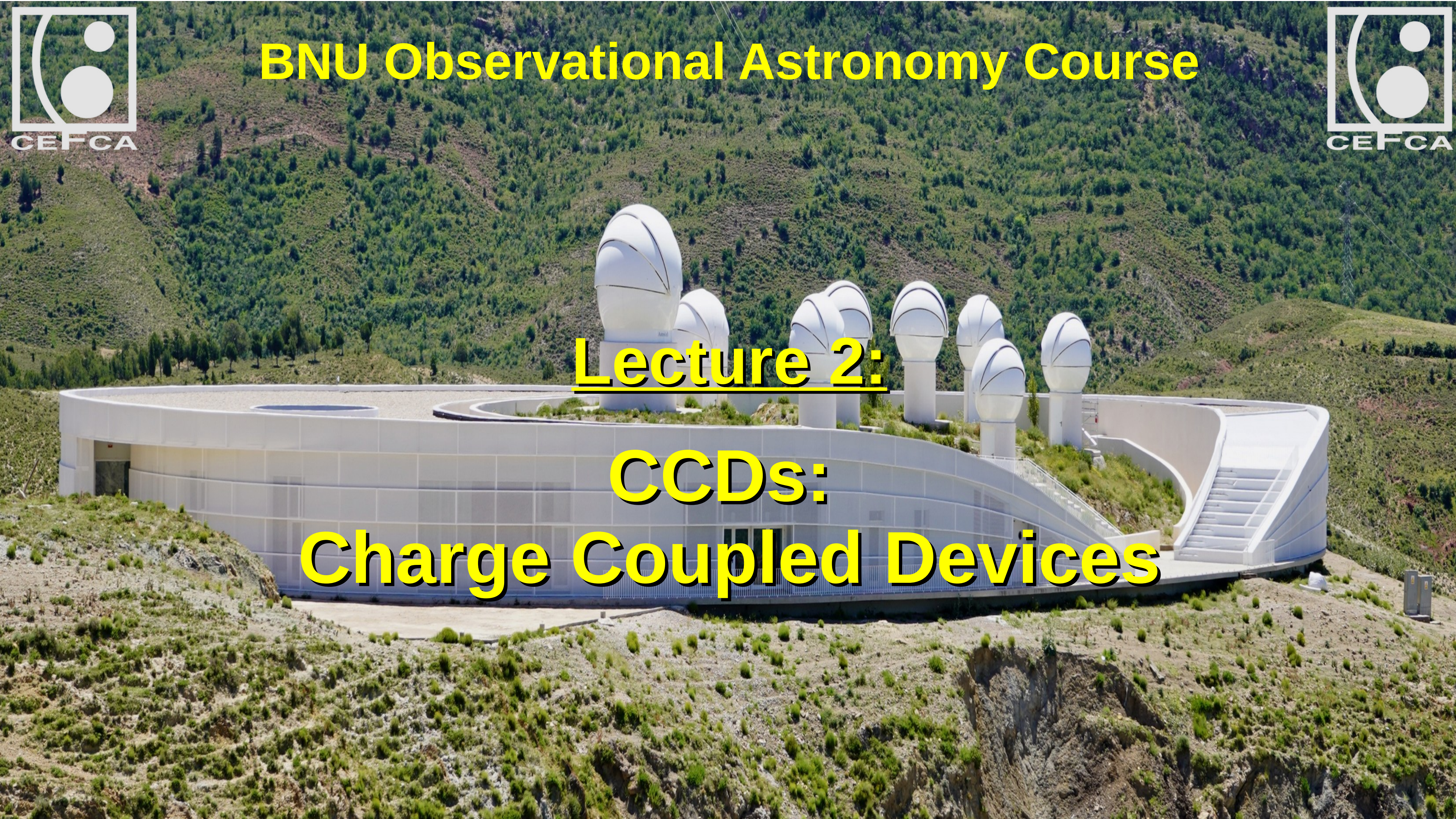
BNU Observational Astronomy Course

Lecture 2:

