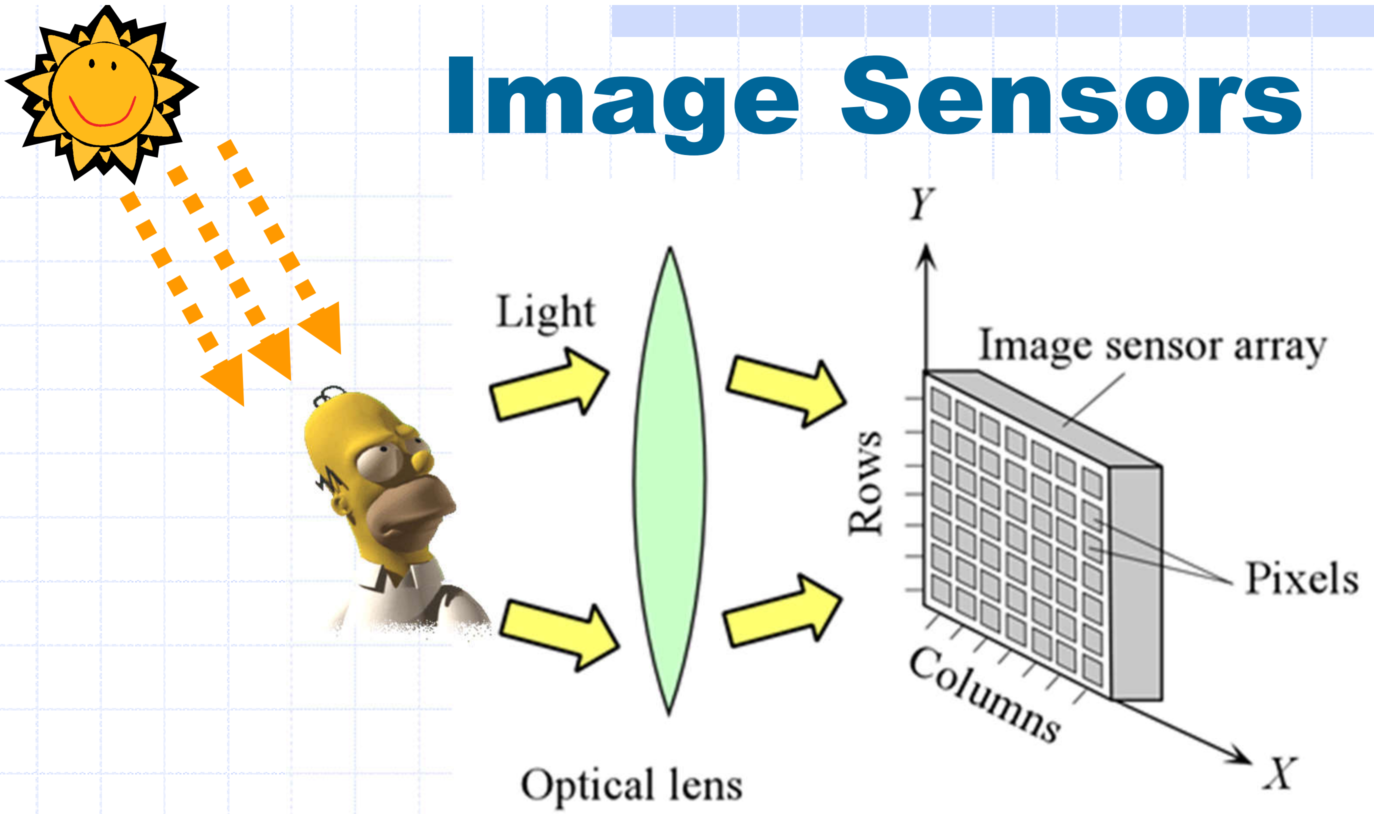
- **An image sensor:** is an integrated circuit chip made up of an array of photosensitive elements, that is able to capture an image and provide an output in the form of an electrical signal, e.g., current, charge, or voltage, that is proportional to the light intensity received at this element.
- An image sensor consists of ***N* × *M* pixels**, ranging from 320 × 240 for end PC digital camera to 7000 × 9000 for scientific/astronomy applications.
  - Pixel from "**picture element**"
  - The pixel size ranges from 3 × 3 to 15 × 15 μm^2.
  - **Fill factor (FF):** is the fraction of pixel area occupied by the photodetector. The FF ranges from 0.2 to 0.9; a high FF is desirable.
- Each pixel contains a photodetector and devices for **readout circuits**.
  - The readout circuits determine the sensor **conversion gain**, which is the output voltage per photon collected by the PD.
  - The **readout speed** determines the frame rate, which is typically 30 frames per second (fps). High frame rates are required for many industrial and measurement applications.

INTRODUCTION

- There are two major solid state image sensors technologies:
  - Charge-coupled device (CCD) and
  - Complementary metal oxide semiconductor (CMOS) sensors.
- Each has its own strengths and weaknesses.

Examples of Image Sensor Applications

Image Sensors



- A lens forms an image of the object on the image sensor, and the light intensity $I(X,Y)$ at each point of this image (on the sensor) excites the corresponding pixel at the X,Y location.
- The image point X,Y excites the pixel at that location, that is, the pixel in row x and column y, and the pixel (x,y) has an electrical signal (e.g., charge, current, or voltage) proportional to $I(X,Y)$.
  - Thus, each pixel (x,y) carries a piece of the image information, a pixel of it.

Image Sensors

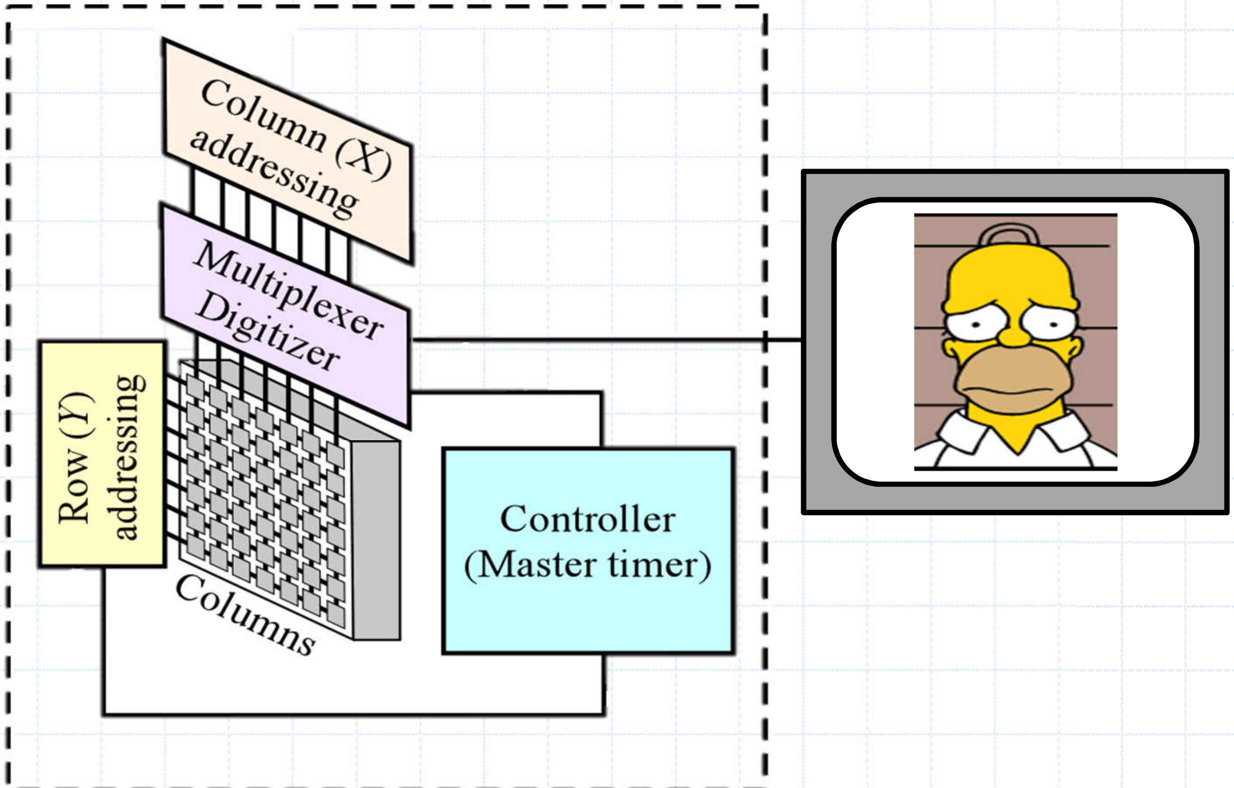
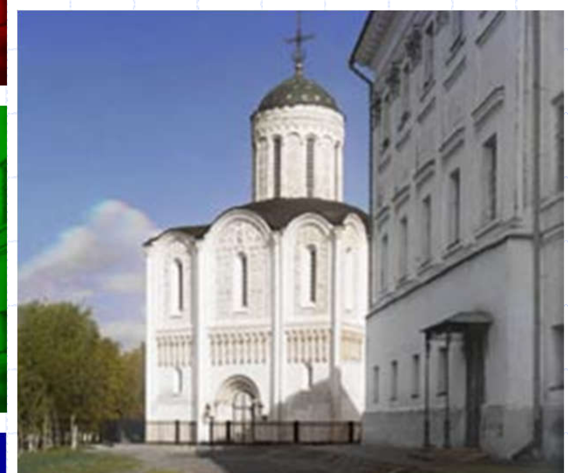


