Intelligent Control Systems

Cameras and Image Sensors

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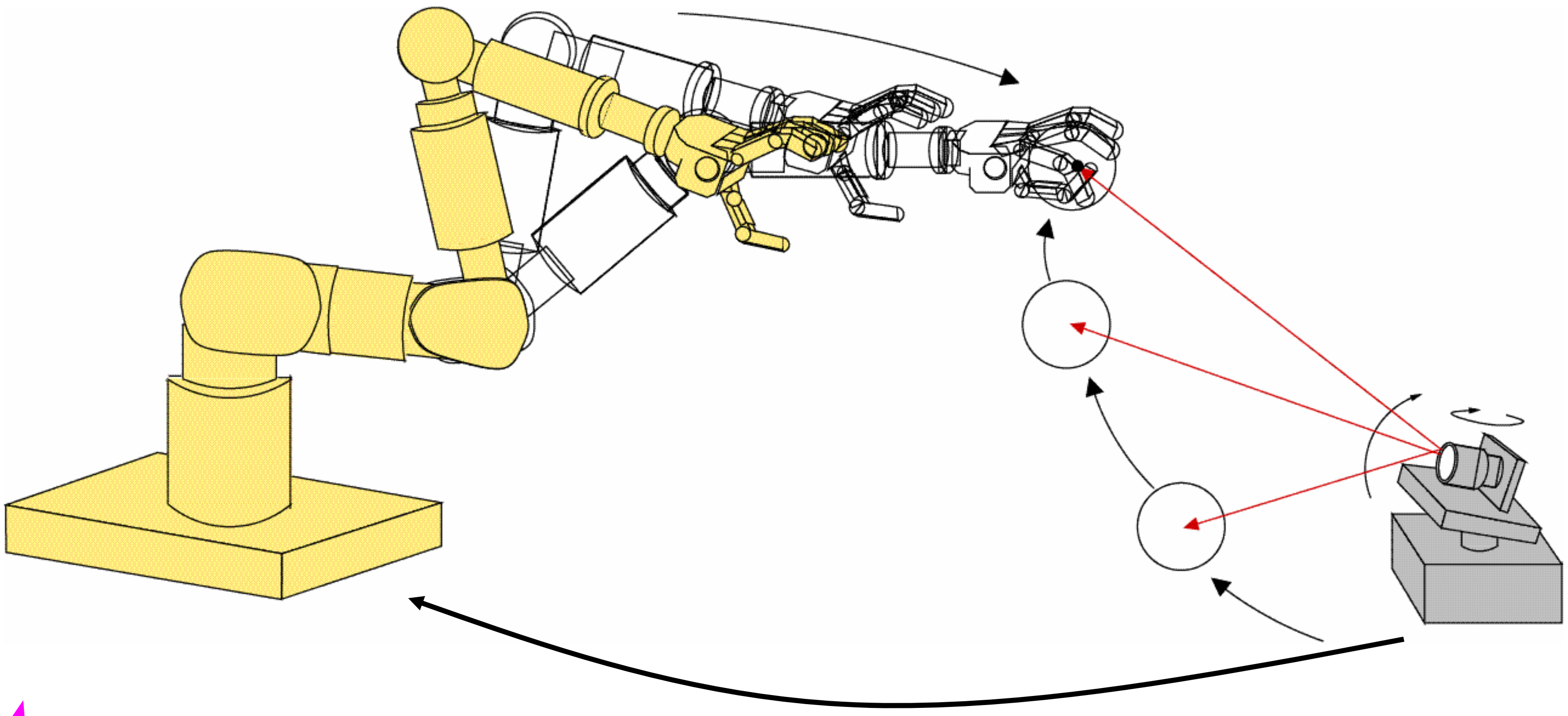
Basic Motivation

e.g. Vision-based Control of Robots

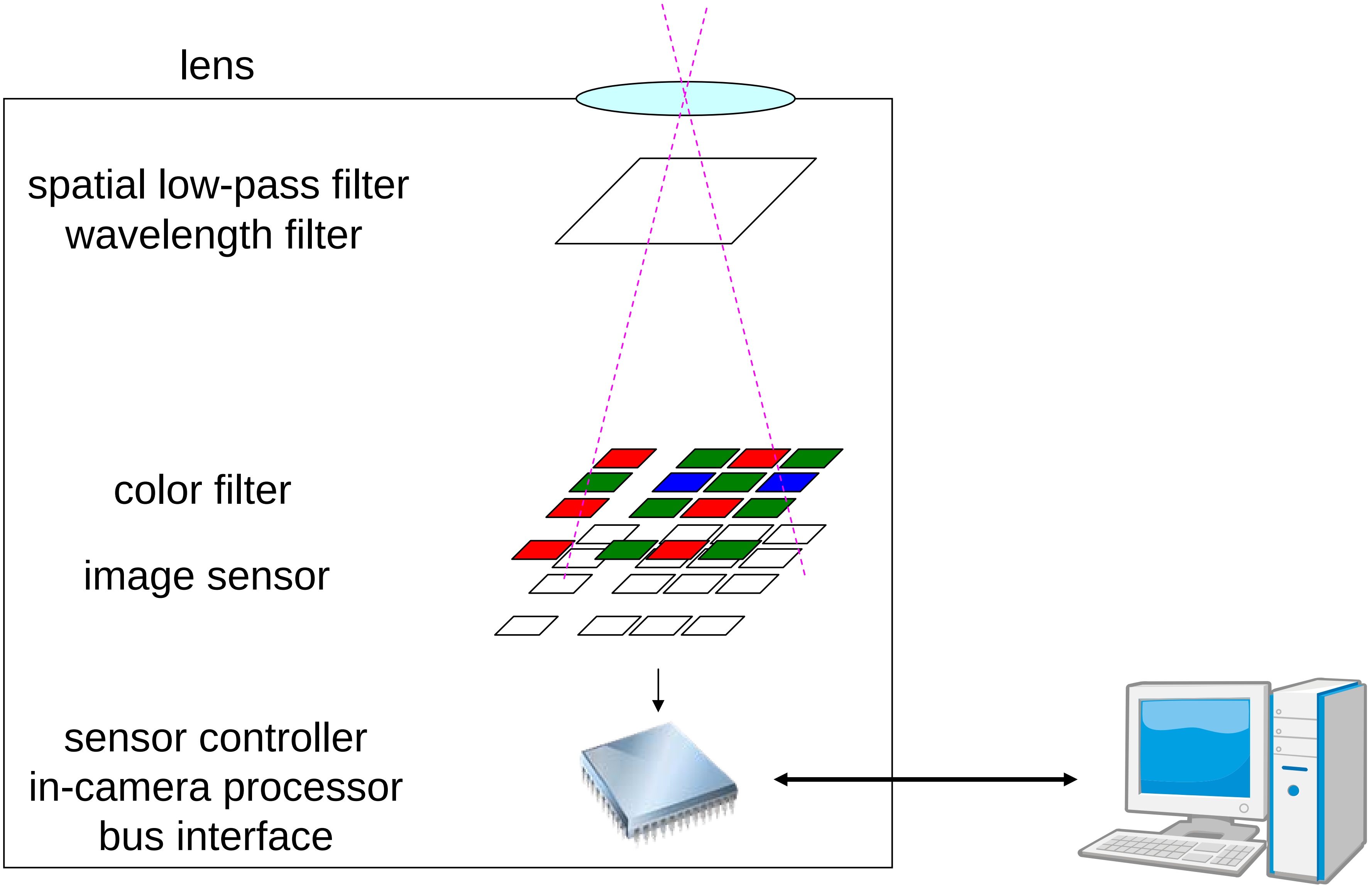


- image acquisition (today)
- image processing (from June 3 and on)
- robot control

Outline

- Lens and Optical Parts
- Image Sensors
  - CCD / CMOS sensors
  - Integration / Shutter Modes
- In-Camera Image Processing
- Image Data Transfer
- Dynamic Range Enhancement