CCDs: Charge Coupled Devices

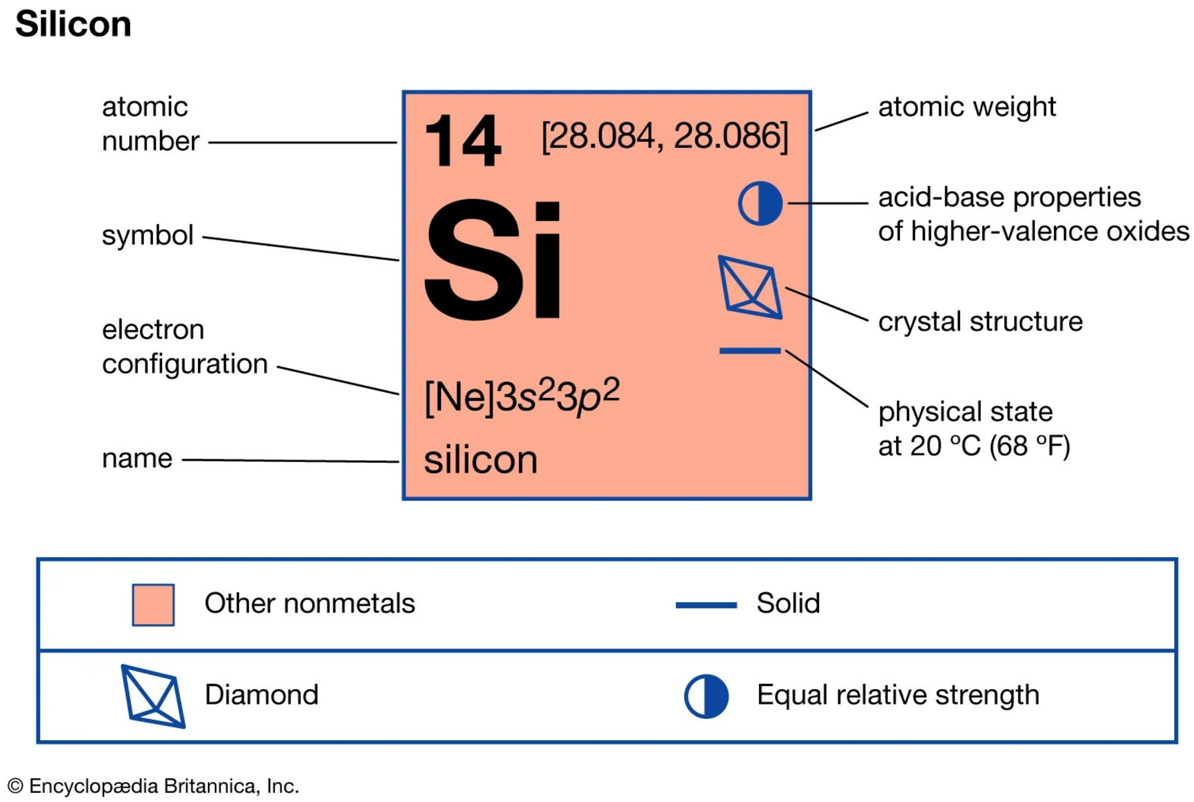


CONTENTS

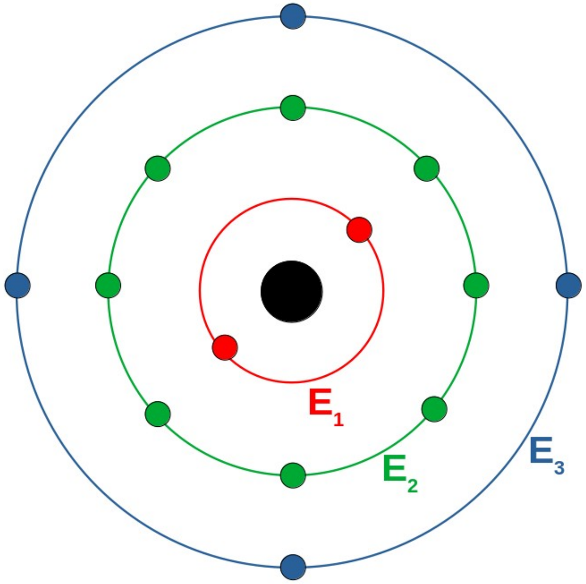
The basics

of Charge Coupled Devices

Silicon

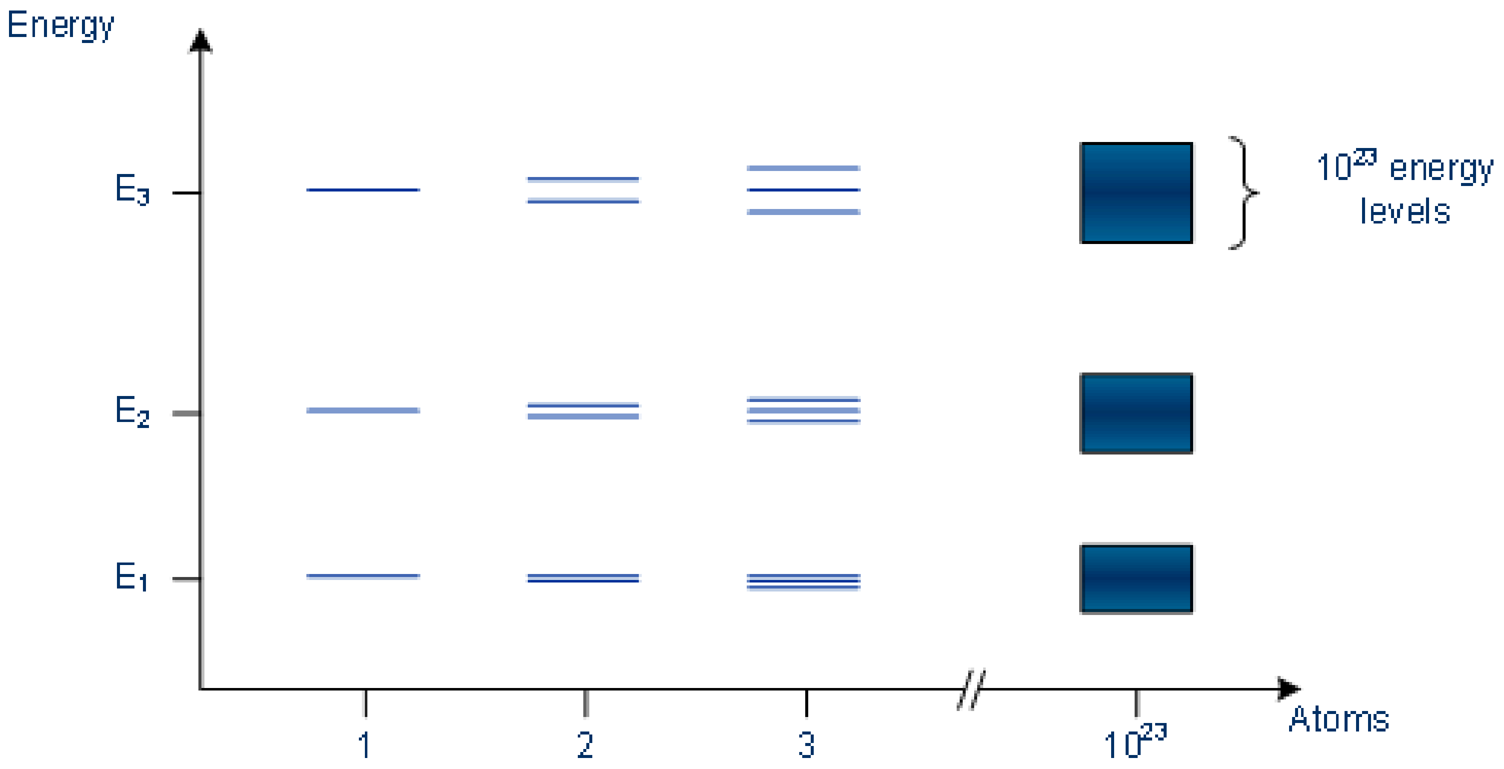


Silicon is a ***semiconductor***



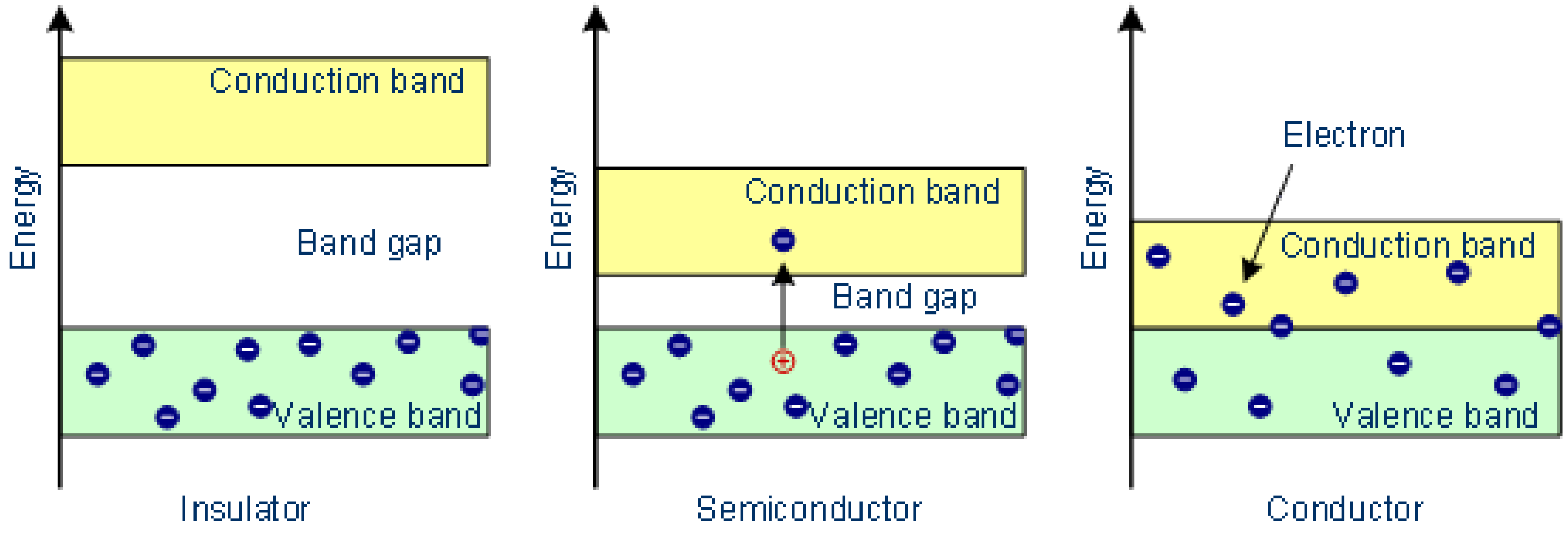