Image sensor chip

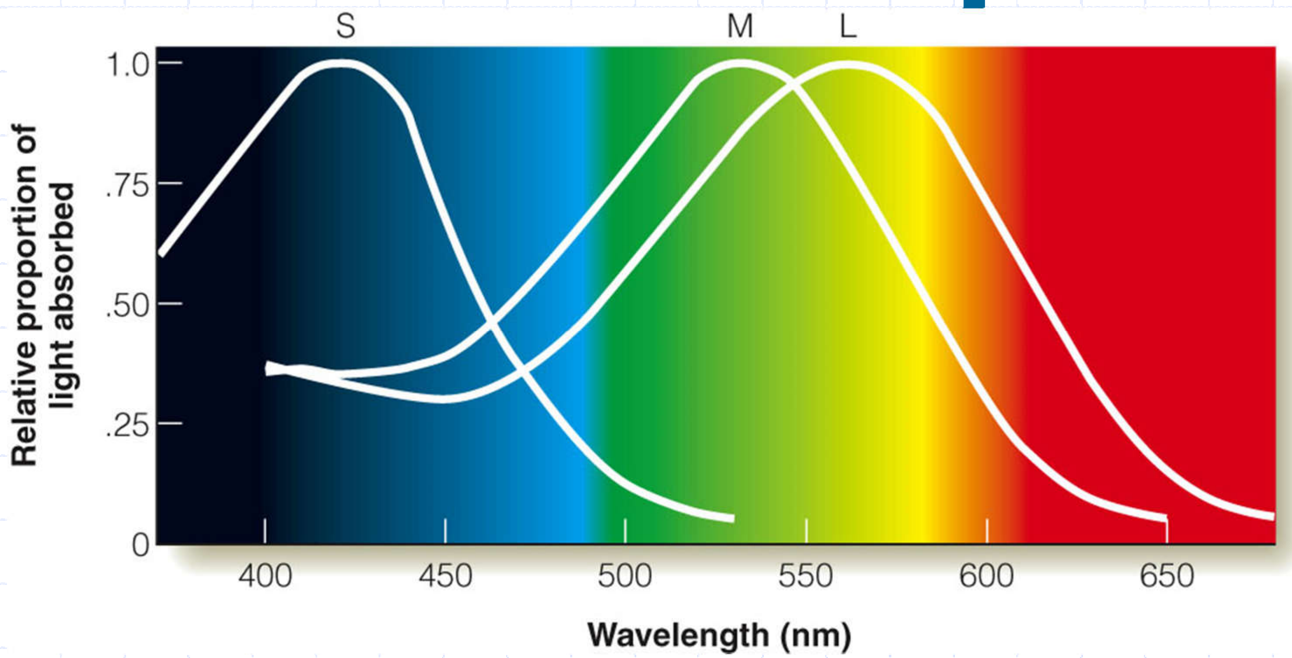
- The imaging array is addressed from a master timer (controller) to read out the signals (charges) at the pixels and hence provide an electronically recorded image.
- The output is usually put through a multiplexer and an analog-to-digital converter to obtain a digital form of the image.

Color Rendering

Most digital images are comprised of three color channels – red, green, and, blue – which combine to create most of the colors we can see



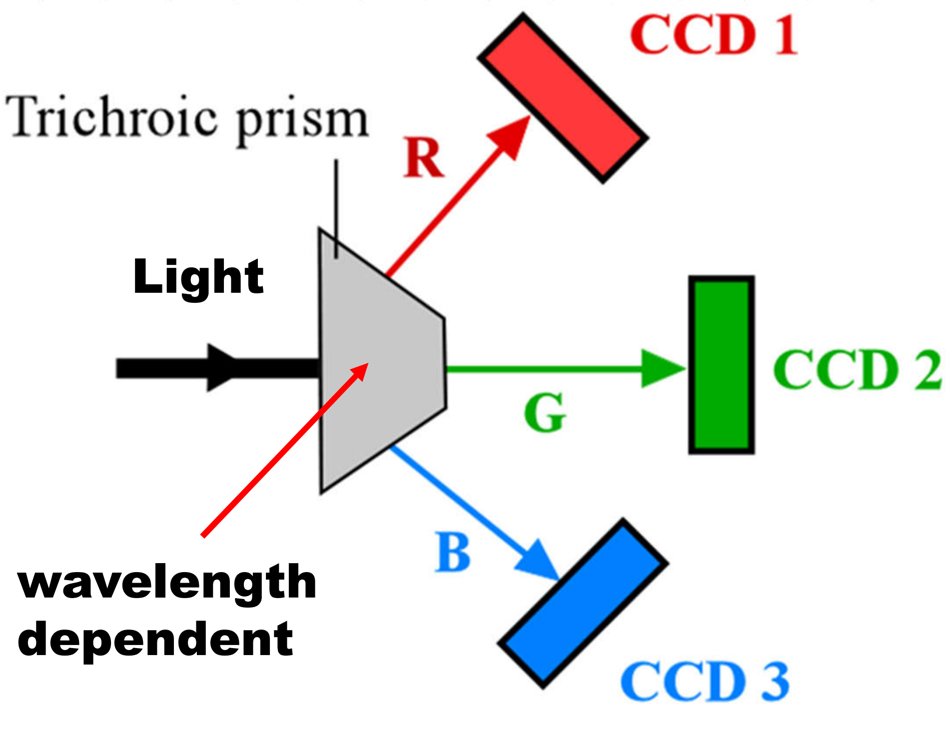
Color Perception

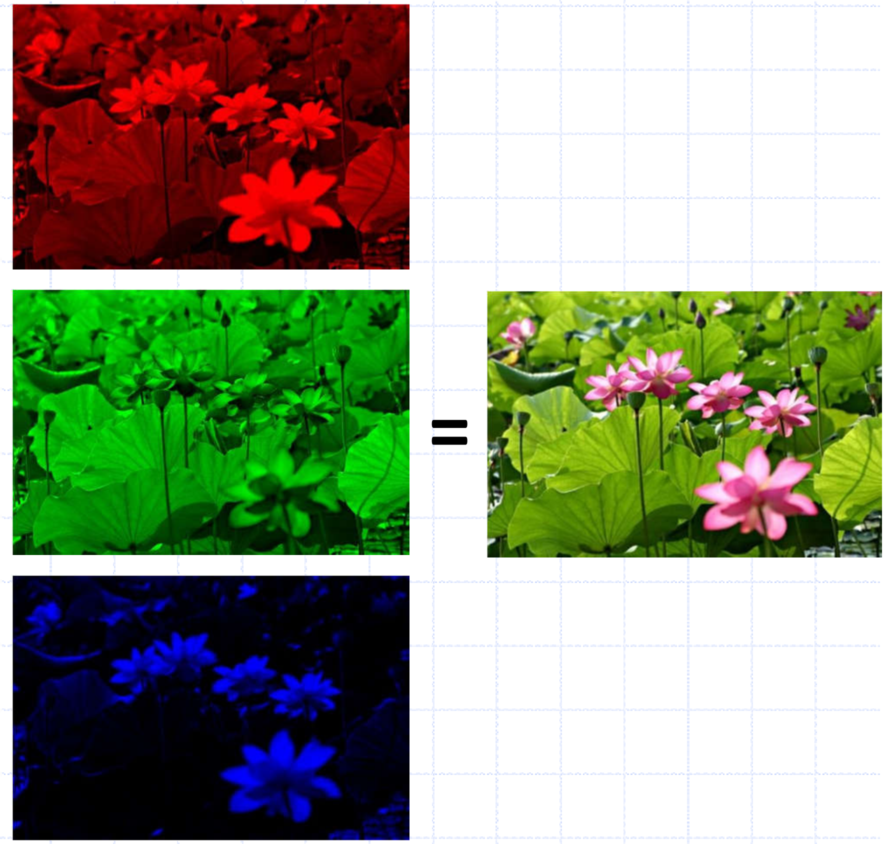


Absorption spectra of the three cone pigments

- Three types of cones
  - Each is sensitive in a different region of the spectrum
    - but regions overlap
    - Short (S) corresponds to blue
    - Medium (M) corresponds to green
    - Long (L) corresponds to red
  - Different sensitivities: we are more sensitive to green than red
    - varies from person to person (and with age)
  - Colorblindness—deficiency in at least one type of cone

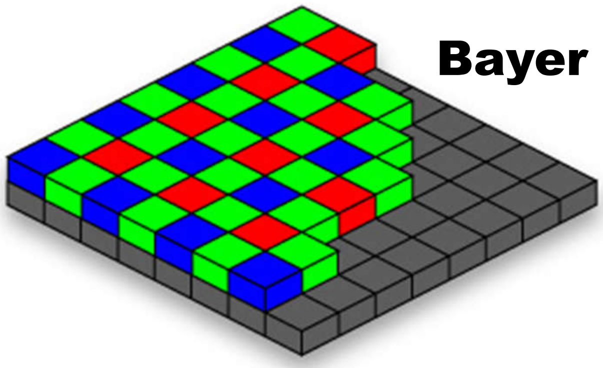
1- Multi-chip



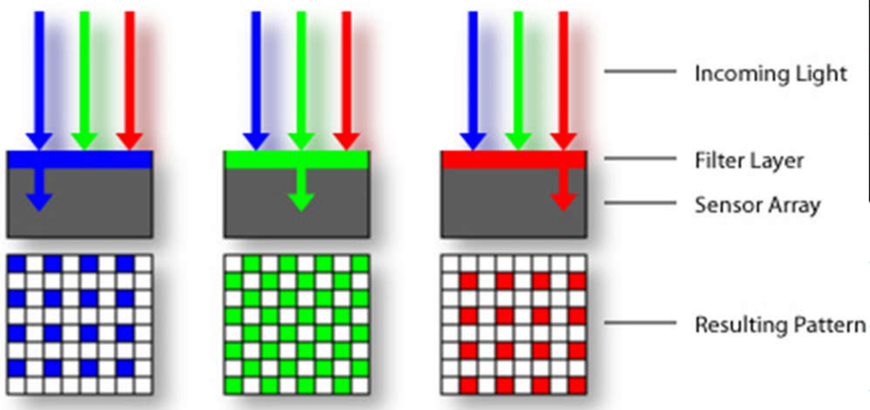


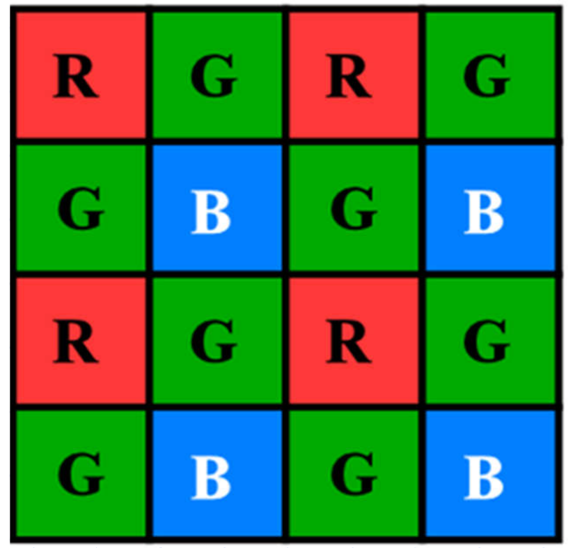
Three CCD imaging (Multi-chip): where a trichroic prism assembly is used to separate the light from the object into its red, green, and blue components, and three different CCDs are used to detect each component.