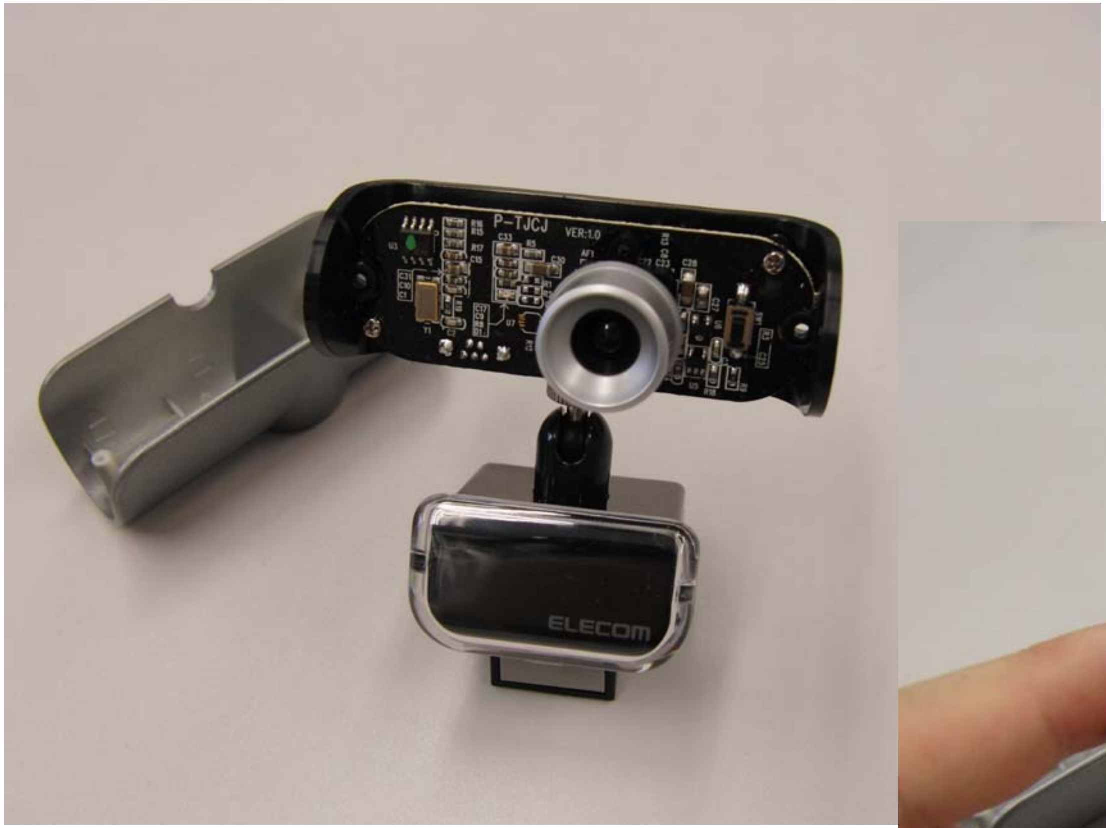
Cameras and Image Sensors



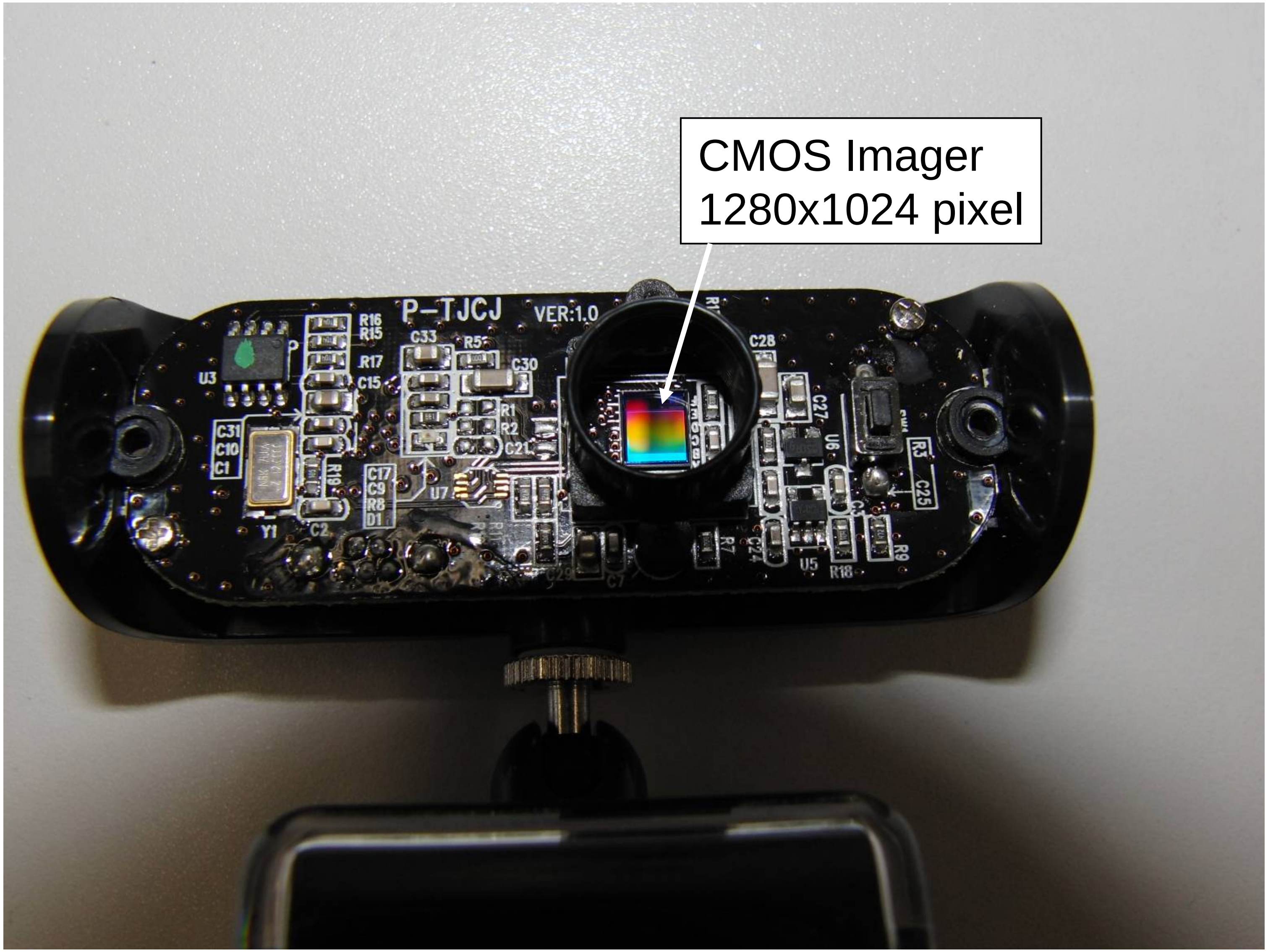
Examples

USB camera
with unremovable lens

Example



Example



Camera and Lens

Cameras with unremovable lens

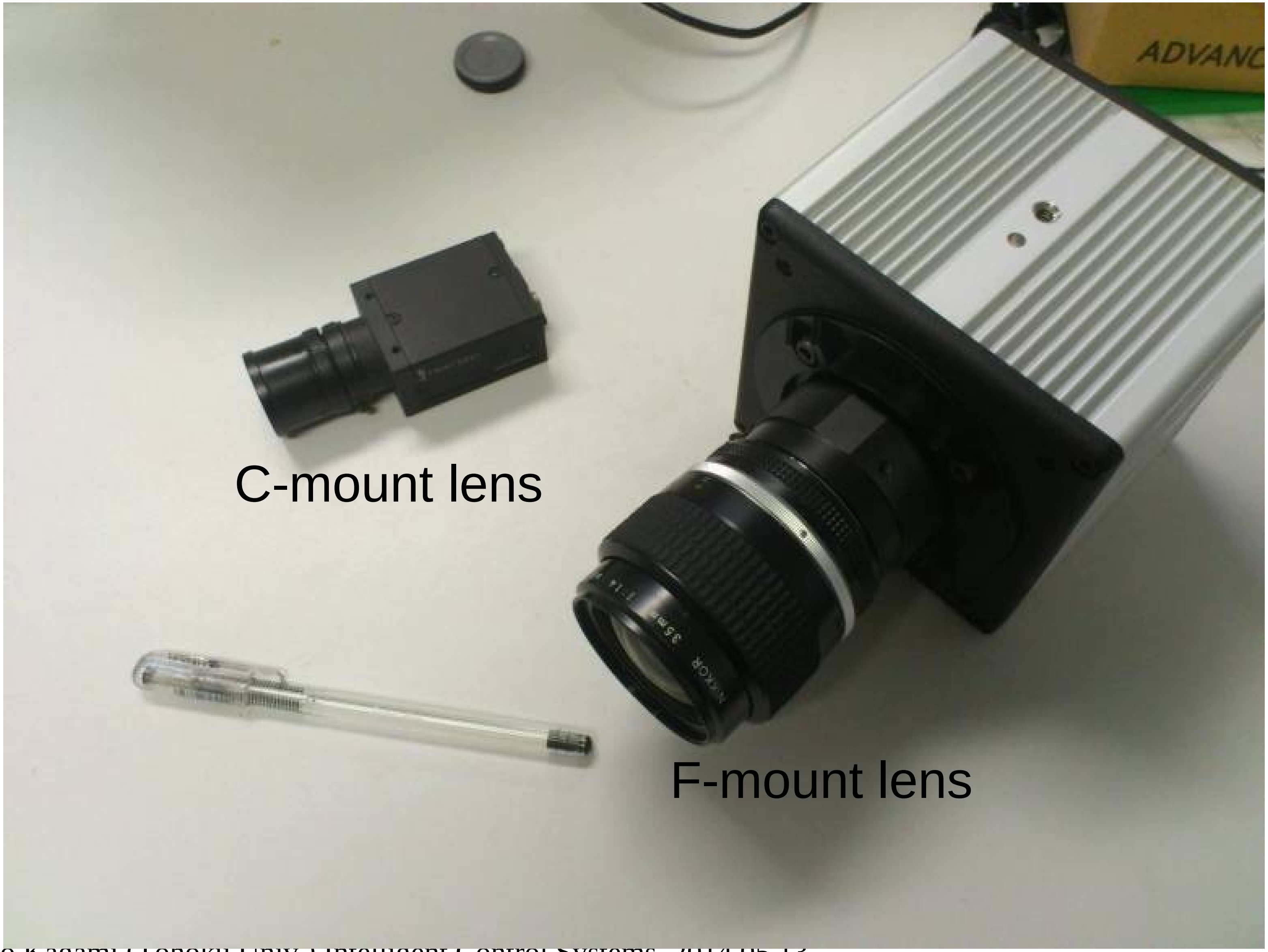
- most of inexpensive web cameras

Cameras with removable lens

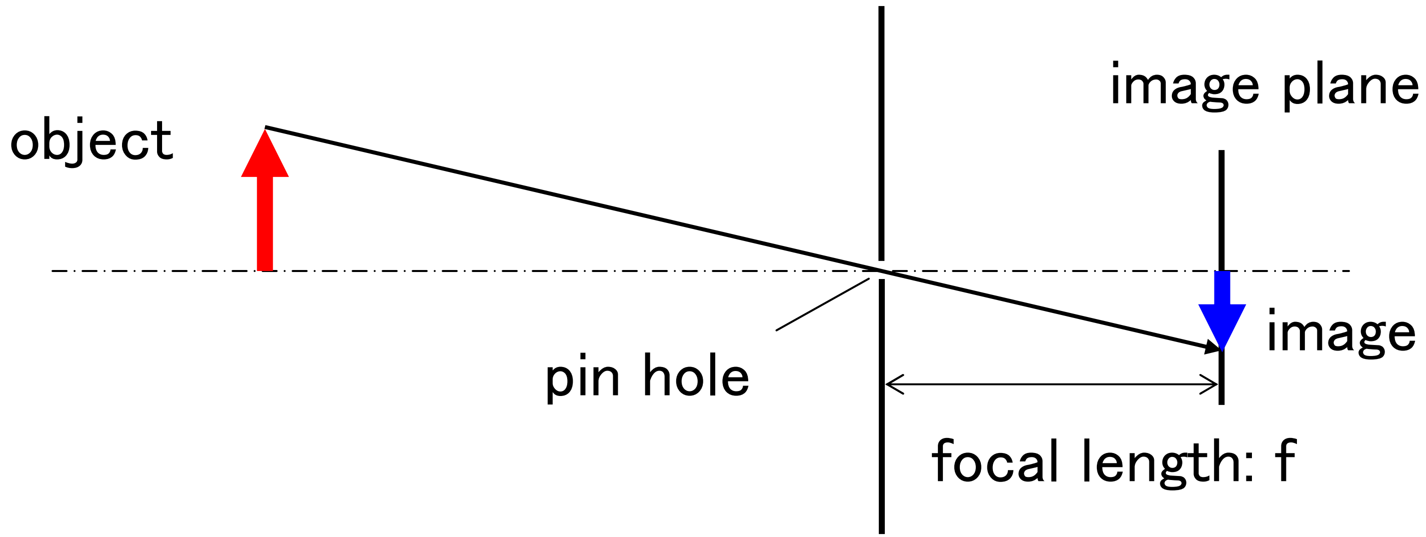
- Nikon F-mount (large aperture size)
- C-mount (small aperture, long flange back)
- CS-mount (same aperture with C-mount, short flange back)

- The lens must be selected considering the imager size
  - 1’’, 2/3’’ 1/2‘’, 1/3‘’, 1/4’’
  - 1’’ corresponds approx. to diagonal length D = 16 mm
- View angle θ determined by D and focal length f
  - $\tan(\theta/2) = D/2f$
- F-number: f / A (A: aperture size)
  - The smaller, the brighter but narrower depth of field

C-mount / F-mount Lenses

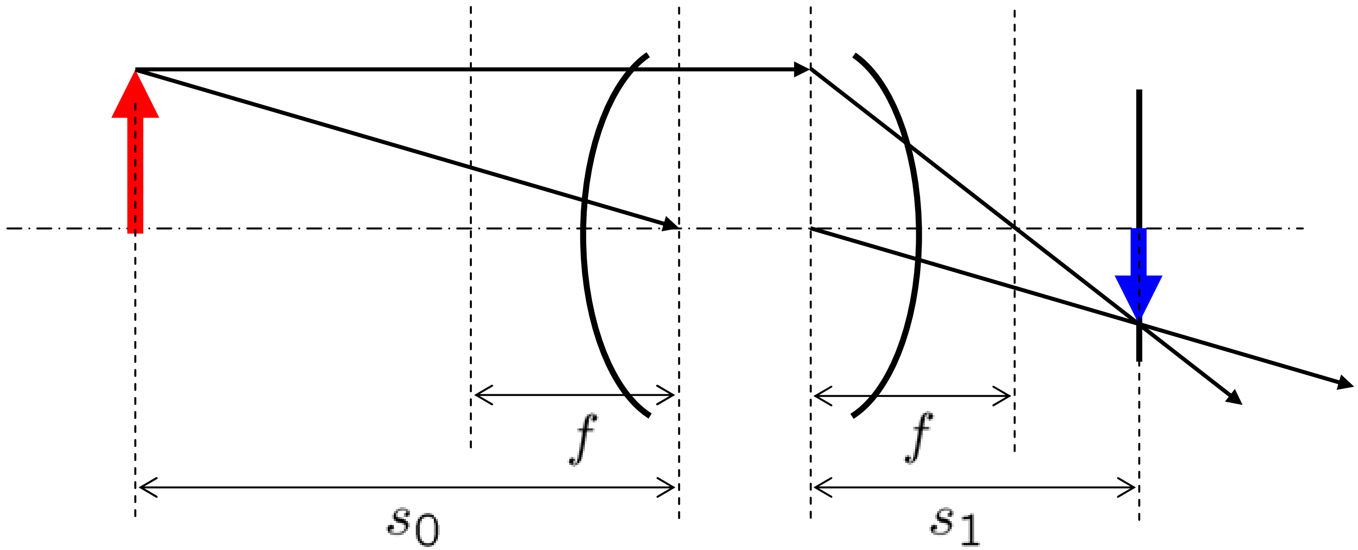


Pin-Hole Camera Model



- No restriction on the distance from camera to object
- Limited light amount available (dark image)

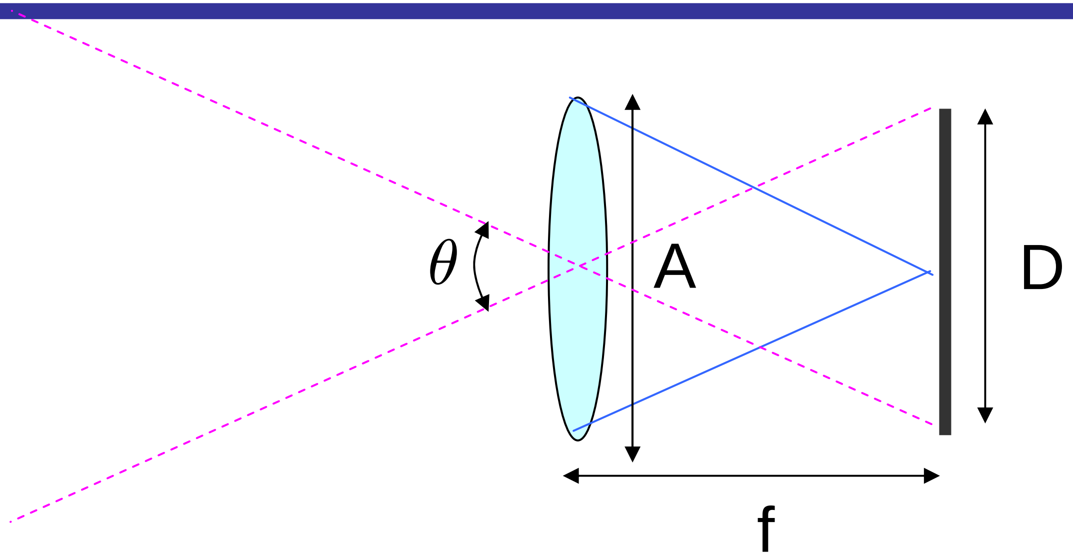
Lens formula

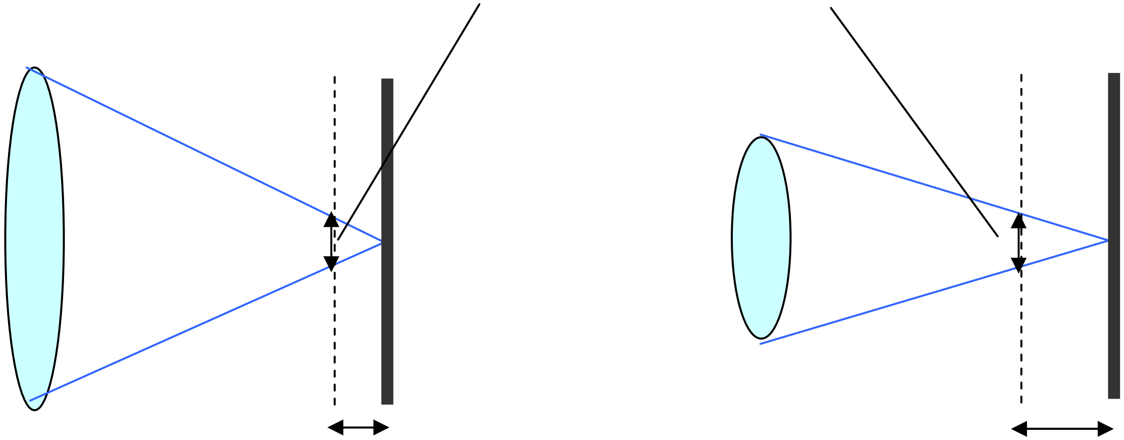


$$\frac{1}{f} = \frac{1}{s_0} + \frac{1}{s_1}$$

- More light is available (through finite lens aperture)
- Restricted distance from camera to object (Once f and s_1 are given, s_0 is uniquely determined)

