Detectors:

The purpose of astronomical detectors is generally to receive photons from an astronomical source and produce some corresponding signal.

Qualities of a detector:

Detection Mode

- Photon detectors produce signal based on number of incoming photons. Suited to IR or shorter wavelengths where photon energy is large compared to thermal energy of electrons in the detector. These include photographic film/plates, photomultipliers, and CCDs.
- Thermal detectors produce a signal based on the energy of the incoming photons. In this case, the signal is the temperature change in the body of the detector. Includes bolometers, especially used in IR, X-ray, γ-ray.
- Wave detectors measure the oscillating electric or magnetic field of EM waves, usually based on interference effect on wave produced by a local oscillator. These are "coherent", they preserve phase and even polarization. Usually used in radio and microwave.

Efficiency:

- Quantum Efficiency (QE) - number of incoming photons that contribute to signal

$$QE = \frac{N_{detect}}{N_{in}}$$

why would a detector be inefficient?

- photons reflected, pass through, absorbed by non-detecting area

Photographic emulsions have QE of 0.5-5%, modern solid state devices have 20-95%.

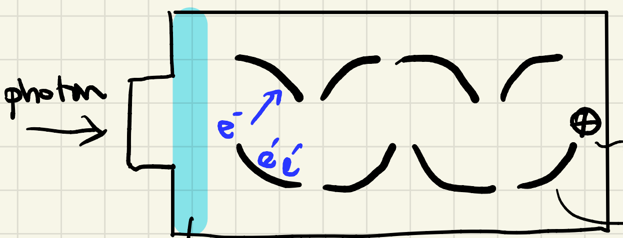
Types of detectors:

Bolometers:

- these are total power, or energy, detectors
- they have a coiled wire which heats up with the incident flux
- as the wire heats, the resistence changes with a current through the wire
- so the wire tells something about the incident energy flux
- often used in radio/millimeters

Photomultiplier Tube (PMT):

- start w/ 1 e^-, it accelerates to dynode and knocks 2-10 more, these go to next dynode and so on



anode, positively charged electrode where e^- leave device

dynode, electrode w/ more positive electric potential

photocathode
(turns photons to e^- via photoelectric effect, i.e. photons come in and knock e^- of of surface)

MAMA on HST is variant of this

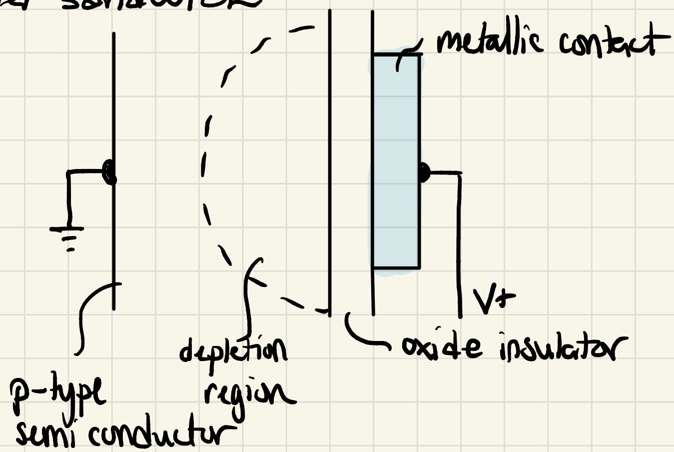
Charge Couple Devices (CCDs):

CCDs are the most common optical detectors.

- Preferred for low noise (2-10 e^- per pixel compared to >200 previously), good QE (photographic plates had ~2%, modern CCDs get to 90-95%) and good bandpass (3,000 – 11,000 Å).
- use in optical is because of physical properties of Silicon from which they're made. → Silicon has 1.1eV bandgap and easily absorbs 1.1eV < E < 4.0eV photons (optical λ)