2- Color Filter Array



Bayer grid





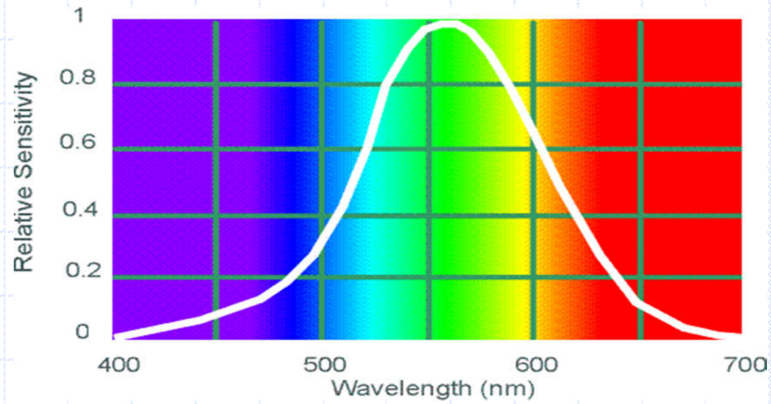
GRGB Bayer filter

Why more green?

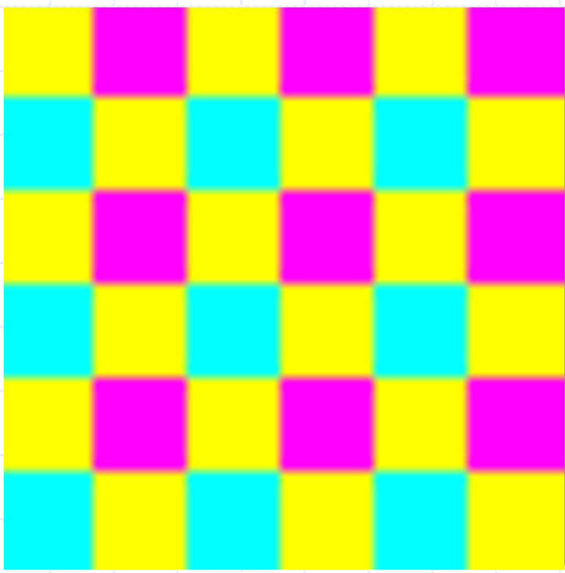
Estimate missing components from neighboring values (demosaicing)

Bayer filtering: the most common is to use **red (R)**, **green (G)**, and **blue (B)** filters to separate out the colors at a point onto three different adjacent pixels, such as in the Bayer color image sensor shown in the above figure.

