Properties of a Detector

**Quantum Efficiency**
- fraction of photons detected
- wavelength and spatially dependent

**Dynamic Range**
- difference between lowest and highest measurable flux

**Linearity**
- detection rate should scale linearly with photon flux

**Noise:**
- Low noise on measured signal
- Low background noise

**Stability**
- repeatable measurements and calibration

**Spatial dynamic range**
- combination of pixel size and detector area
The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

*Does such a thing exist?*
The Perfect Detector

• Counts every photon it receives.
• Notes the photon’s position and energy.
• Has uniform wavelength and spatial response.
• Has a linear response.
• Has no noise.
• Has a high dynamic range.

Human Eye?
The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Photographic Plate?
The Perfect Detector

- Counts every photon it receives.
- Notes the photon’s position and energy.
- Has uniform wavelength and spatial response.
- Has a linear response.
- Has no noise.
- Has a high dynamic range.

Charge Coupled Device (CCD)
Charge Coupled Devices (CCDs)

Consider a silicon crystal semiconductor, where the electrons live in discrete energy bands.

Electrons in the low energy **valence bands** are locked in place in the crystal lattice and cannot move.

If you add energy (ie absorb a photon), an electron can jump into the **conduction band**, where it is free to move around the lattice.

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap</th>
<th>$\lambda_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>1.1 eV</td>
<td>11,000 Å (1.1μ)</td>
</tr>
<tr>
<td>Germanium</td>
<td>0.67 eV</td>
<td>18,000 Å (1.8μ)</td>
</tr>
<tr>
<td>InSb</td>
<td>0.18 eV</td>
<td>6.7μ</td>
</tr>
</tbody>
</table>

So the material used sets the **wavelength coverage** and **noise characteristics** of the CCD.
Silicon absorption

![Graph showing the absorption length of silicon as a function of wavelength. The x-axis represents wavelength in micrometers (μm), and the y-axis represents absorption length in micrometers (μm). The graph shows an increasing trend as the wavelength increases.]
Front (thick) and Back (thin) Illuminated CCDs

CCD consists of a layer of nearly pure silicon covered on one side (front) by electronic gates that control the movement of the photoelectrons.

In front illuminated chips, the photons go through the gate structures before being absorbed. This lowers the quantum efficiency, particularly in the blue.

In back illuminated chips, the photons avoid the gates (raising QE), but they need to be thinned so that the absorption happens close to the gates.
Quantum efficiency
Each pixel consists of gates which have voltages applied to keep the electrons in place during the exposure.
CCD pixels

Each pixel consists of gates which have voltages applied to keep the electrons in place during the exposure.

A pixel can hold a maximum accumulated charge (full well capacity or saturation). If exceeded, charge will bleed out to adjacent pixels.
CCD Operations:
Reading out and the bucket analogy.
CCD pixels and charge motion ("clocking")

Charge transfer efficiency

The fraction of electrons which are successfully transferred at each step.

You want $CTE \geq 0.99999$ or so!
CCD Readout Electronics

Amplifier(s)

- converts the read-out charge to a voltage
- adds a **bias** or **pedestal** value to the signal to avoid negative numbers (don’t want to waste a digital bit on the sign; improves dynamic range.)

Analog to Digital Converter(s) (A/D Converters)

- turns output voltage into **counts**, aka “analog/digit units” (**ADU**)
- characterized by a **gain** measured in $e^-/ADU$.

Readout Noise

- CCD electronics inserting spurious electrons into the stream.
- conversion from analog signal to digital number is not perfectly repeatable.
- *faster readout usually produces higher readout noise*
- characterized as a certain number of electrons ($e^-$)
CCD Data Reduction: Conceptual Steps

Zero or Bias subtraction

Read out the CCD without exposing it to light. This shows the readout noise and any systematic spatial pattern associated with it.

Schmidt CCD readout noise is $3.6 \times 10^{-2}$ or about 1.4 ADU.

Schmidt 4Kx4K CCD zero image, showing fluctuations at the +/- 5 ADU level.
CCD Data Reduction: Conceptual Steps

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Schmidt CCD readout noise is $3.6 \times 10^{-2}$ or about 1.4 ADU.

By co-adding many zero images, you can beat down the readout noise (hopefully by $\sqrt{N}$) and see the underlying systematic pattern.

This pattern can be removed by subtracting the co-added zero from every image taken, but the basic readout noise of each pixel will remain.

25 co-added Schmidt 4Kx4K CCD zero images, showing fluctuations at the +/- 1 ADU level.
CCD Data Reduction: Conceptual Steps

Dark subtraction

Over the course of a long exposure, thermal electrons can jump from the valence band to the conduction band and introduce a thermal or dark current.

To correct for this, take long exposures (dark frames) with the CCD blocked from being exposed to light. This dark frame can then also be subtracted from all your images.

Most modern optical CCDs have very low dark current, but the problem is much worse with infrared CCDs.
CCD Data Reduction: Conceptual Steps

Flat fielding

The pixel-to-pixel sensitivity can vary across the image, and there can be large scale variations as well. Correct for this by making a flat field image using various techniques:

- **dome flat**: pointing telescope at a white screen on the dome
- **twilight flat**: pointing telescope at the twilight sky
- **dark sky flat**: co-adding many images of sparsely crowded night sky.

Normalize to an average value of one and divide science images by the flat field.

These sensitivity variations are wavelength dependent, so you must have a flat field taken through every filter you are observing with!
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*These sensitivity variations are wavelength dependent, so you must have a flat field taken through every filter you are observing with!*
CCD Data Reduction: Flat field features

- dust spot
- CCD blemish
- vignetting and large scale features
- bad columns
CCD Data Reduction: Conceptual Steps

Reduced Image = ( Raw image – Pedestal – Master Zero [ – Dark] ) / Flat