Imager size, Aperture size and Focal length





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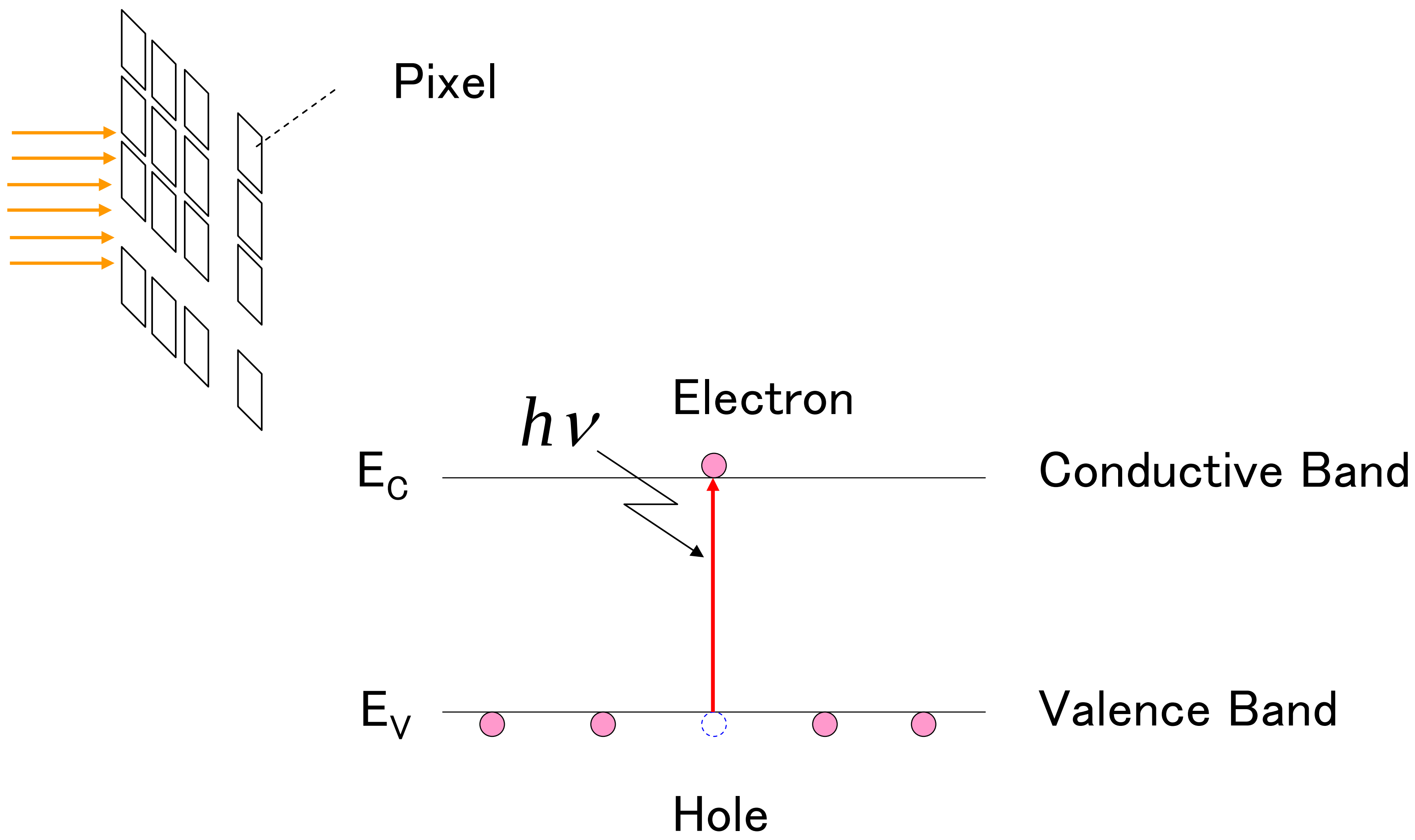
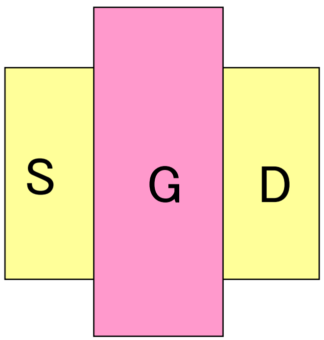
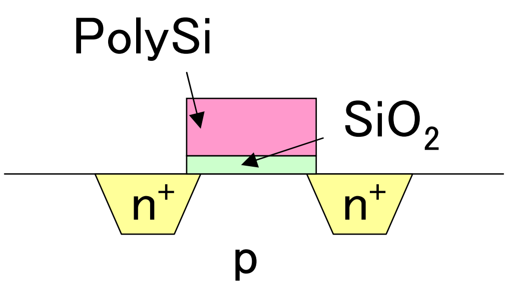
Solid-State Image Sensor



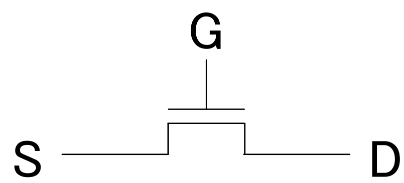
Minimal Knowledge of Semiconductor Devices

top view



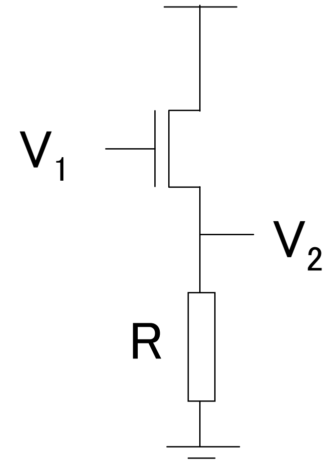


side section view



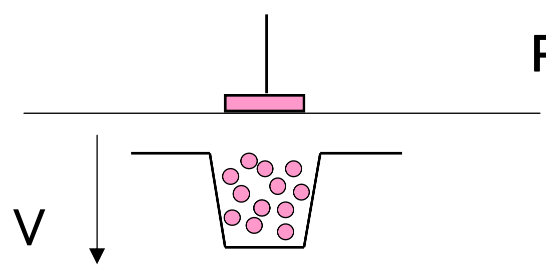
MOS switch

When V_G is high, S and G are connected (switch on)



Source Follower Amp.

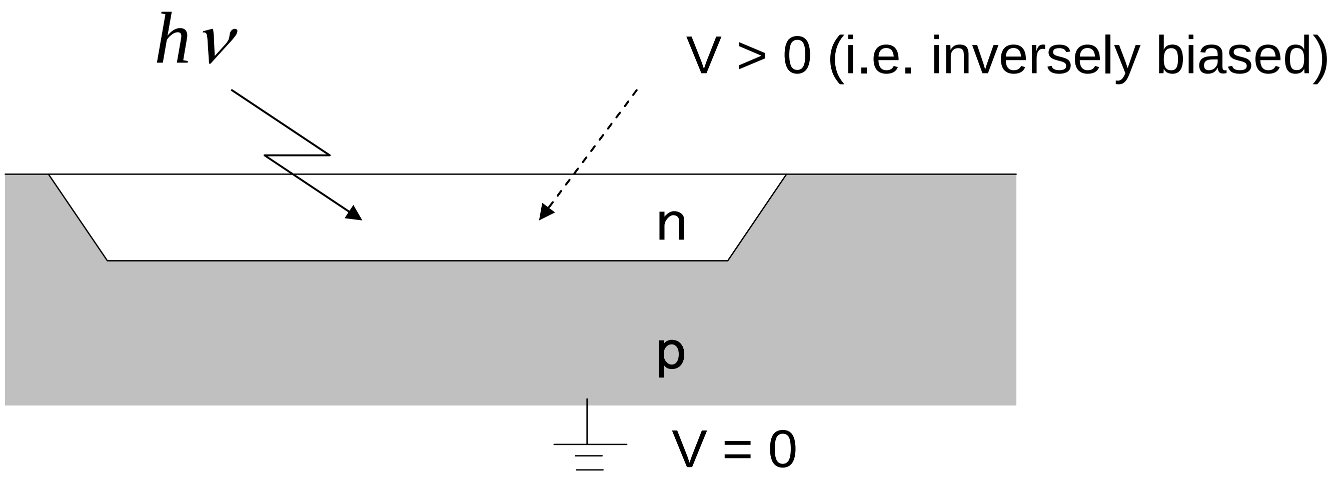
$V_2 = V_1 + \alpha$



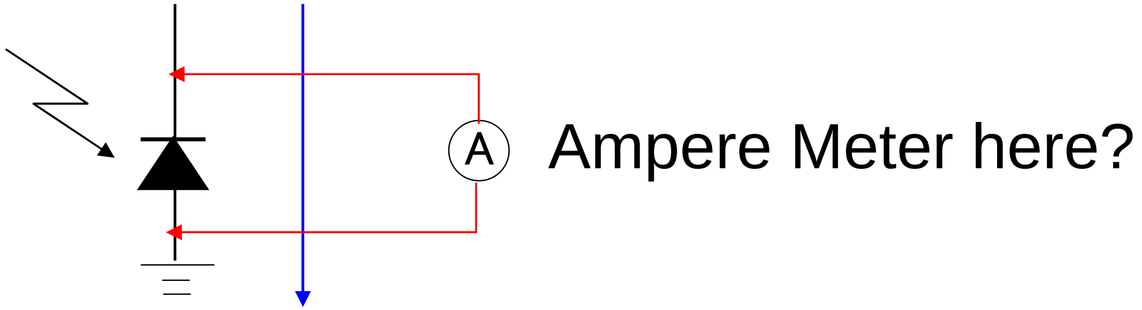
Potential Well

By applying locally high voltage, electronic charges can be collected

Photodiode

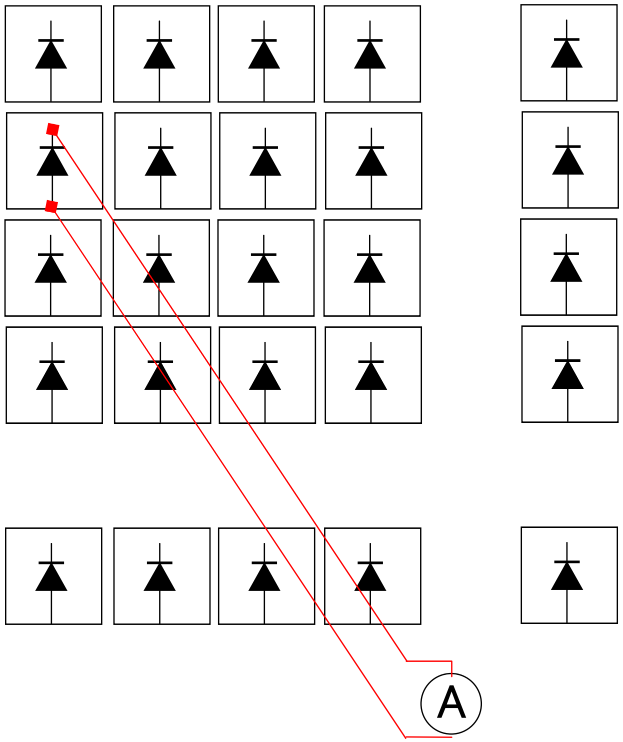


An intuitive interpretation:



photocurrent *i*: proportional to brightness

What if ampere meter is used



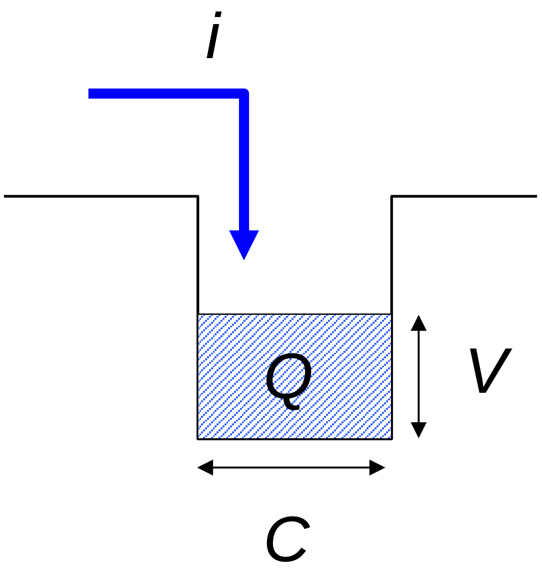
- Photocurrent is very weak
  - order of pA ~ fA
  - too susceptible to noise
- Difficult to measure millions of pixels at the same time, so time division is mandatory
  - for most of the time, photocurrent is just disposed

Photo Integration

That is why we need integration:

$$Q = \int_0^{t_{\text{int}}} i\,dt$$: charge

$$V = \frac{Q}{C}$$: voltage



C: capacitance of the node where the charges are integrated

Photocurrent is *integrated over a certain integration time* in a pixel *while the other pixels are read out*

Shot Noise

Fundamental noise in optical measurement: fluctuation in the number of the particles such as electrons and photons

$$N_{\mathrm{shot,rms}} = \sqrt{\bar{N}}$$

$N_{\mathrm{shot,rms}}$: root mean square # of shot noise charges

$\bar{N}$: # of signal charges

Equivalently,

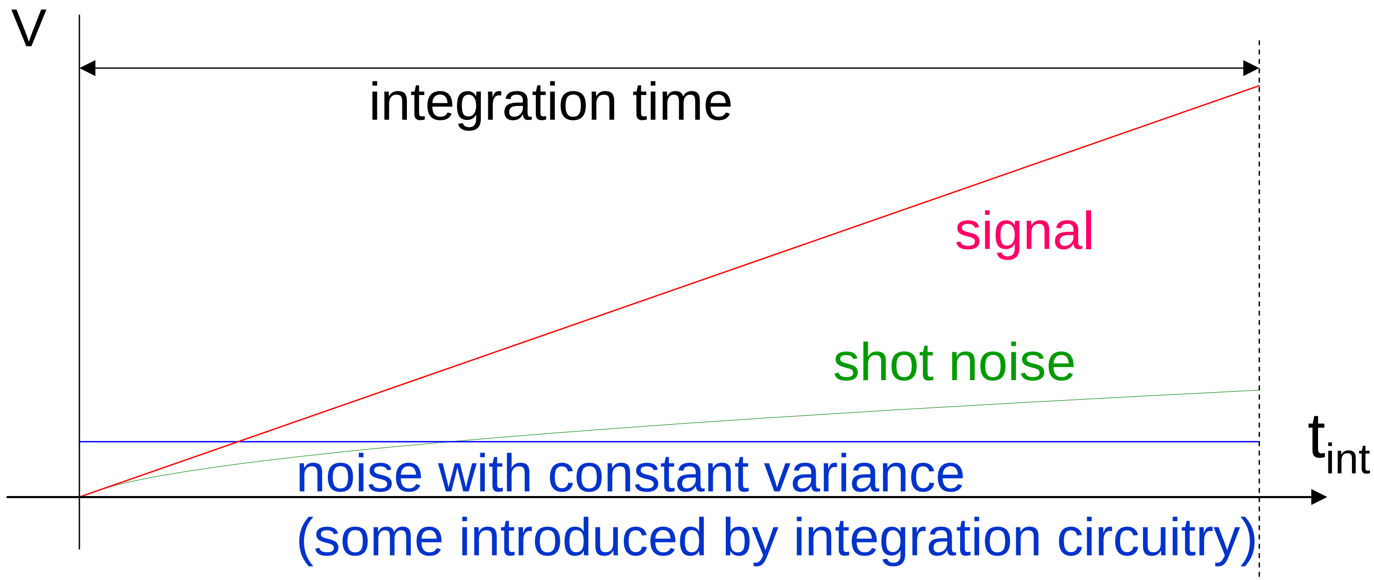
$$Q_{\mathrm{shot,rms}} = e\sqrt{\bar{N}} = e\sqrt{\bar{i}t_{\mathrm{int}}/e} = \sqrt{e\bar{i}t_{\mathrm{int}}}$$

e: electron charge

$\bar{i}$: average photocurrent plus dark current

t_{int}: integration time

Noise and Integration time



$$V_{\text{signal}} = \frac{i_{\text{signal}} t_{\text{int}}}{C} \qquad V_{\text{shot,rms}} = \frac{Q_{\text{shot,rms}}}{C} = \frac{\sqrt{e\bar{i}t_{\text{int}}}}{C}$$