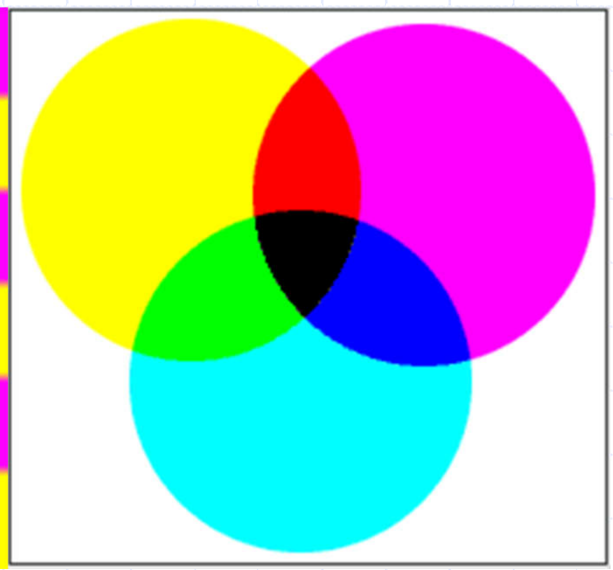
2- Color Filter Array



Human Luminance Sensitivity Function



CYYM filter



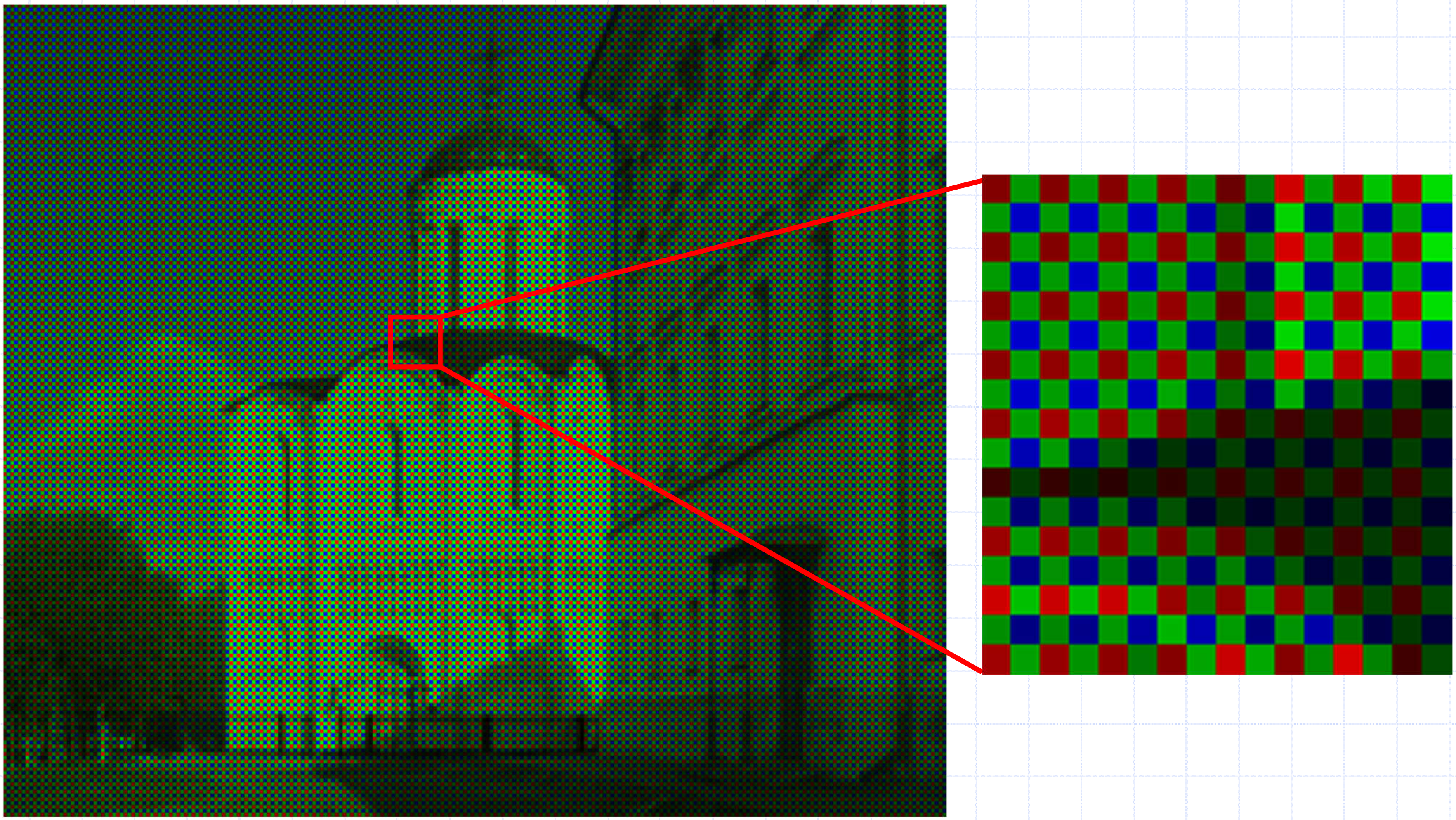
Kodak DCS620x

Red = Yellow + Magenta

Green = Yellow + Cyan

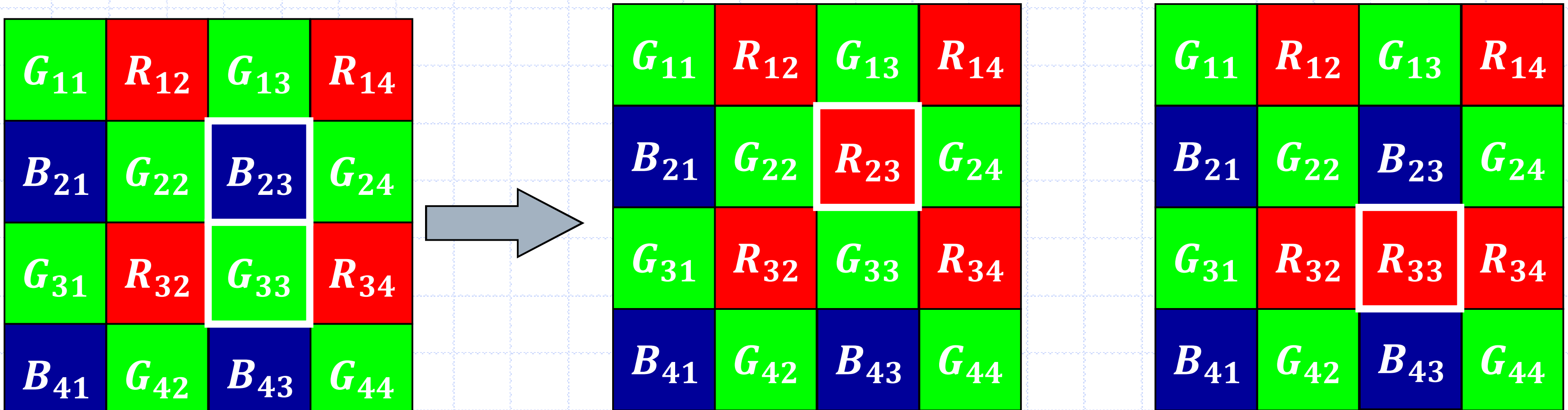
Blue = Magenta + Cyan

Bayer's Pattern



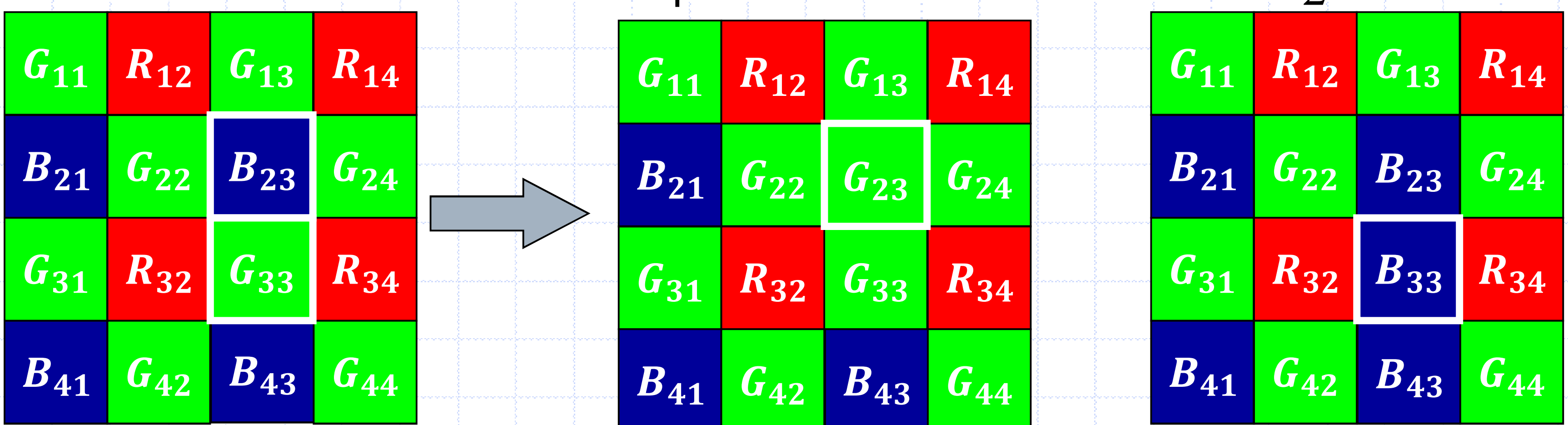
Demosaicing CFA's

bilinear interpolation



$$\hat{R}_{23} = \frac{1}{4}(R_{12} + R_{14} + R_{34} + R_{32})$$

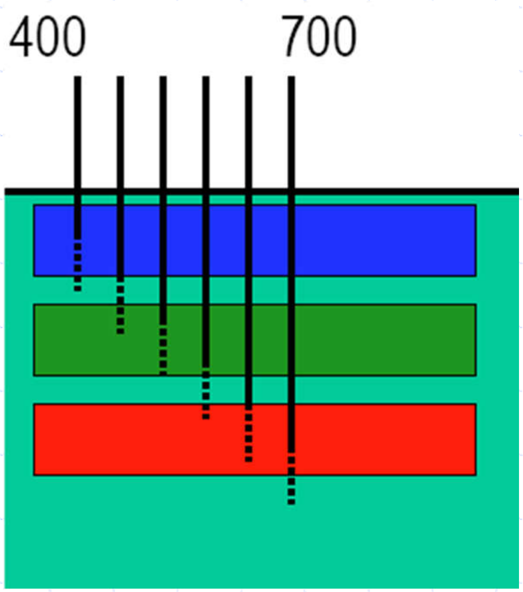
$$\hat{R}_{33} = \frac{1}{2}(R_{32} + R_{34})$$

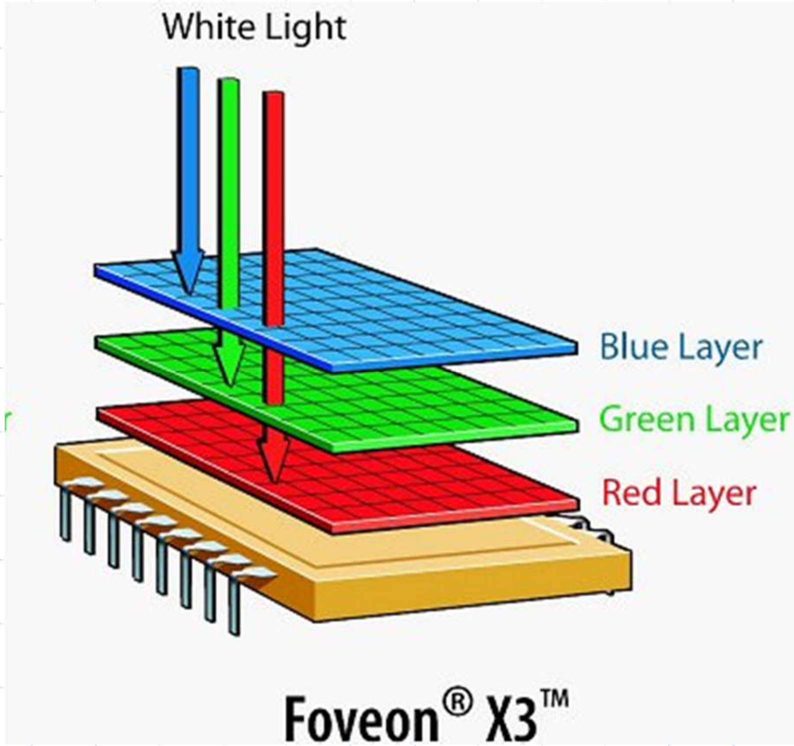


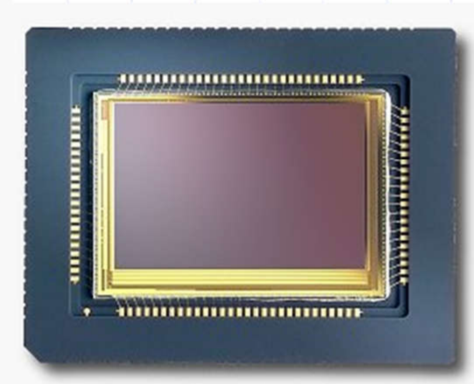
$$\hat{G}_{23} = \frac{1}{4}(G_{22} + G_{13} + G_{24} + G_{33})$$