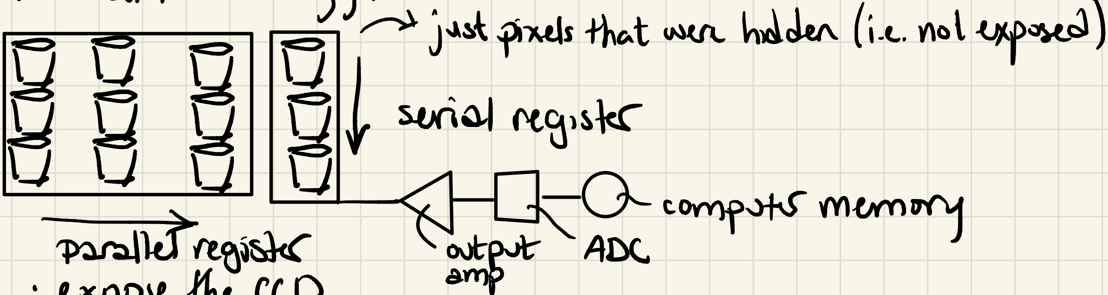
Metal-oxide-semiconductor (MOS) capacitors:

- Basic element of a CCD, each pixel gets one
- 3-layer sandwich



- p-type semi-conductors have been doped (i.e. impurities are added). Since Silicon has 4 electrons, doping with Boron or Aluminum which have 3 effectively creates an electron "hole". This lets the electron move around.
- The energy structure of this device makes electrons produced by ionization stream towards the insulator and stay
- this acts as a well to store electrons generated by ionization during an exposure
- the "full well" is the number of electrons you can store, typically 25,000-500,000. Determined by pixel size.

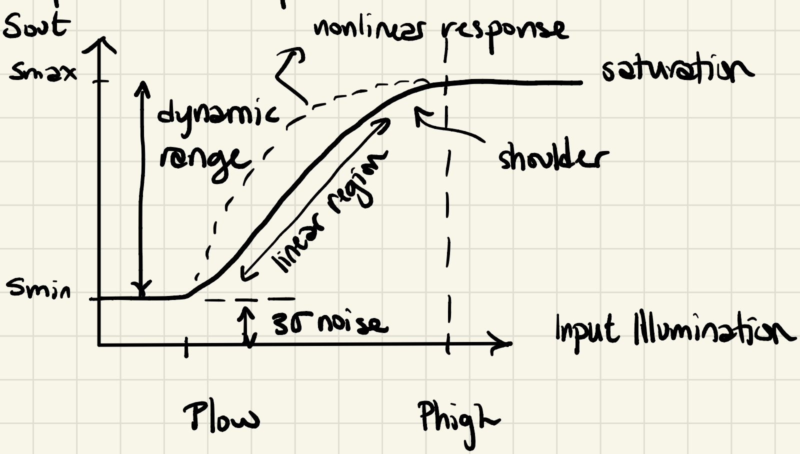
Rain bucket analogy:



- expose the CCD
  - photon collection method: photoelectric effect
  - collect charges in the MOS potential wells
- manipulate (clock) voltage to read out CCD one column at a time (this is why they're called CCDs)
- pass the charge packets in serial fashion to the readout electronics to detect and measure
  - measure as a voltage, use an amplifier
  - convert voltage to a digital number to be stored in computer memory, job of analog-to-digital converter (ADC)
  - electrons are related to counts or Analog digital units (ADU) by the gain → the number of e^- needed to produce 1 ADU.

Linearity and Dynamic Range:

Ideally, the detector linearlly translates photons into signal, but departures are common. It's not a problem if the relation between input and output is known.



- zB. a CCD with a full well of 300,000 is equipped with a 16-bit ADC. You can have digital outputs between 0 and $2^{16}-1 = 65,535$.

$G = 2 \Rightarrow 65,353 \cdot 2 \approx 130,000$ not taking full advantage of full well depth

$G = 5 \Rightarrow 65,353 \cdot 5 \approx 327,000$ prone to saturation, spill-over

Stastical Techniques for Estimating Error

Source: Chromey Ch. 2

- accuracy tells how close an answer is to the truth (which can be difficult to assess when the truth is not known)
  - systematic error characterizes accuracy
- precision tells how well an answer is known (i.e. how specific is an answer?)
  - random error characterizes precision

Accuracy and precision both contribute to estimating uncertainty.

Populations:

It is useful to think about populations when trying to determine a parameter. If the population is the hypothetical set of all possible measurements, then you can sample the population by taking a finite number of actual measurements.