With N times longer t_{int}, signal-to-noise ratio (SNR) is multiplied by:

- $\sqrt{N}$ with respect to shot noise
- N with respect to other noise

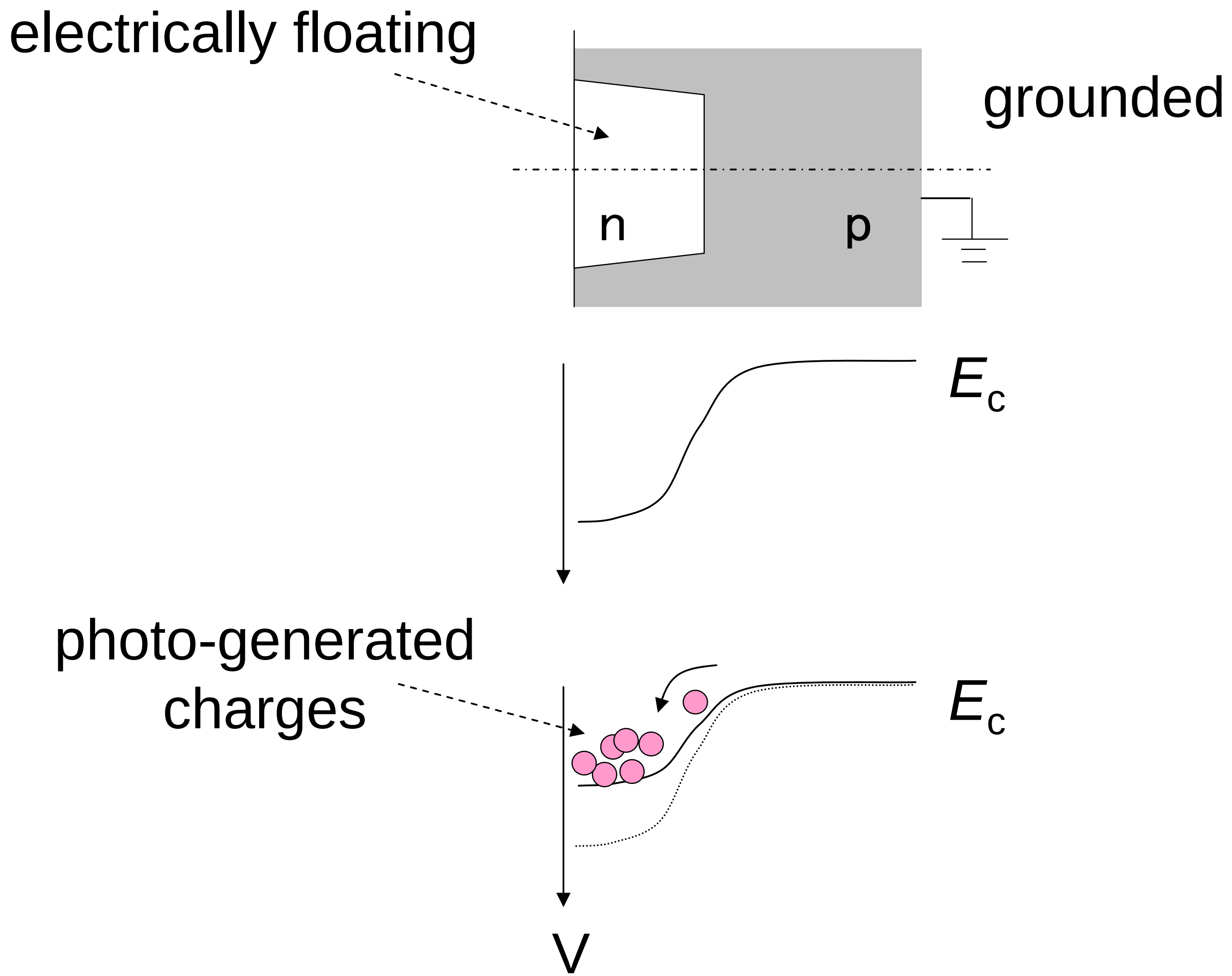
Effects of Integration

- The longer the integration time is, the brighter the image becomes (because more photo signal is collected)
  - This is intuitive way of understanding; but it should be understood in terms of SNR

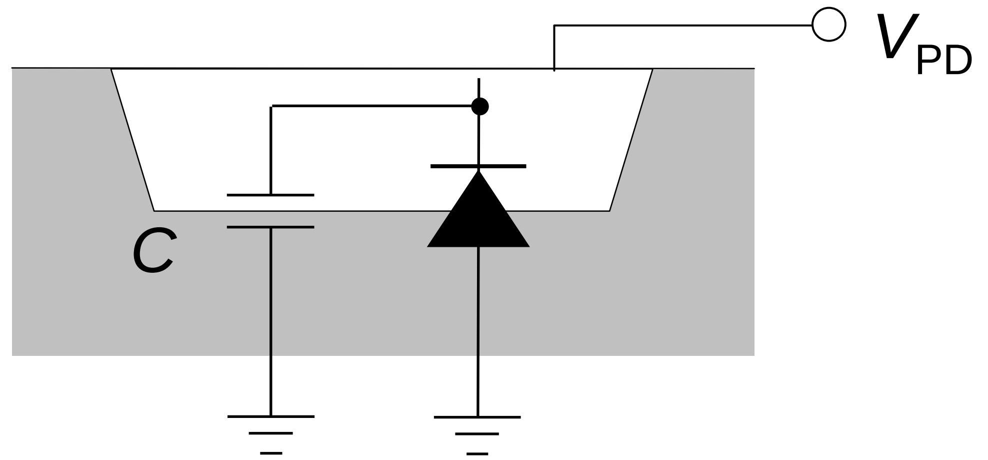
- Integration time $\leq$ Frame time: Thus high frame rate imaging makes images darker (or more correctly, noisier)
  - Strong illumination may be needed

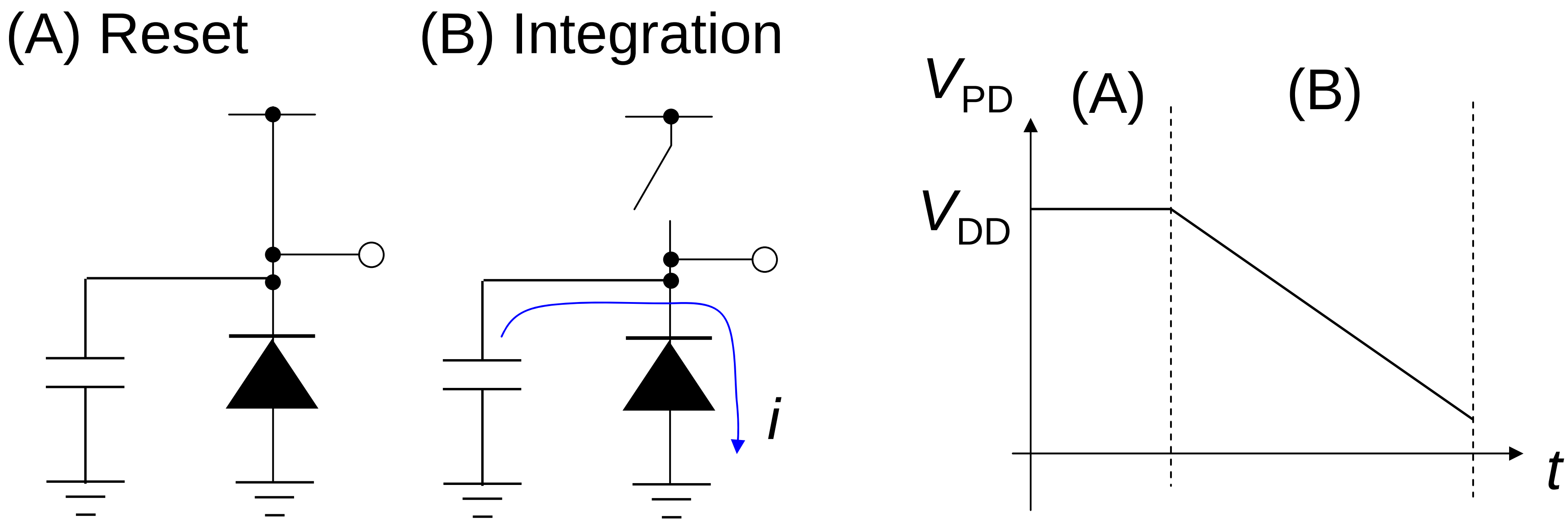
- Motion blur is caused when the scene moves fast

Integration-mode photodiode

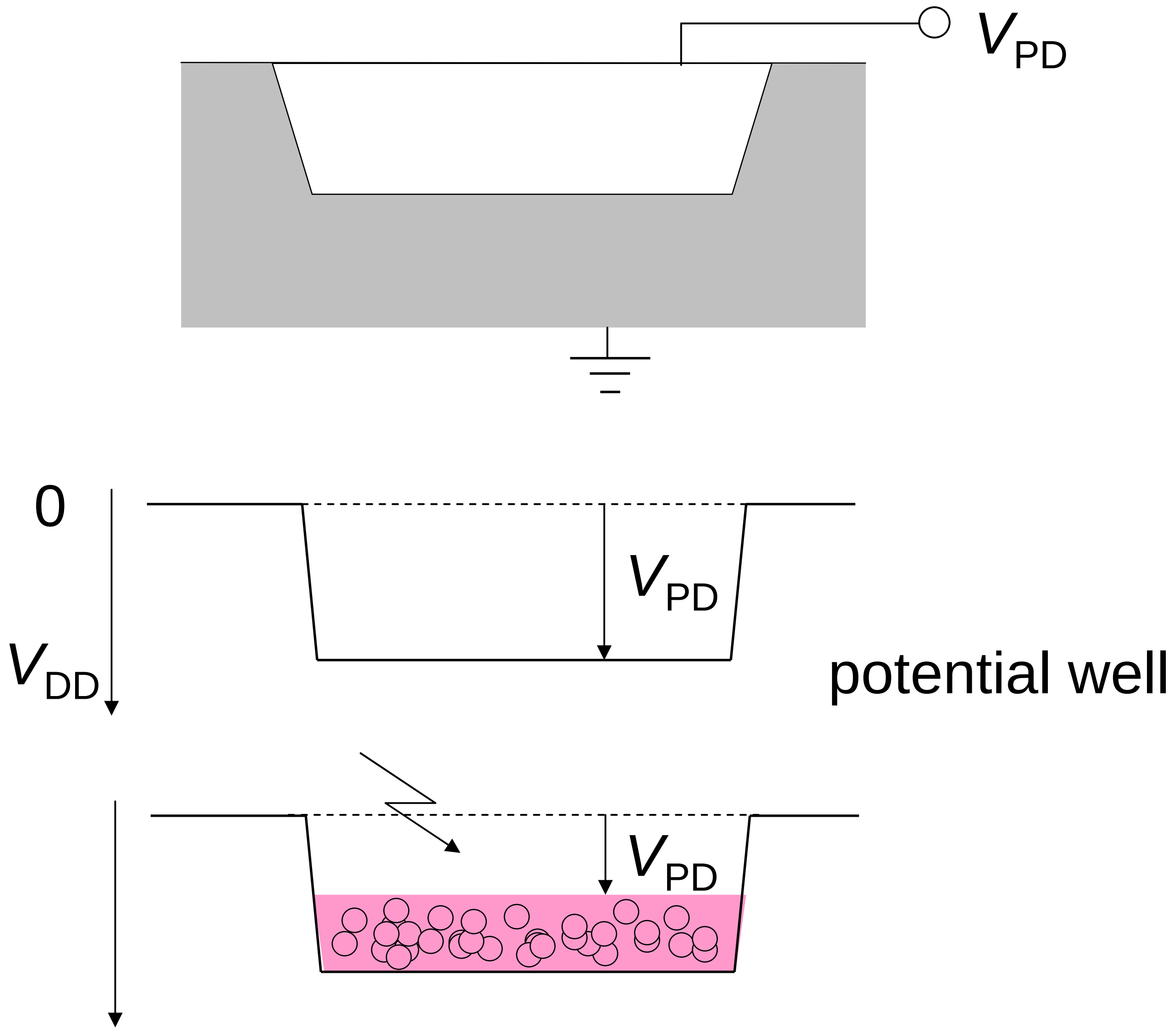


Schematic Description of Integration





Potential Description of Integration



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- Lens and Optical Parts
- Image Sensors
  - CCD / CMOS sensors
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CCD and CMOS image sensors