$$\hat{B}_{33} = \frac{1}{2}(B_{23} + B_{43})$$

3- X3 Sensor

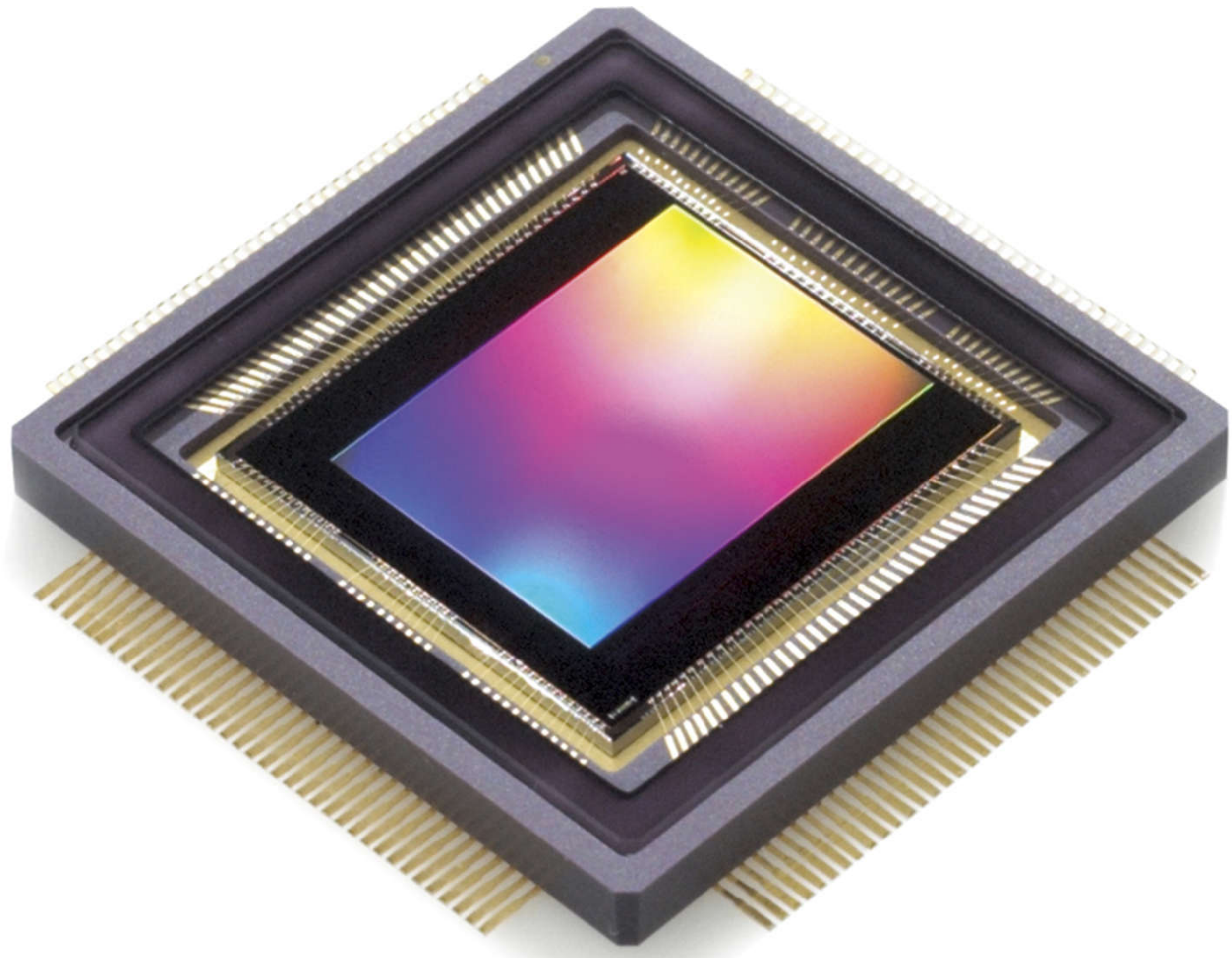






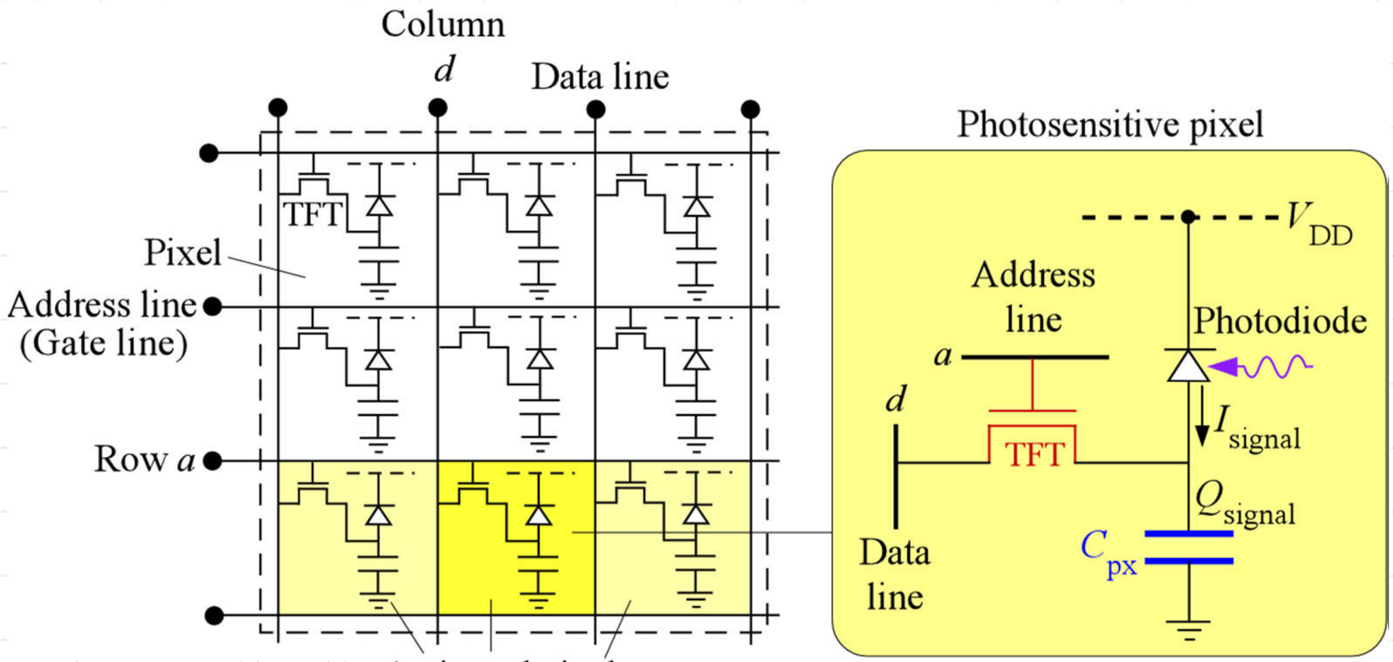
X3 sensor: is a technique that uses different absorption depths for red, green, and blue light in silicon. The red, green, and blue light have different penetration depths into silicon so that, in principle, we can use photodiodes at different depths to distinguish between the colors.

CMOS Image Sensor



4 Megapixel CMOS image sensor
(Courtesy of Teledyne-DALSA)

Active Matrix Readout



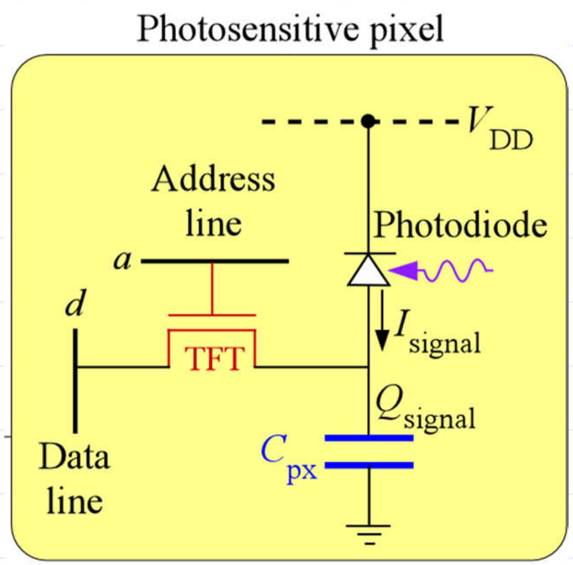
An active matrix array (AMA)

(a) **(b)**

- **An active matrix array (AMA):** is a 2D array of pixels in which each pixel has a thin film transistor (TFT) that can be externally addressed to read a signal from a sensor located at that pixel.
- Depending on the application, an AMA can have few pixels or millions of pixels.
- Each pixel has a photodiode and a capacitor C_{px}.

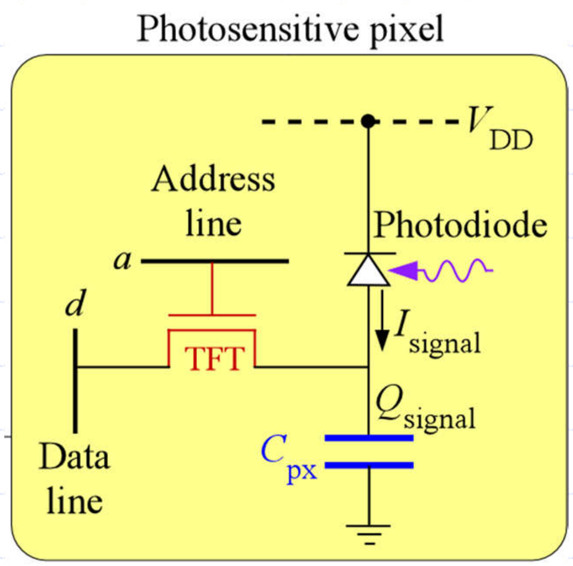
Active Matrix Readout

- When a pixel receives light from a particular point on the illuminated object, the photodiode generates a current I_{signal} which charges the pixel capacitor C_{px}.
- The signal is the charge Q_{signal} stored on C_{px}.
- The array of pixels therefore has the image stored as charges on pixel capacitances.
- All we have to do is read the charges out.
- Each pixel with its TFT gate connected to a particular address line and the source to a particular data line.



Active Matrix Readout

- A row $a \in \{1,2,\dots,N\}$ is addressed by the controller, and all the pixels in this row provide their signals (Q_{signal} on each C_{px}) to the columns (data lines) $d = 1$ to M (that is, the data are read out onto the data lines as parallel data).
- The parallel data are multiplexed (converted into serial data) and digitized to provide a digital image.
  - The image sensor quantizes the image because it breaks into $N \times M$ number of pixels.
  - The pixel size imposes a resolution limit because the image is sampled by the pixels, which are of finite size.
- We can scan the whole image row by row (line by line) by starting from the top row and sequentially activating one row after another.



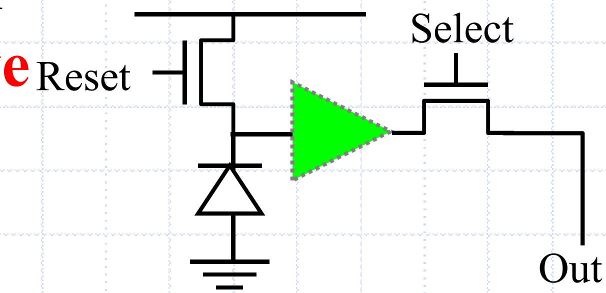
CMOS Image Sensor

A CMOS image sensor is basically an AMA in which each pixel has a photodiode and one or more CMOS transistors to read and amplify the electrical signal that has been generated by the light incident on this pixel.

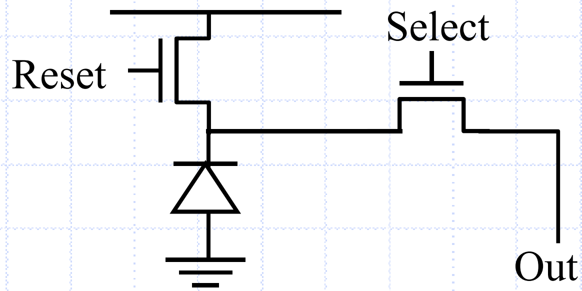
The pixel read-out operation is essentially the same as that in AMA.

If the pixel is active with gain, then the imager is called an **active pixel image sensor,** or **active pixel sensor**.

Fast, higher SNR, but larger pixel, lower FF



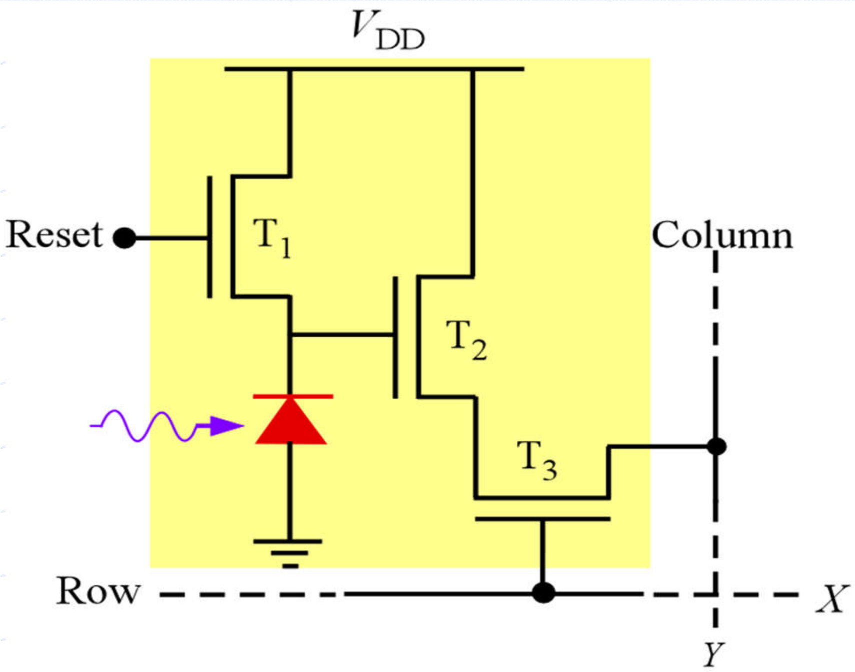
In a **passive pixel sensor** there is only a switching transistor to read the charge out when the transistor switch is addressed.



Nearly all modern CMOS imagers are active pixel sensors.