The mean, median, and mode are measurements of a populations "center". For a sample,

$$\mu = \lim_{N\to\infty} \frac{1}{N}\sum_{i=1}^{N} x_i = \lim_{N\to\infty} \bar{x} \quad \text{and} \quad \bar{x} \approx \mu$$

$\bar{x}$ → sample mean; μ → pop. mean

The variance is a measure of the width:

$$s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

The square root of the variance is the standard deviation of the sample. This is often referred to as just "the standard deviation" or σ, so use context to distinguish from the population standard deviation.

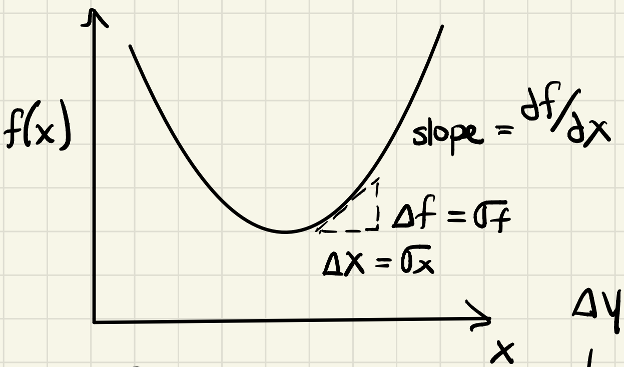
Propogating Uncertainty

If measurement uncertainties are Gaussian distributed, then combinations of uncertainties may be expressed analytically and are Gaussian.

For a function, $f(x,y)$, the uncertainty, σ_f, on f in terms of the uncertainties σ_x and σ_y on x and y is:

$$\sigma_f^2 = \left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2 + \underbrace{\frac{\partial f}{\partial x}\frac{\partial f}{\partial y} \cdot 2\sigma_x\sigma_y}$$

covariance is 0 if uncertainty in x and y is uncorrelated



$\Delta y = m\Delta x$

$\hookrightarrow \sigma_f = \left|\frac{\partial f}{\partial x}\right| \sigma_x$

z. B.

$$f(x,y) = Ax + By$$

$$\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}(Ax + By) = A$$

$$\partial f/\partial y = \frac{\partial}{\partial y}(Ax + By) = B$$

$$\Rightarrow \sigma_f^2 = A^2\sigma_x^2 + B^2\sigma_y^2$$

Probability Distributions

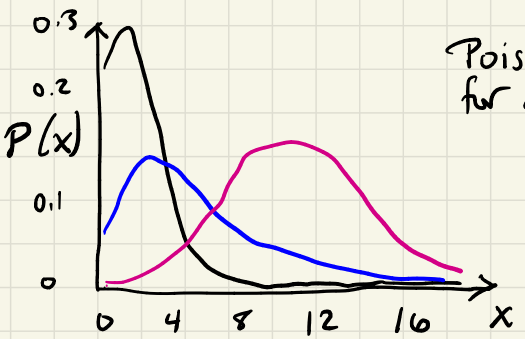
Assume you have a large population Q. If you make a selection/measurement of this distribution, it is called a trial. The thing you measure is called the random variable, x.

Q – population
x – random variable (what is your population of?)
$P_Q(x)$ – probability of x in Q, describes how likely a single trial is to yield a value x

Poisson Distribution

The Poisson distribution describes the population that you encounter in counting experiments – it is especially relevant for counting photons.

$$P_P(x, \mu) = \frac{\mu^x}{x!} e^{-\mu}$$



Poisson distribution for different μ.

$$\sigma_P^2 = \mu$$

· variance = mean for Poisson → gets wider as mean gets bigger

This is important. Imagine you are counting the photons, N, that arrive at your detector. If you count N in a single trial, you can estimate that the average result of a single trial of duration t seconds will be

$$\mu \approx \bar{x} = N$$

How uncertain is this result? Estimate it with the standard deviation of the population from which you sampled:

$$\sigma^2_{poisson} = \mu \Rightarrow \sigma_{poisson} = \sqrt{\mu} \approx \sqrt{N}$$

fractional uncertainty in counted photon events

$$= \frac{\sigma_{poisson}}{\mu} \approx \frac{1}{\sqrt{N}}$$