CCD sensors	CMOS sensors
Special fabrication process	Standard CMOS process can be used (but special process is also used for high quality)
Large power dissipation (multiple high voltage required)	Low power consumption (single CMOS level voltage)
Difficult to be integrated with computational functionality	Easy to be integrated with CMOS processing circuits
High image quality - high cost	Varies from low quality – low cost to high quality – high cost

CCD and CMOS image sensors

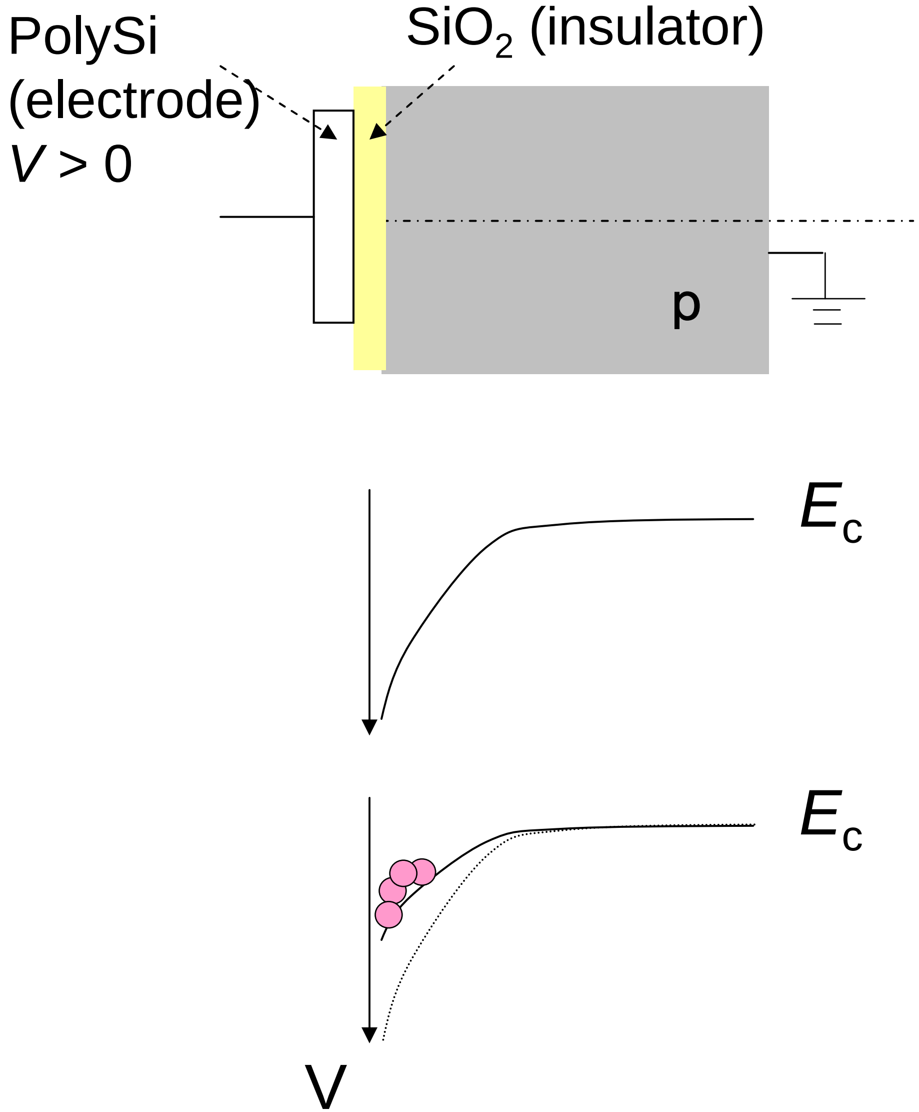
CCD: Charge-Coupled Devices
CMOS: Complementary Metal-Oxide-Semiconductor

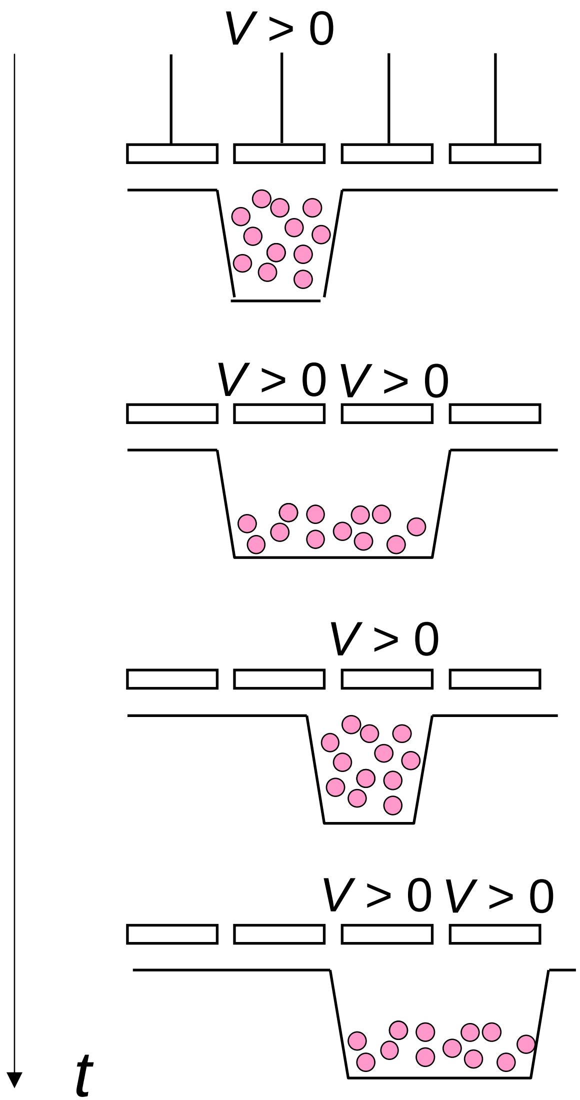
- These terms do not refer to photo detecting structures!
- Fundamental difference is “how to readout the signal charge amount”

CCD sensor: $$\underbrace{h\nu \longrightarrow Q}_{\text{within pixel}} \longrightarrow V$$

CMOS sensor: $$\underbrace{h\nu \longrightarrow Q \longrightarrow V}_{\text{within pixel}}$$

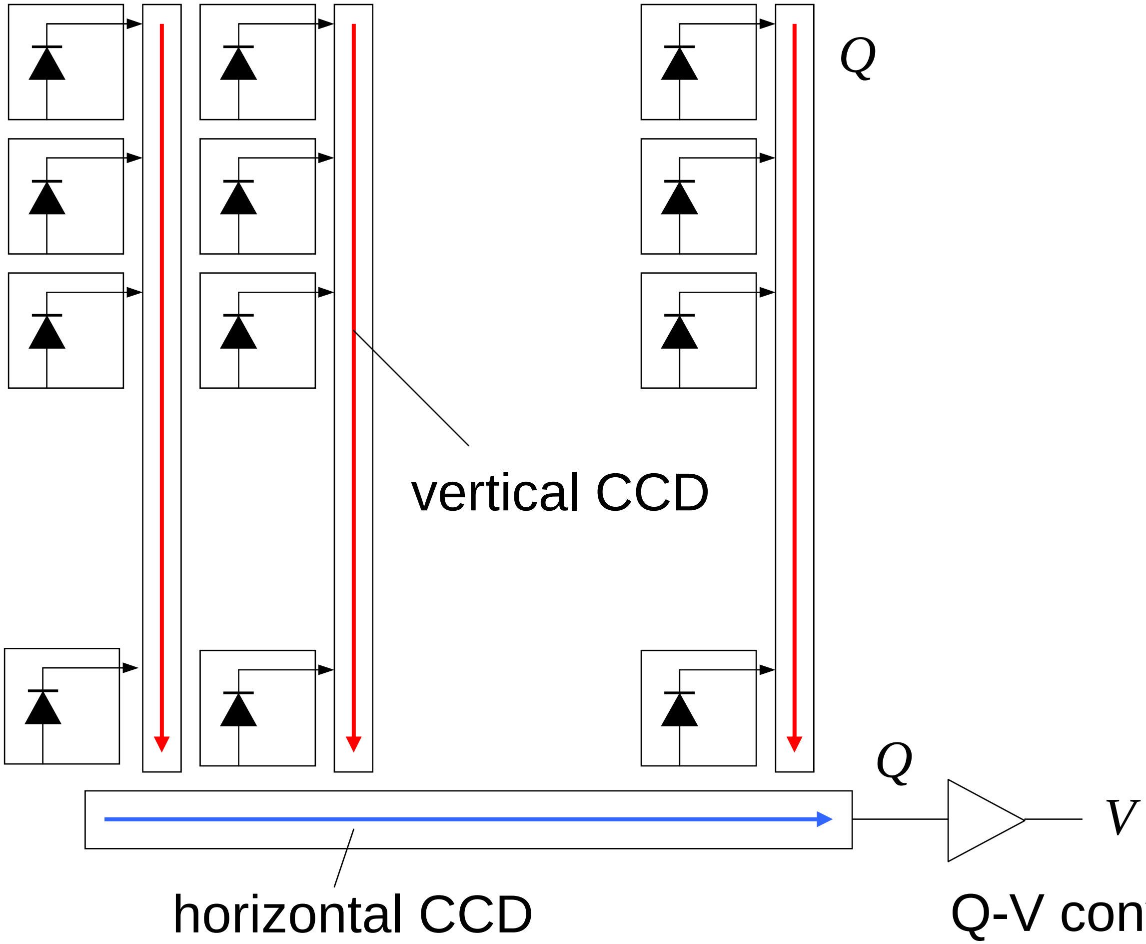
CCD (Charge-Coupled Device)