CMOS Image Sensor

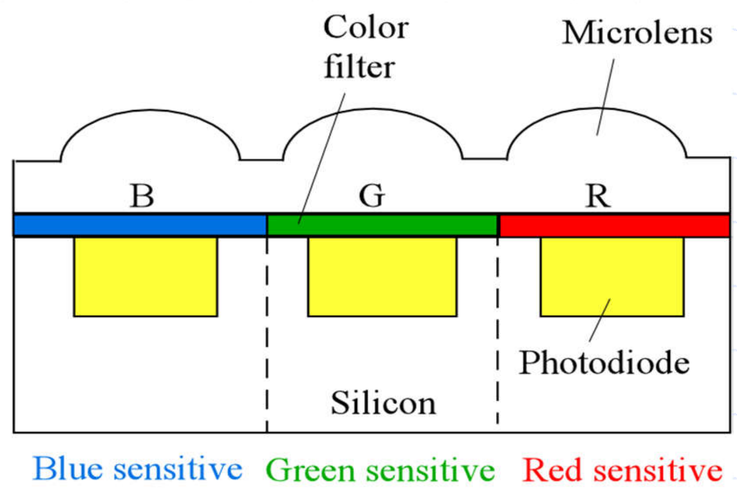
- T_1 is the reset transistor, T_2 works as a source follower (i.e., a buffer), and T_3 is a pixel switch transistor.
- With T_1 off, the photocurrent charges the self-capacitance of the photodiode to a certain voltage.
- When the row X receives a signal, T_3 is turned on, and the signal voltage on the photodiode is transferred through the buffer T_2 to the column Y.
- The pixel is then reset, and T_1 connects the photodiode to V_{DD} to clear the accumulated charge.



The pixel architecture in a CMOS image sensor.

CMOS Image Sensor

A cross section of a CMOS imager with microlenses and color filters (B = blue, G = green, R = red) for color imaging



- **CMOS imagers** have a number of distinct advantages.
  - Standard and well-established CMOS fabrication, and hence lower fabrication cost
  - low power consumption ⇒ longer battery life
  - on-chip integration such as a camera on a chip.
- A **camera on a chip** has a microlens at each pixel—a red, green, or blue filter at each pixel for color imaging—as illustrated in the figure, analog signal processing after the readout of the image, and analog-to-digital conversion.
- Active pixel architecture can include pixel amplification as well to improve the overall efficiency.

CCD Image Sensor

(Courtesy of Teledyne-DALSA)

CCD Image Sensor

A Charge-coupled device (CCD) is a 2D array of metal-oxide-semiconductor (MOS) capacitors.

The charges are stored in the depletion region of the MOS capacitors.

Charges are moved in the CCD circuit by manipulating the voltages on the gates of the capacitors so as to allow the charge to spill from one capacitor to the next (thus the name "**charge-coupled**" device).

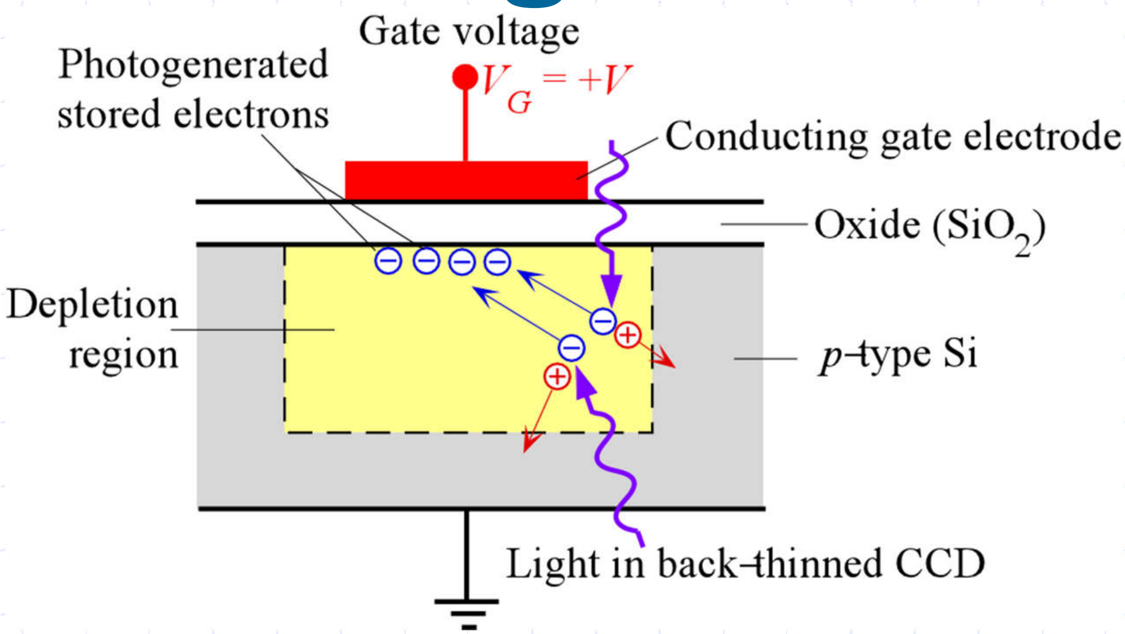
An amplifier provides an output voltage that can be processed.

The CCD is a serial device where charge packets are read one at a time.

CCDs are commonly used as image sensors in professional and consumer TV cameras and camcorders, and as image sensors in digital still cameras.

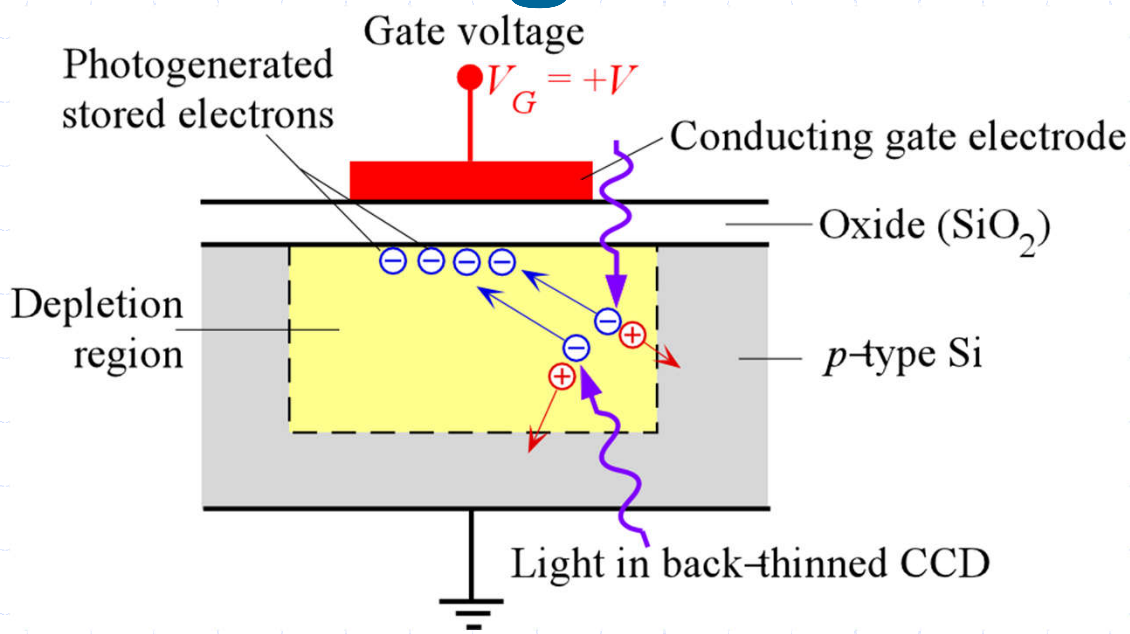
However, the term CCD in general does not imply an image sensor but a chip that is able to store and transfer signals in the form of charge.

CCD Image Sensor



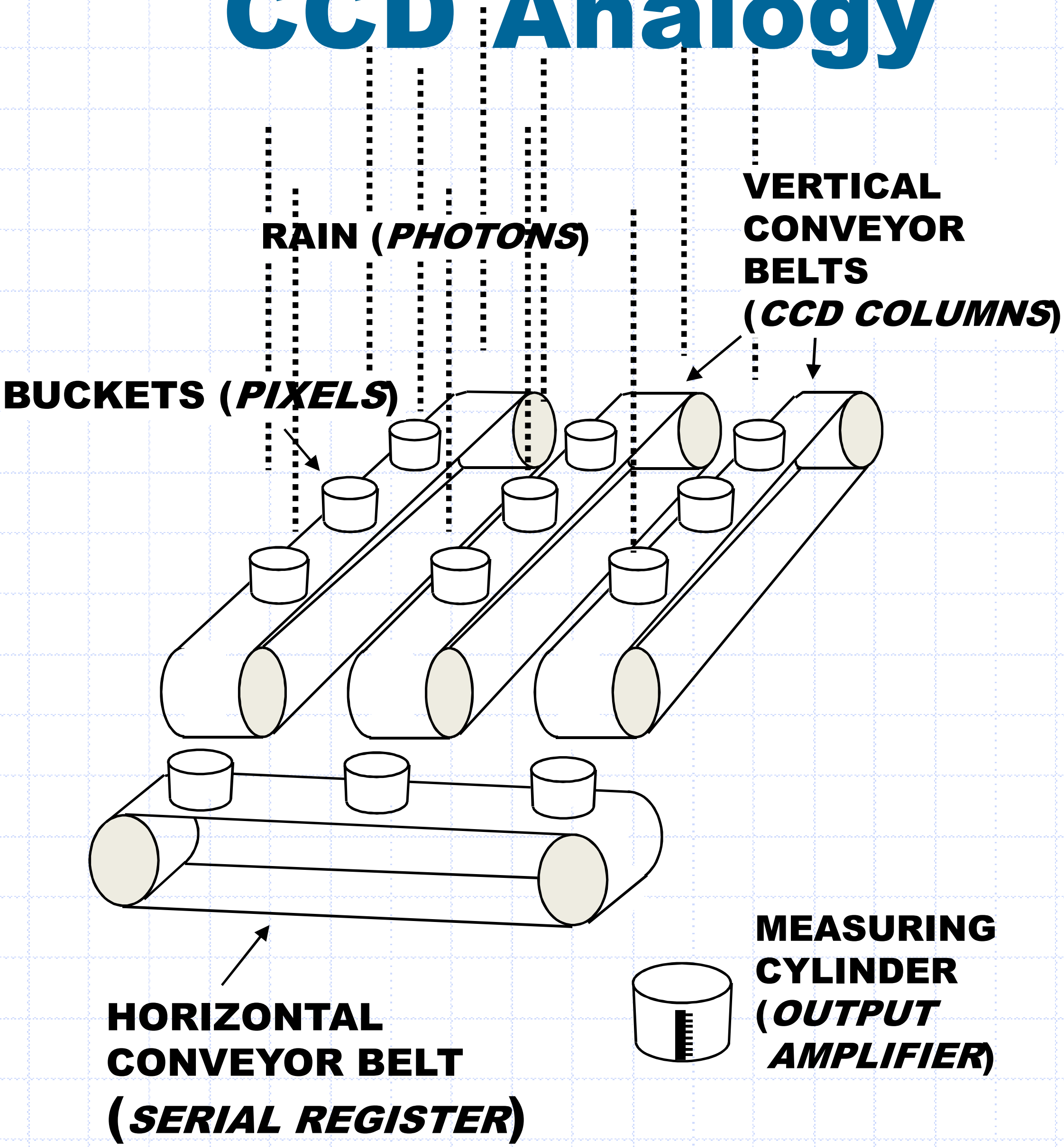
- The basic pixel structure is a MOS (metal-oxide-semiconductor) or a MIS (metal-insulator-semiconductor) device.
  - The structure is based on a *p*-type Si, an oxide layer, and a metal electrode, which is usually transparent.
  - There is a depletion region inside the *p*-type semiconductor.
  - The EHPs are generated inside the depletion region by illumination either from the top surface or from the backside as shown in the figure.
  - In back-thinned CCD, light enters the depletion region not from the gate side but from the "substrate" side, which has been thinned to allow the light to pass through.