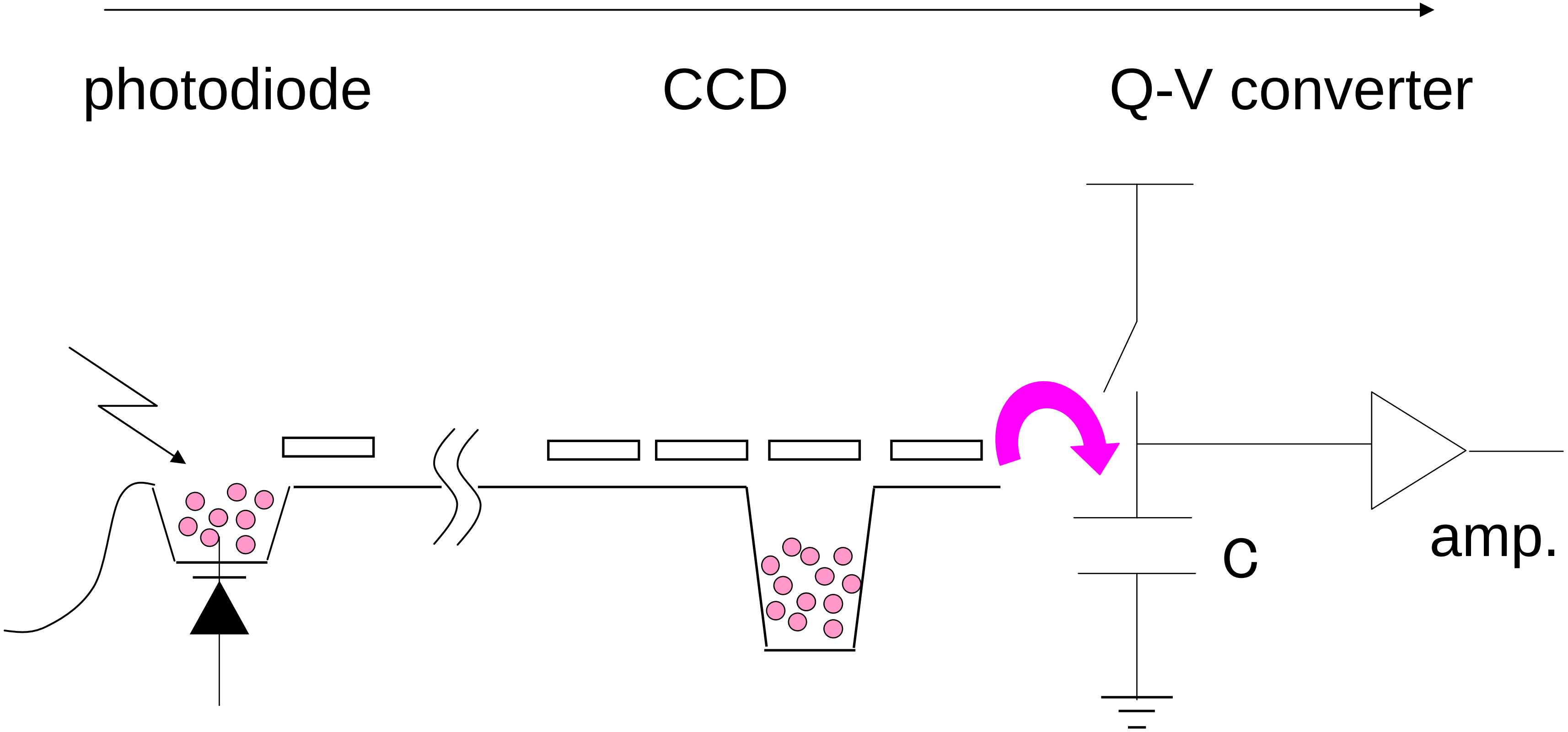


CCD Image Sensor

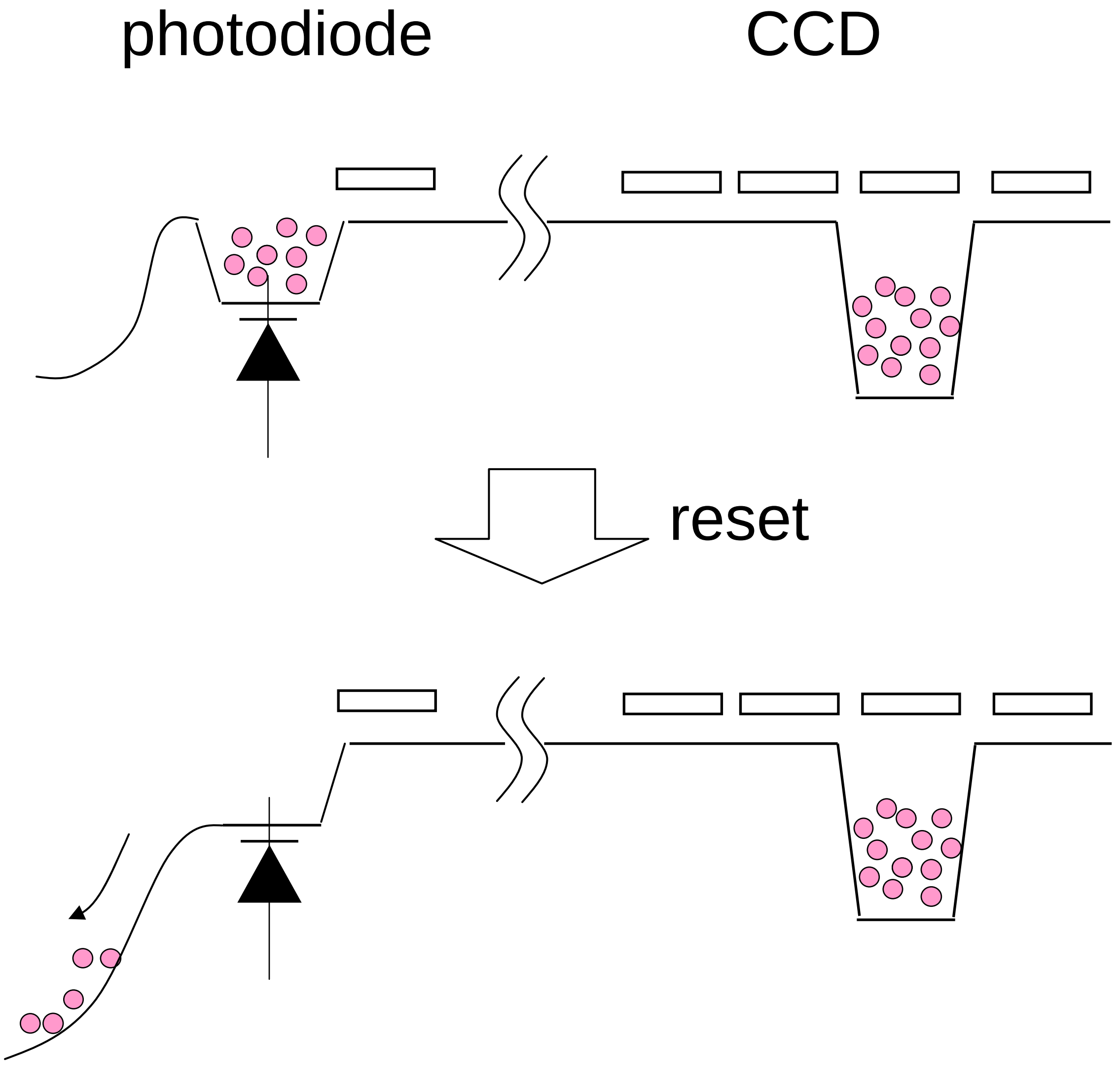
Interline Transfer CCD (IT-CCD)



Signals in a CCD sensor

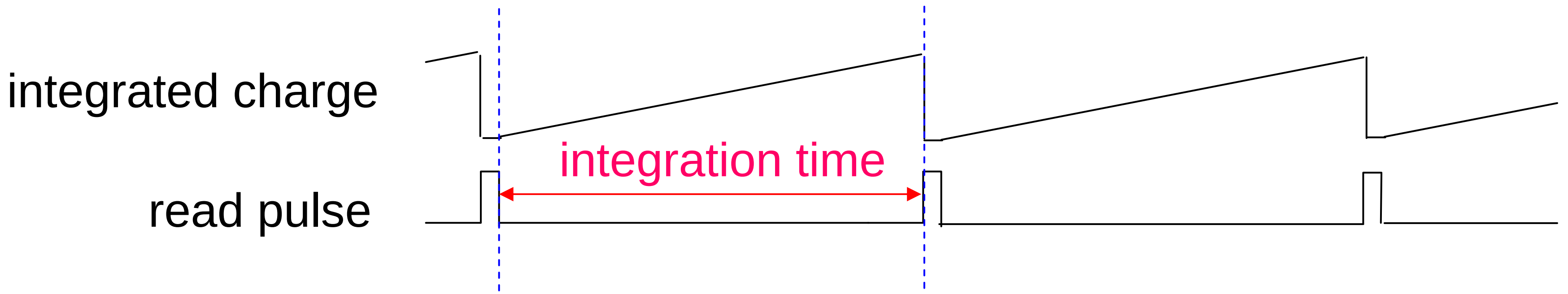


Resetting in IT-CCD

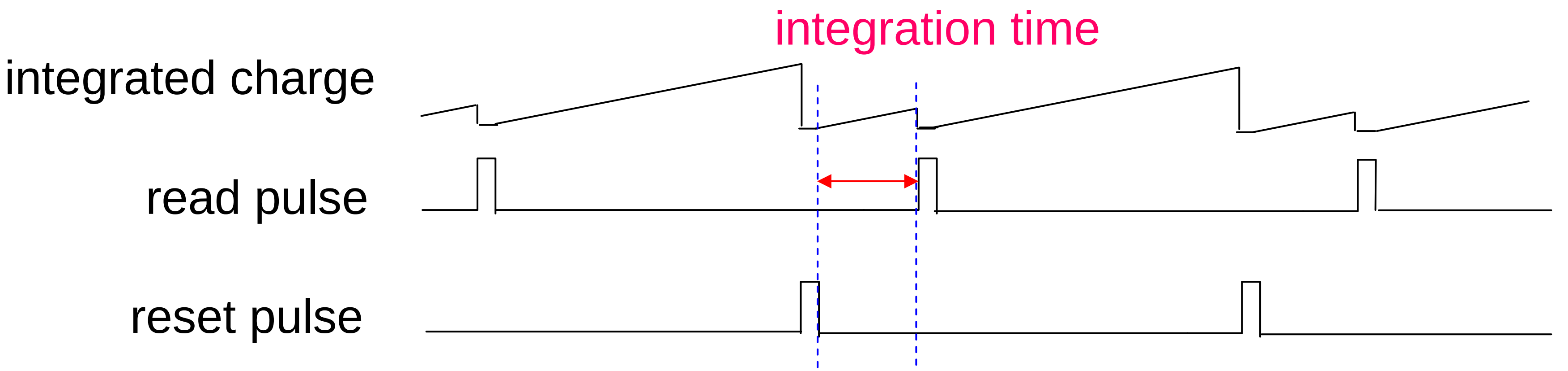


Electronic Shutters in CCD

IT-CCD (w/o electronic shutter):

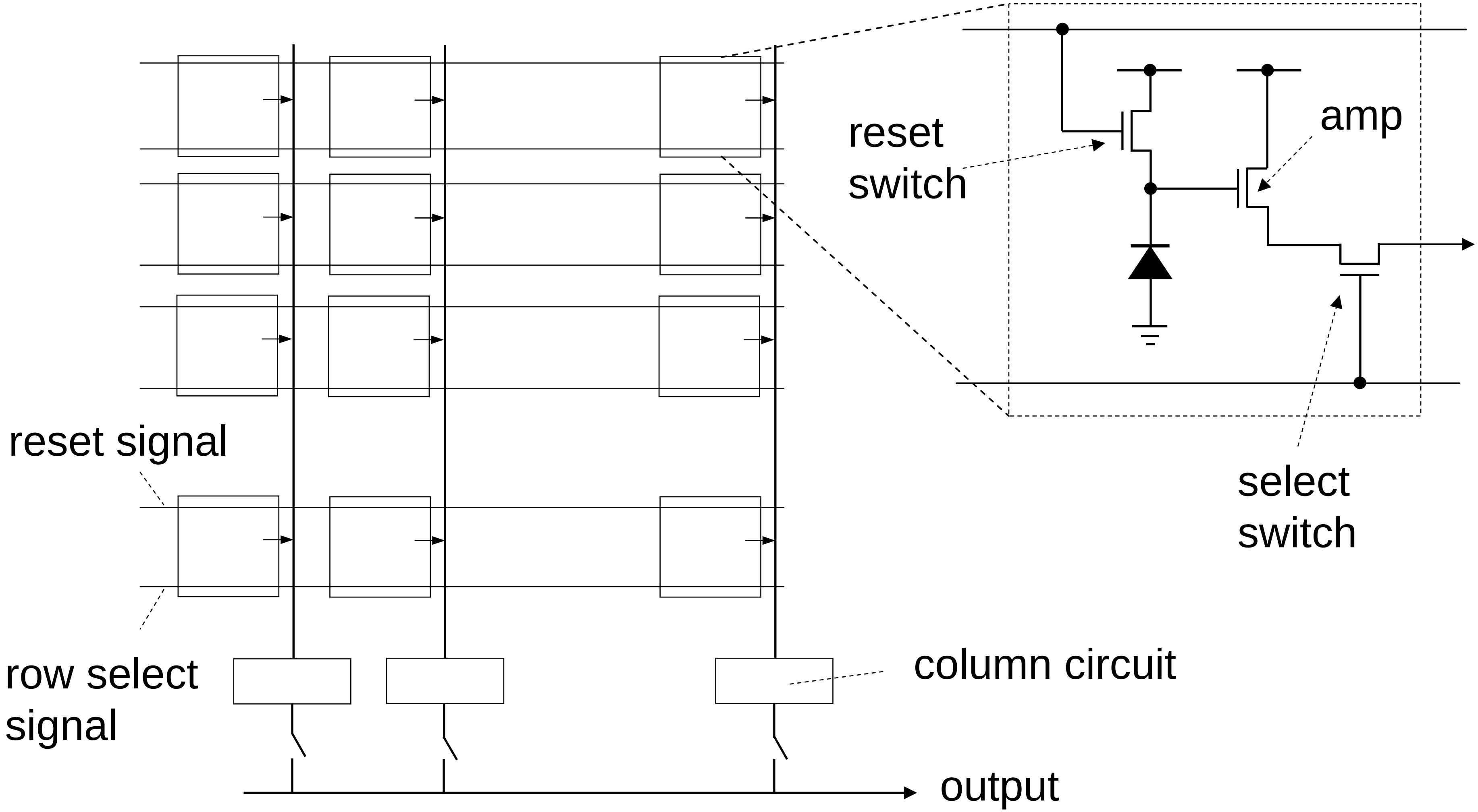


IT-CCD (with electronic shutter):

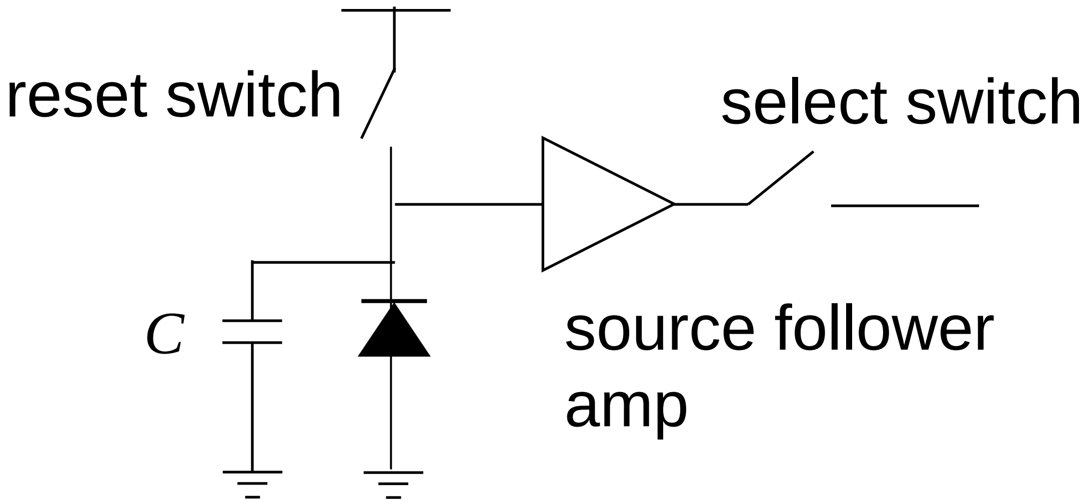


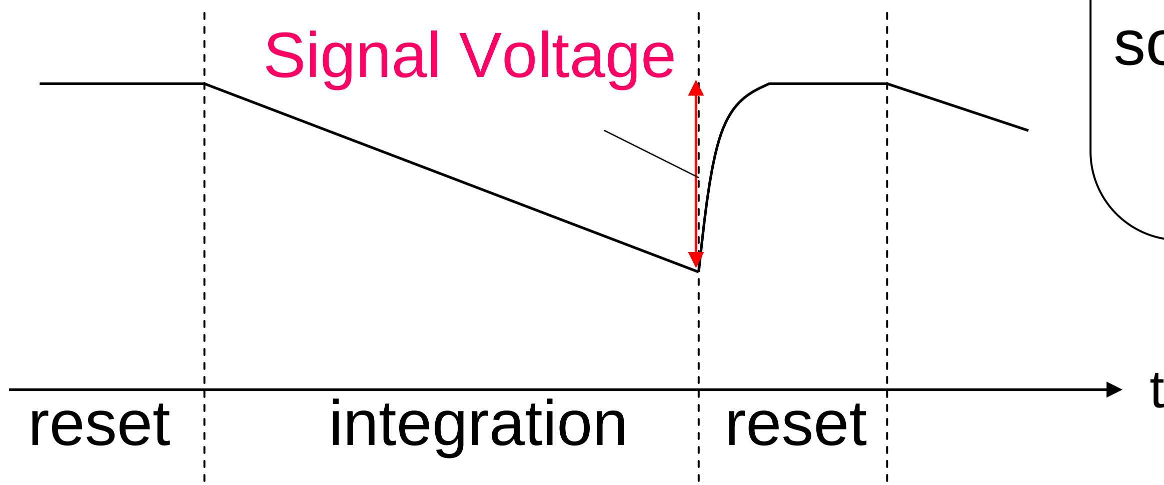
CMOS Image Sensor

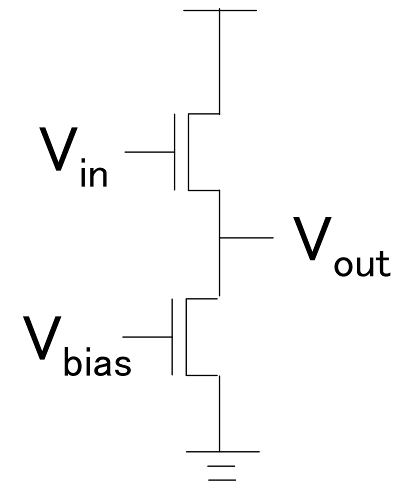
3-transistor Active Pixel Sensor (3T-APS)