CCD Image Sensor



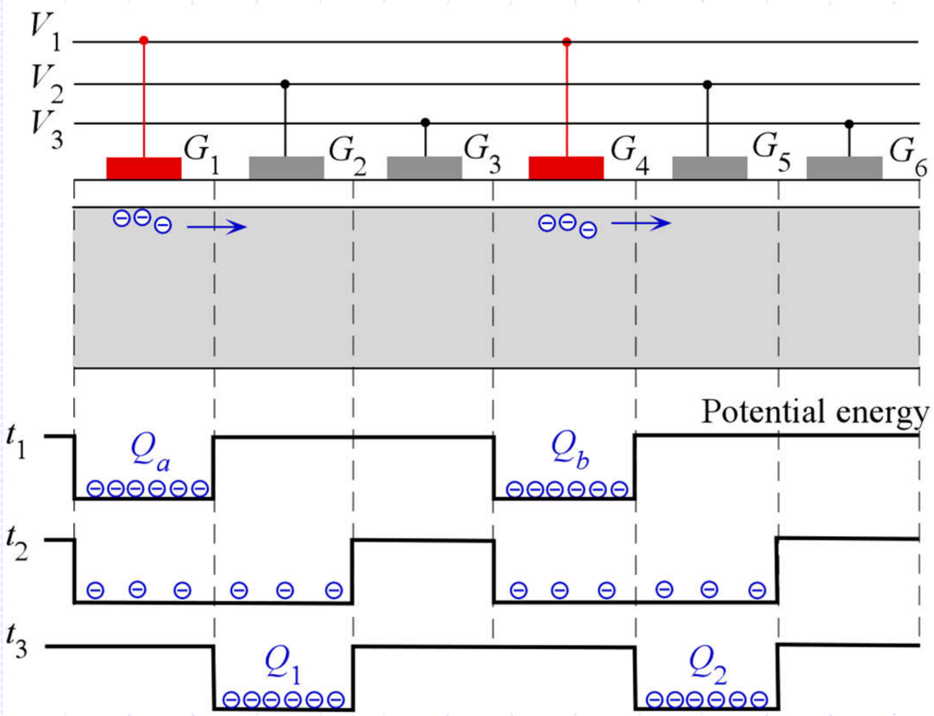
- When a positive voltage $+V$ is applied to the gate V_G ($V_G = +V$), the photogenerated electrons in the depletion region are collected in a layer near the interface as shown in the figure.
  - With no gate voltage ($V_G = 0\ V$), photogenerated electrons and holes disappear by recombination.
- These electrons are trapped inside a potential energy well, introduced by +V on the gate. Their total charge is proportional to the total light exposure.
- This charge constitutes the electrical signal. The objective is to read all these charges stored at the illuminated pixels.

CCD Analogy



RAIN (*PHOTONS*)
VERTICAL CONVEYOR BELTS (*CCD COLUMNS*)
BUCKETS (*PIXELS*)
MEASURING CYLINDER (*OUTPUT AMPLIFIER*)
HORIZONTAL CONVEYOR BELT (*SERIAL REGISTER*)

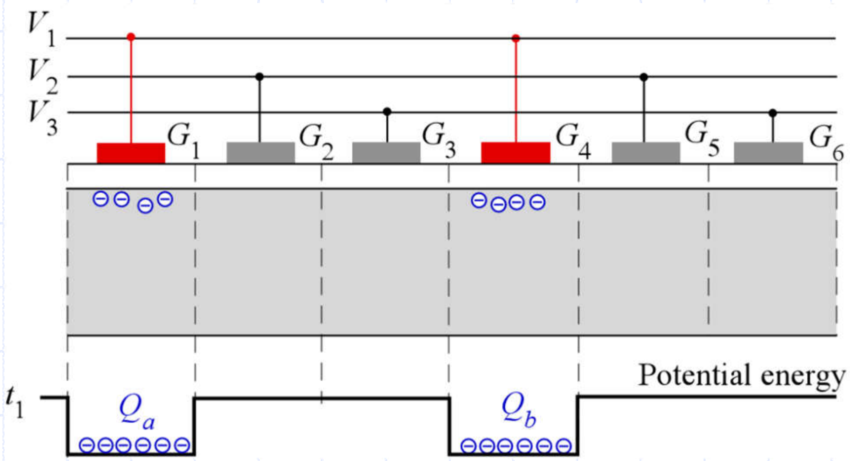
Three-phase CCD read-out

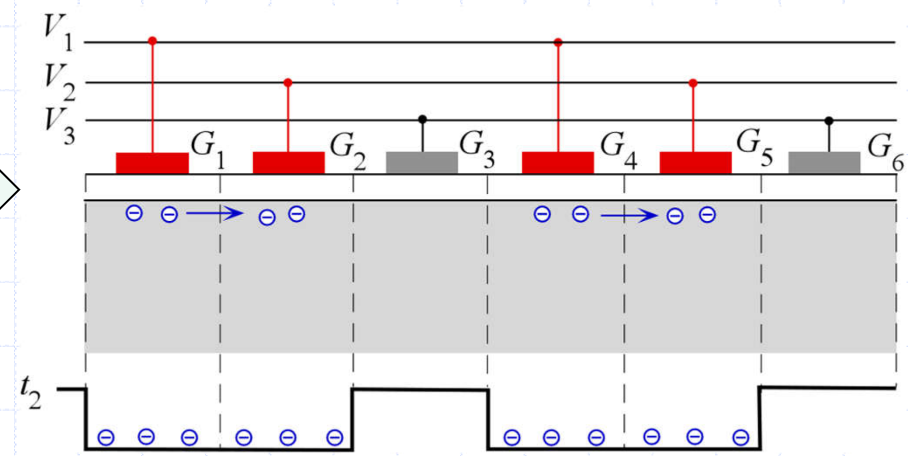


Time	V_1	V_2	V_3
t_1	$+V$	0	0
t_2	$+V$	$+V$	0
t_3	0	$+V$	0

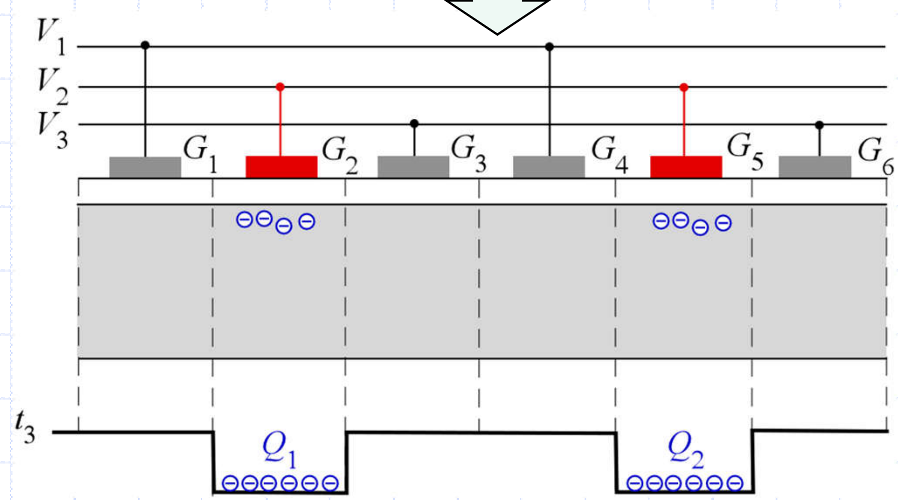
- There are three line voltages V_1, V_2, V_3 to which the gates are connected in an alternating fashion: G_1 to V_1, G_2 to V_2, and G_3 to V_3, G_4 to V_1 again and so on.
- V_1, V_2, and V_3 are appropriately clocked to shift the charges from pixel to pixel to a register located at the end of the chip.
- The CCD read-out therefore functions like a shift register in that clock pulses shift the information along the chain; they are often termed CCD shift registers.