Signals in a CMOS sensor





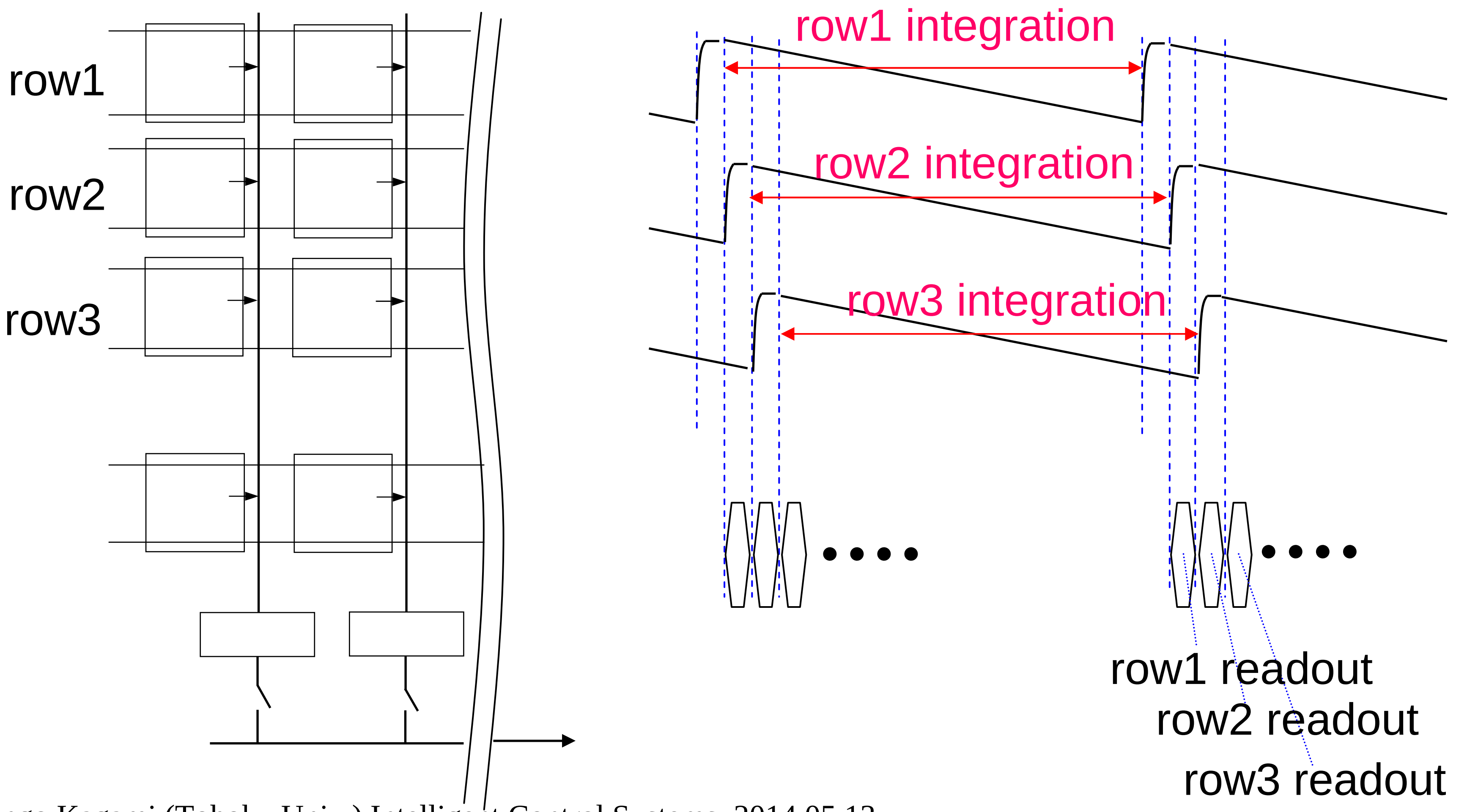


source follower:

- $V_{out} = V_{in} + \alpha$

Shutter Modes

While IT-CCDs operate in the global shutter mode,
3T-APS CMOS sensors operate in the rolling shutter mode



Rolling Shutter Example

A spinning propeller
taken by an iPhone camera

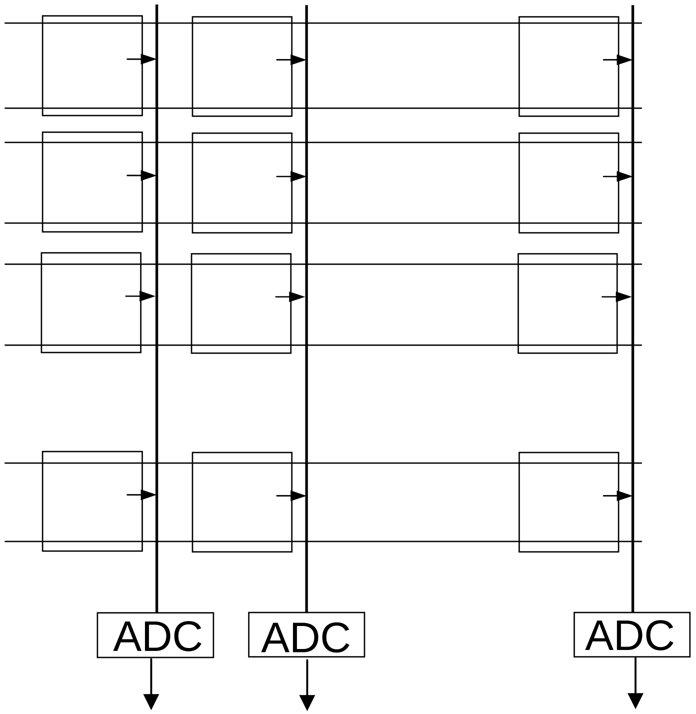
http://scalarmotion.wordpress.com/2009/03/15/propeller-image-aliasing/

Techniques for High-Speed Imaging

Parallel readout / Parallel ADC
- column-parallel
- column-parallel x 2 (upper and lower)

Readout Modes
- sub frame, sub sampling
- binning (neighbor pixels are concatenated)
- (semi-)random access

Low-noise / High-sensitivity pixels
- micro lens
- back-illuminated sensor



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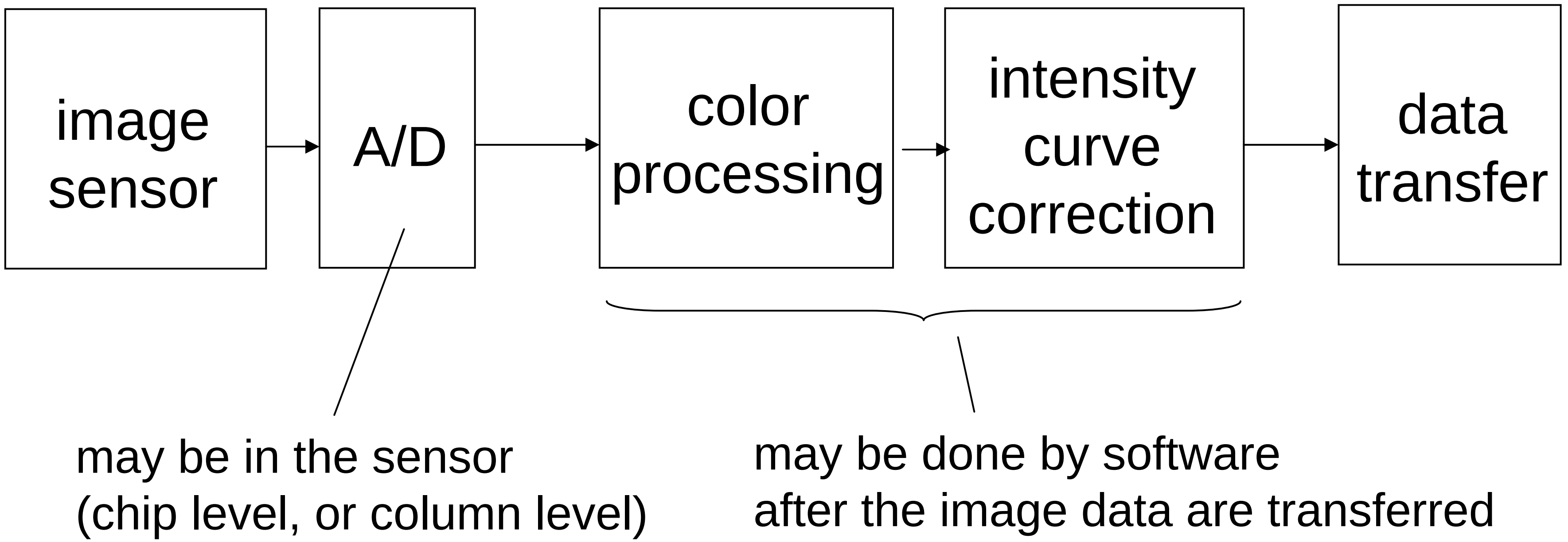
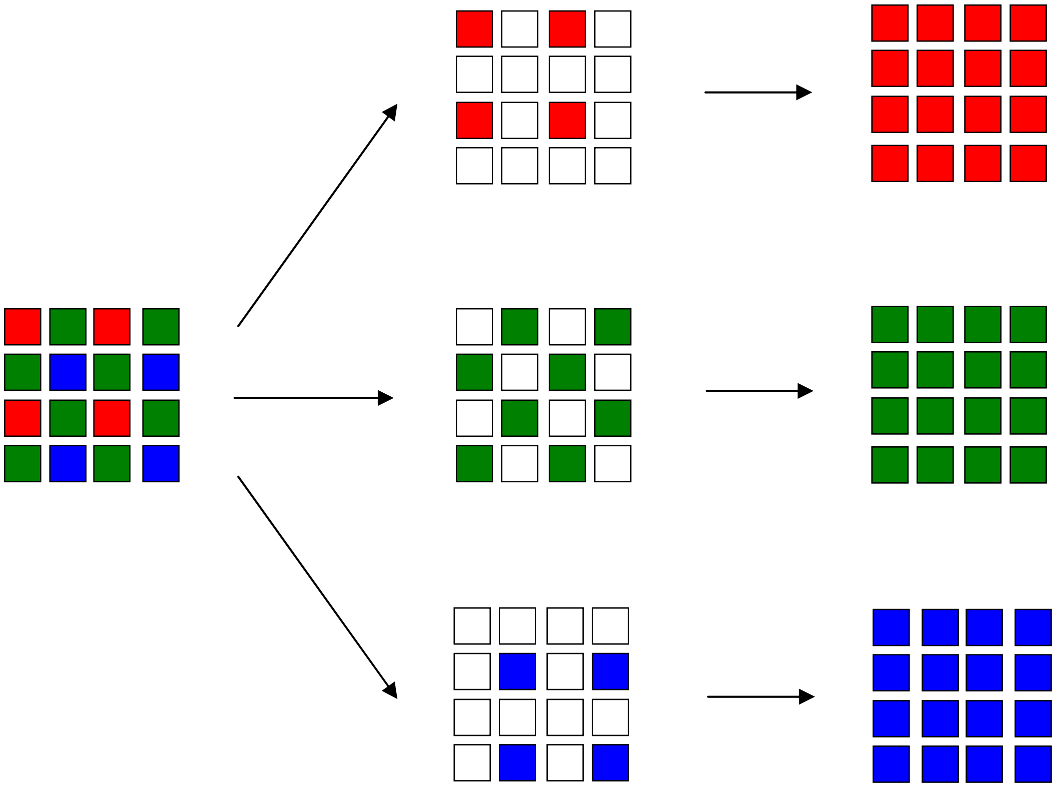
In-Camera Processing

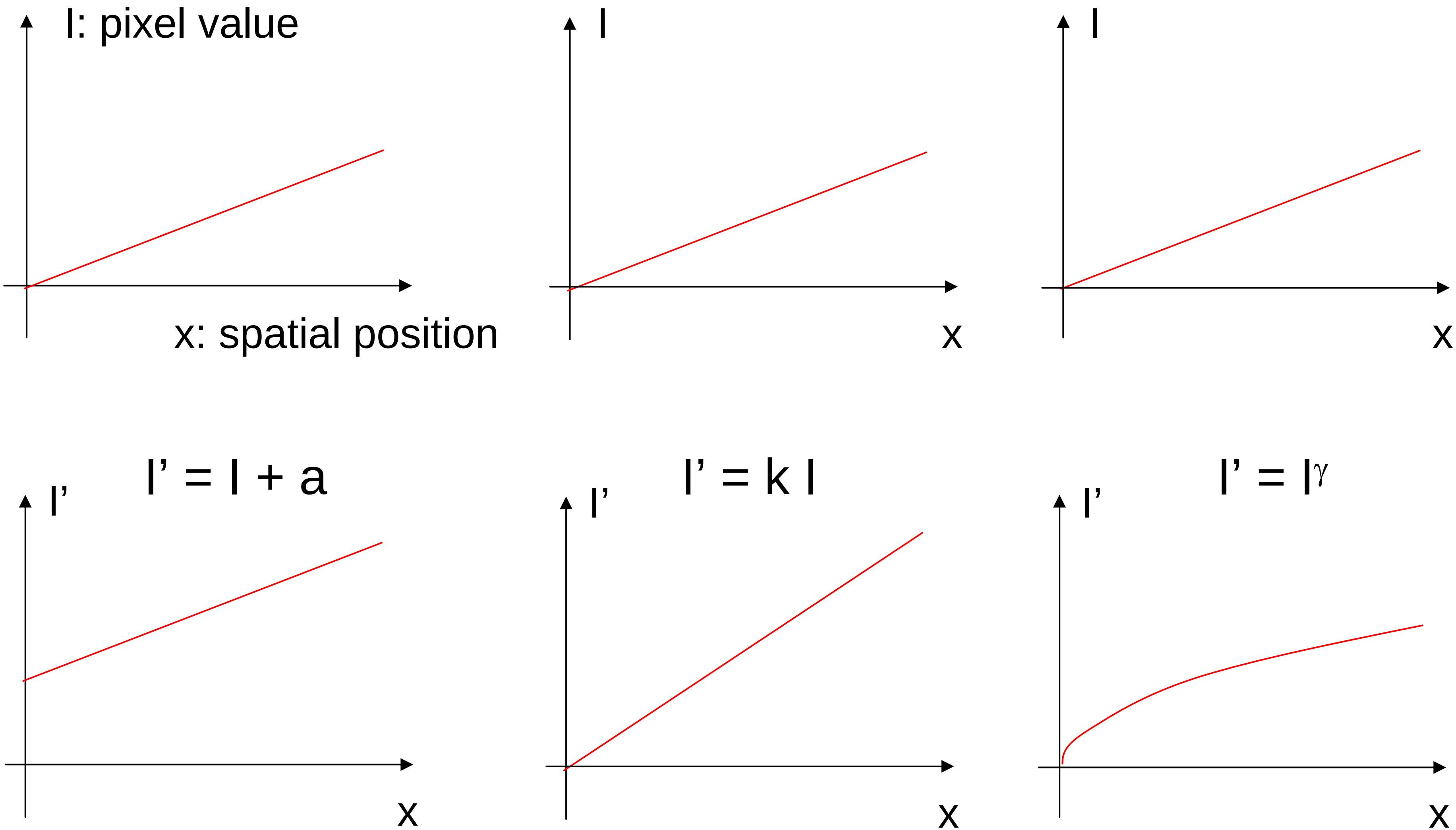


Color Processing (demosaicing)



- Can be done by software; but it takes computation time
- Can be done in camera; but it consumes 3 times transfer bandwidth

Brightness, Contrast, and Gamma



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Data Transfer

8 [bits/pixel] $\times$ 1 M [pixels/frame] $\times$ 30 [fps] = 240 M [bps]

8 [bits/pixel] $\times$ 1 M [pixels/frame] $\times$ 1000 [fps] = 8000 M [bps]

interface	max. bit rate
IEEE 1394a	400 Mbps
IEEE 1394b	800 Mbps
USB 2.0	480 Mbps
USB 3.0	5000 Mbps
Gigabit Ethernet	1000 Mbps
PCI Express 3.0	8000 Mbps / lane
Camera Link	2000 Mbps (base config.) 5440 Mbps (full config.) and more (extended config.)

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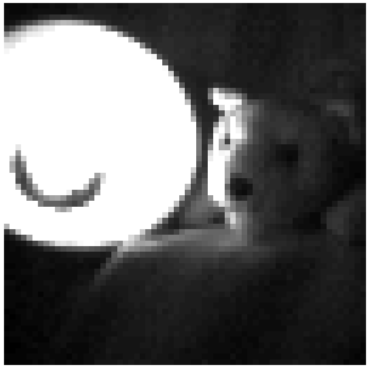
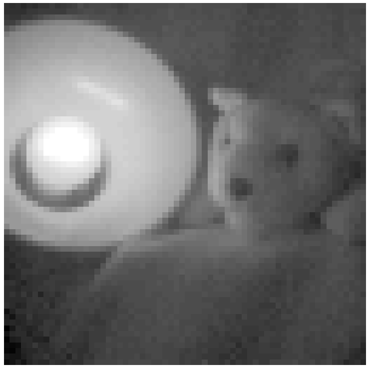
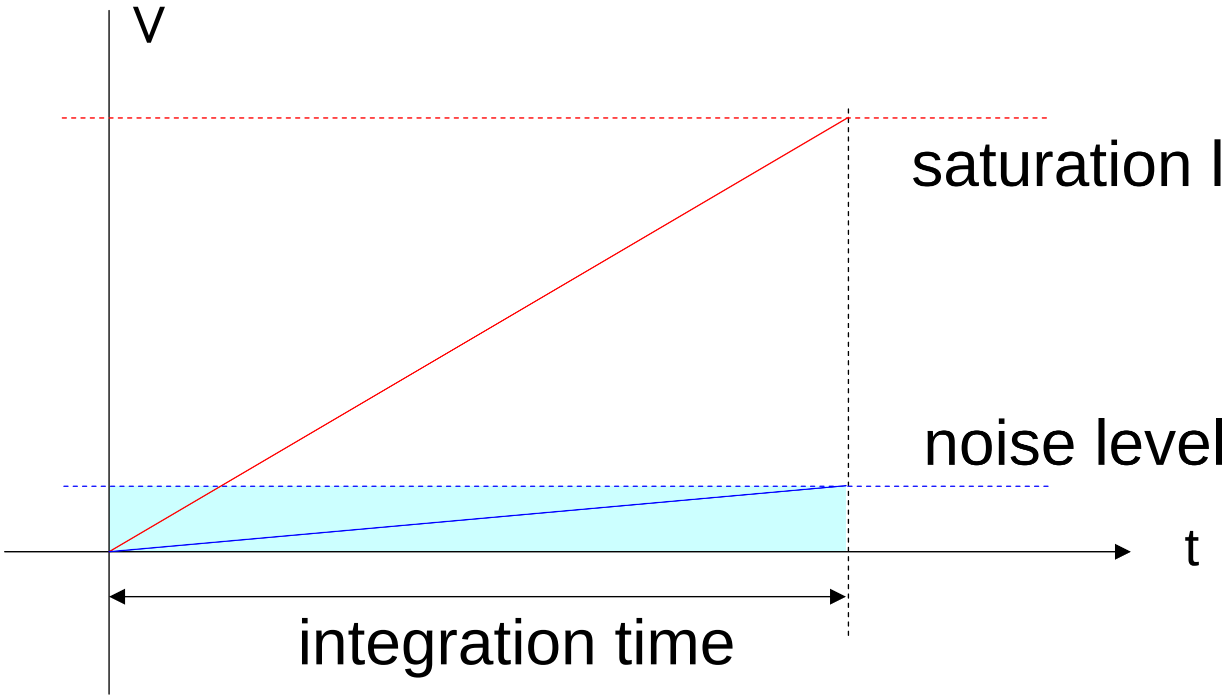
Dynamic Range

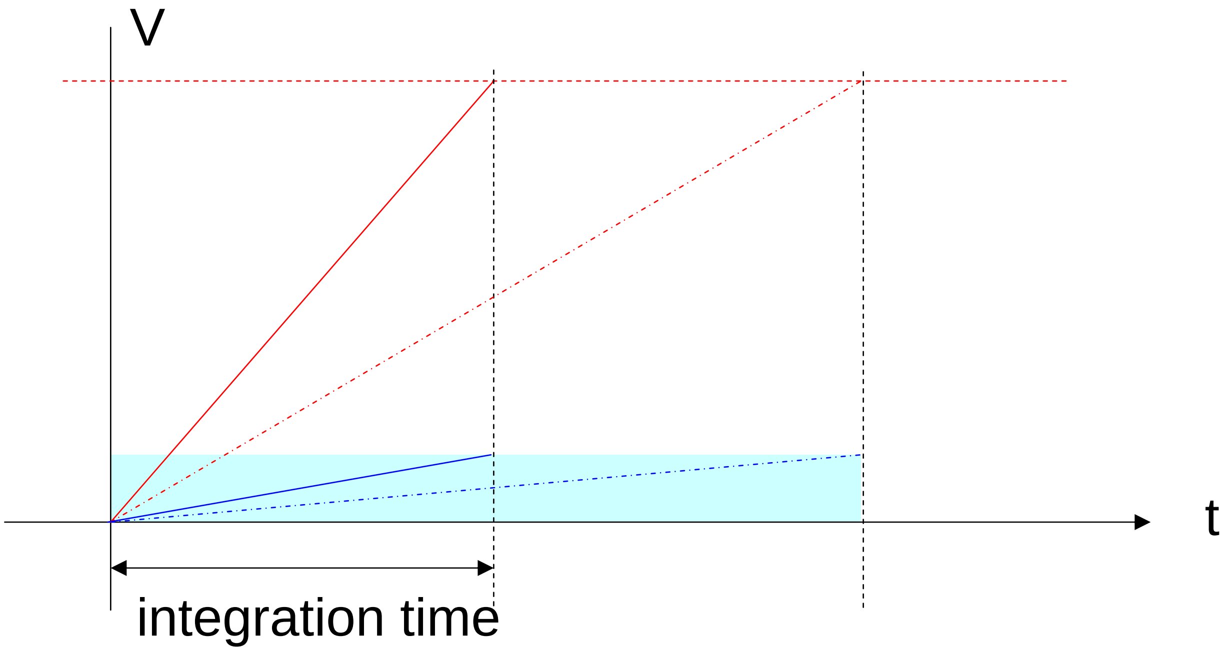
$$\mathrm{DR}\,[\mathrm{dB}] = 20\log\frac{i_{\mathrm{upper}}}{i_{\mathrm{lower}}}$$







Dynamic range and Integration time

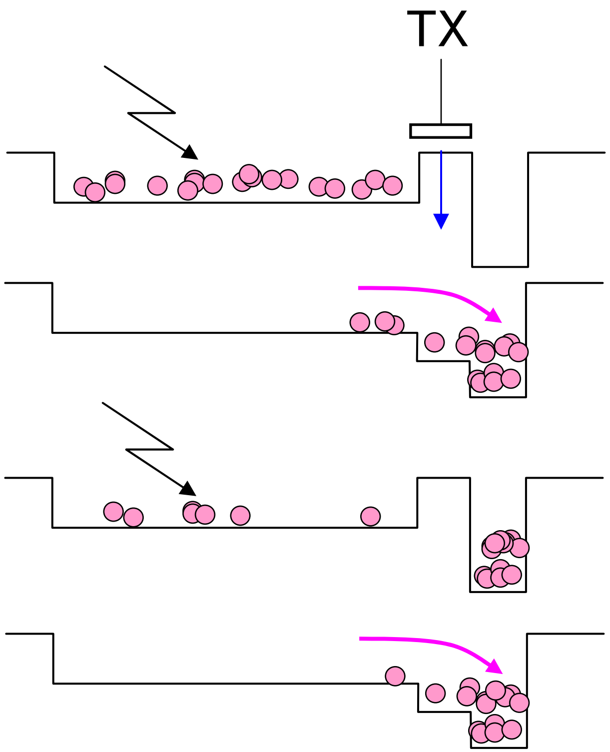


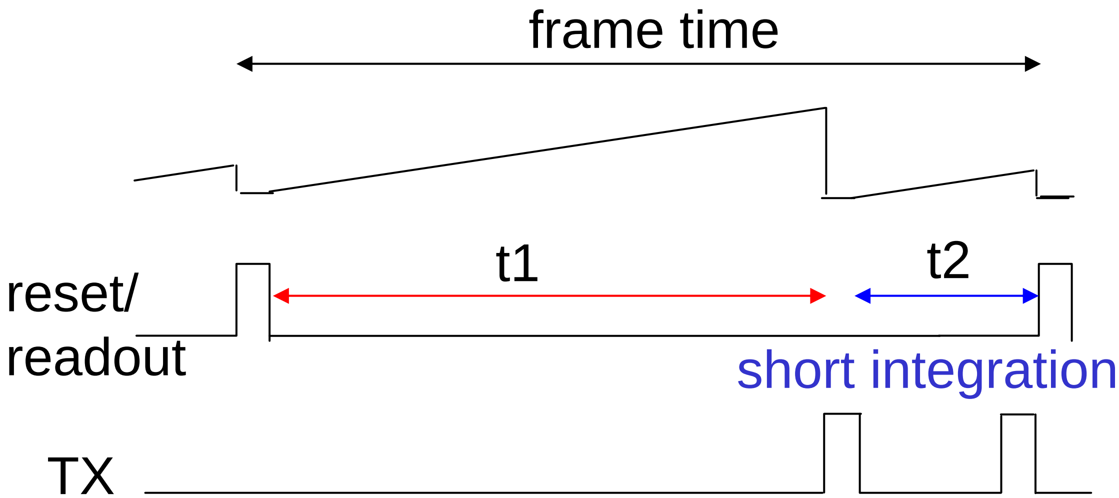
Simply modifying the integration time will not contribute to dynamic range enhancement.

Commonly used techniques utilize multiple integration times.

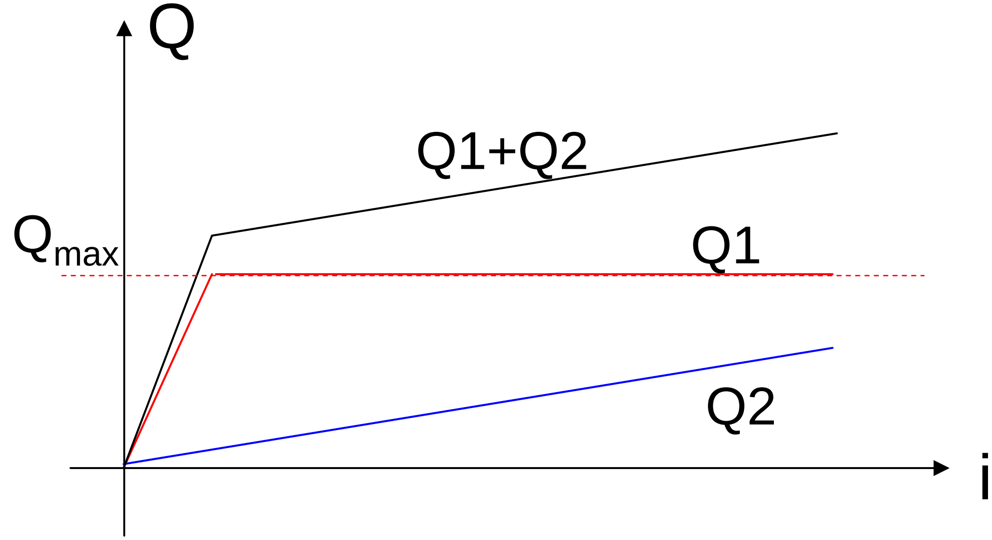
Dynamic Range Enhancement Example

MT9V403, Micron Technologies





$$Q_1 = \max(Q_{\max}, it_1)$$
$$Q_2 = \max(Q_{\max}, it_2)$$
$$Q = Q_1 + Q_2$$



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