Three-phase CCD read-out





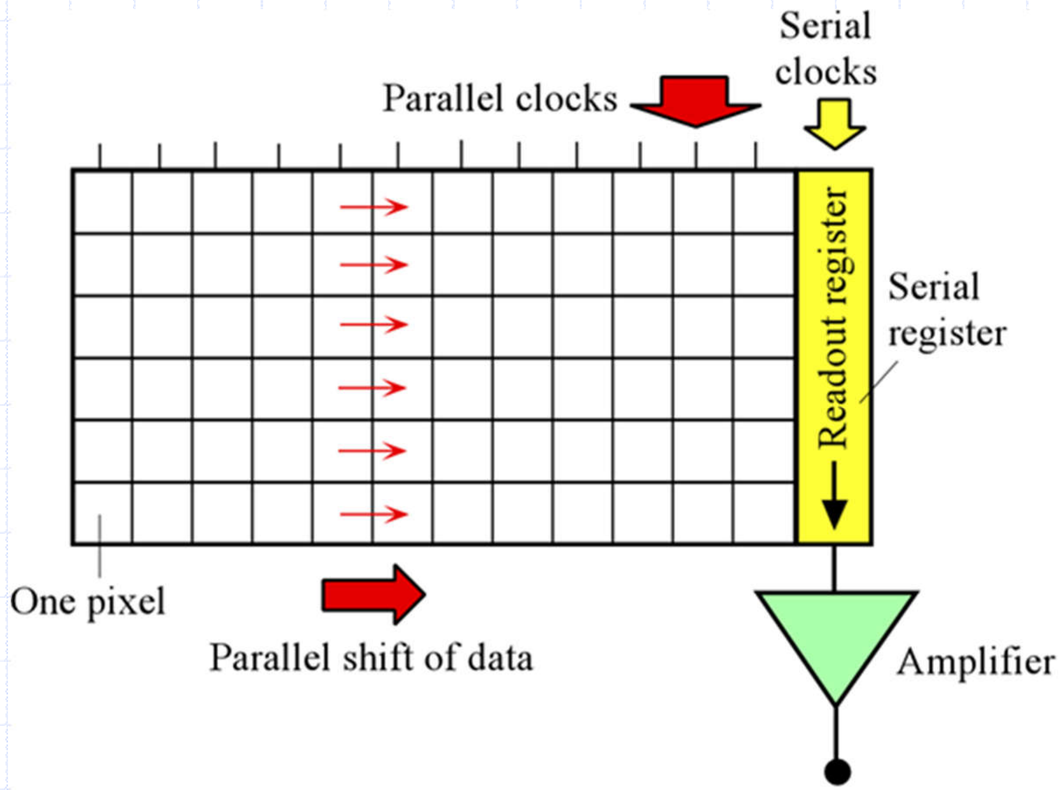
Time	V_1	V_2	V_3
t_1	$+V$	0	0
t_2	$+V$	$+V$	0
t_3	0	$+V$	0



CCD read-out techniques

Full Frame Architectures

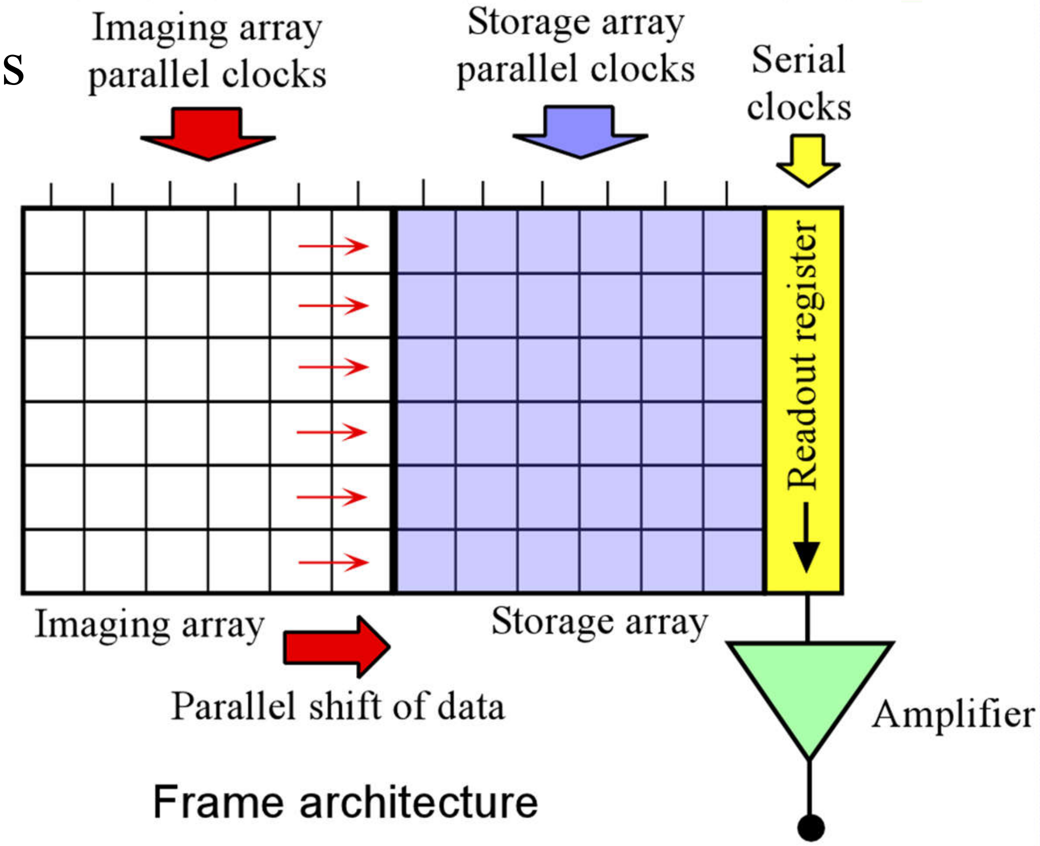
- In a full frame architecture, the sensor consists of parallel CCD shift registers, a serial CCD shift register as a read-out register, and an amplifier.



- The columns of data are fed into the serial register starting soon after the projection of the image onto the array, as the clock signals start transferring the charges pixel to pixel toward the read-out register.
- A short build-up or exposure time is necessary to build up the charges in the imaging arrays. The process continues until all the columns of data have been transferred.
- This architecture has the highest resolution and is the densest.

CCD read-out techniques

Frame Architectures

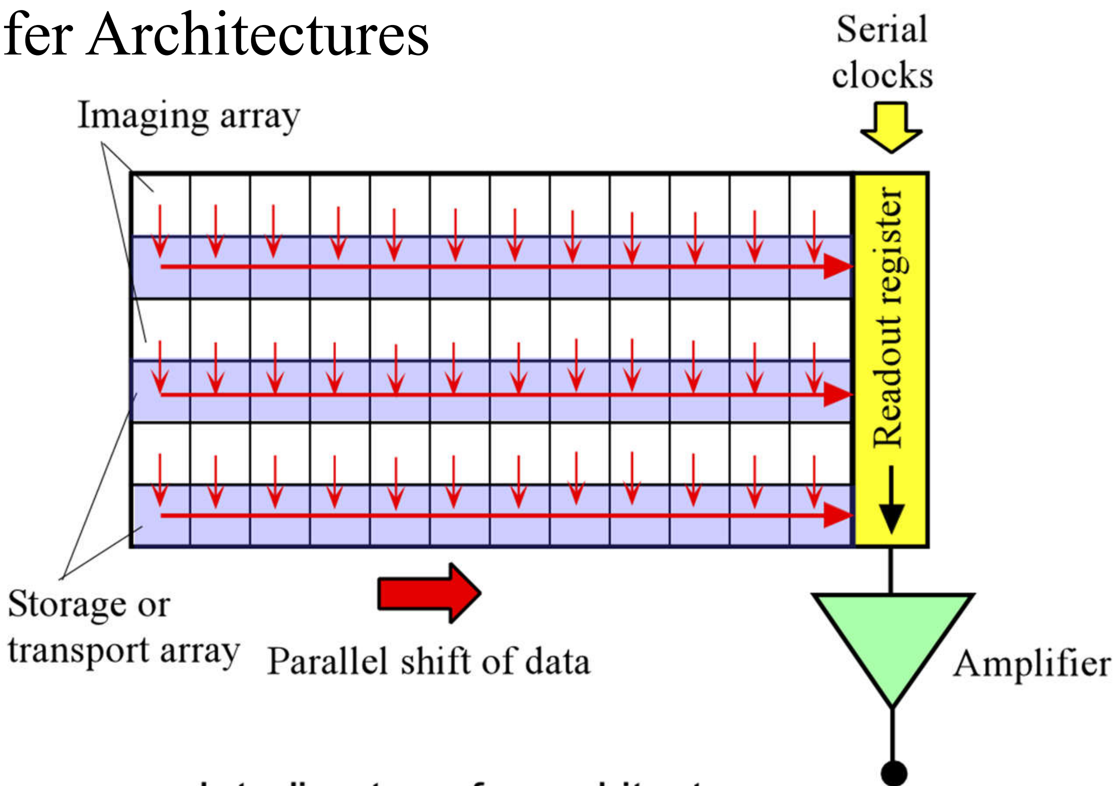


Frame architecture

- The frame architecture is similar to the full frame except that half the array is used as data storage to increase the speed.
- The storage array is blocked from light.
- The idea is to shift the data away from the image sensors quickly so that they can capture the next image soon; these have higher frame rates at the expense of resolution.

CCD read-out techniques

Interline Transfer Architectures



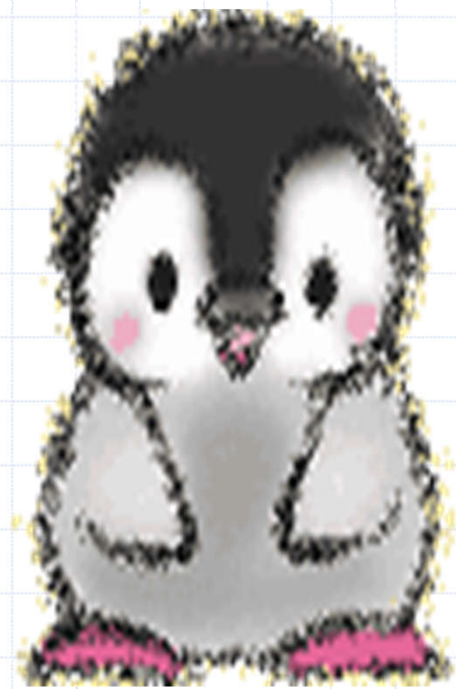
Interline transfer architecture

- The interline transfer architecture uses every other row of the CCD array for storage and transport right next to the imaging array.
- The transport array is blocked from light, and the data from the imaging array are transferred in parallel to the transport array after the image has been built-up in the imaging array.
- The data on the transport array are shifted, just as in the normal CCD.

CCD vs. CMOS

	CCD	CMOS
Sensitivity:	High	Low
Noise:	Low	More susceptible to noise
Power Consumption:	High	Low
Pixel Signal:	Electron packet	Voltage
Chip Output:	Voltage (Analog)	Bits (Digital)
System Complexity:	High	Low
Technology:	Older and more developed technology	Easy to Manufacture
Speed:	Moderately fast	Very fast
Cost to Manufacture:	High	Low
Fill Factor:	High	Moderate

Thank you



Have a nice day.