Energy levels and bands

- When considering a single atom, energy levels are well defined and determined
- But when considering a solid, the energy levels of single atoms overlap and form ***bands***

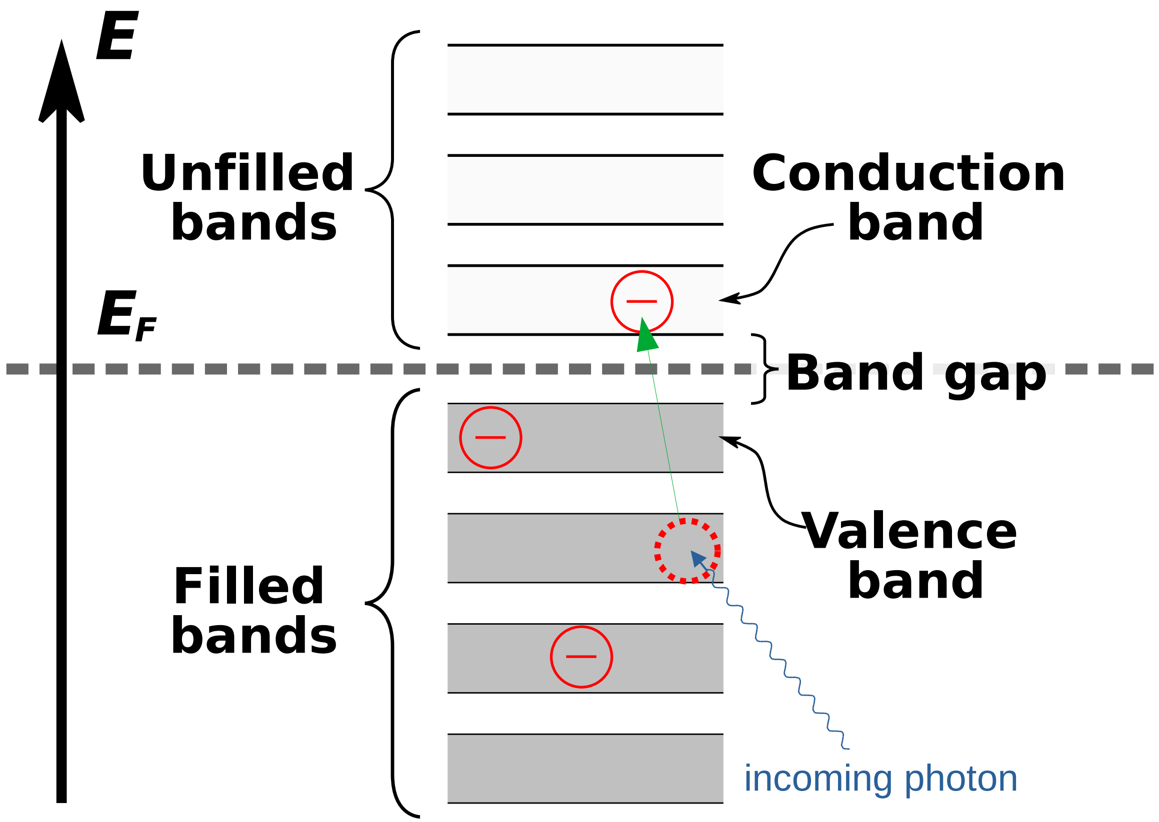


Valence and Conduction bands

- The last occupied energy band is called the ***valence*** band.
- Energy bands above the valence form the, so-called, ***conduction*** band, where electrons can move freely.



Photoelectric effect



Normally, electrons occupy the valence band and the conduction band is empty.

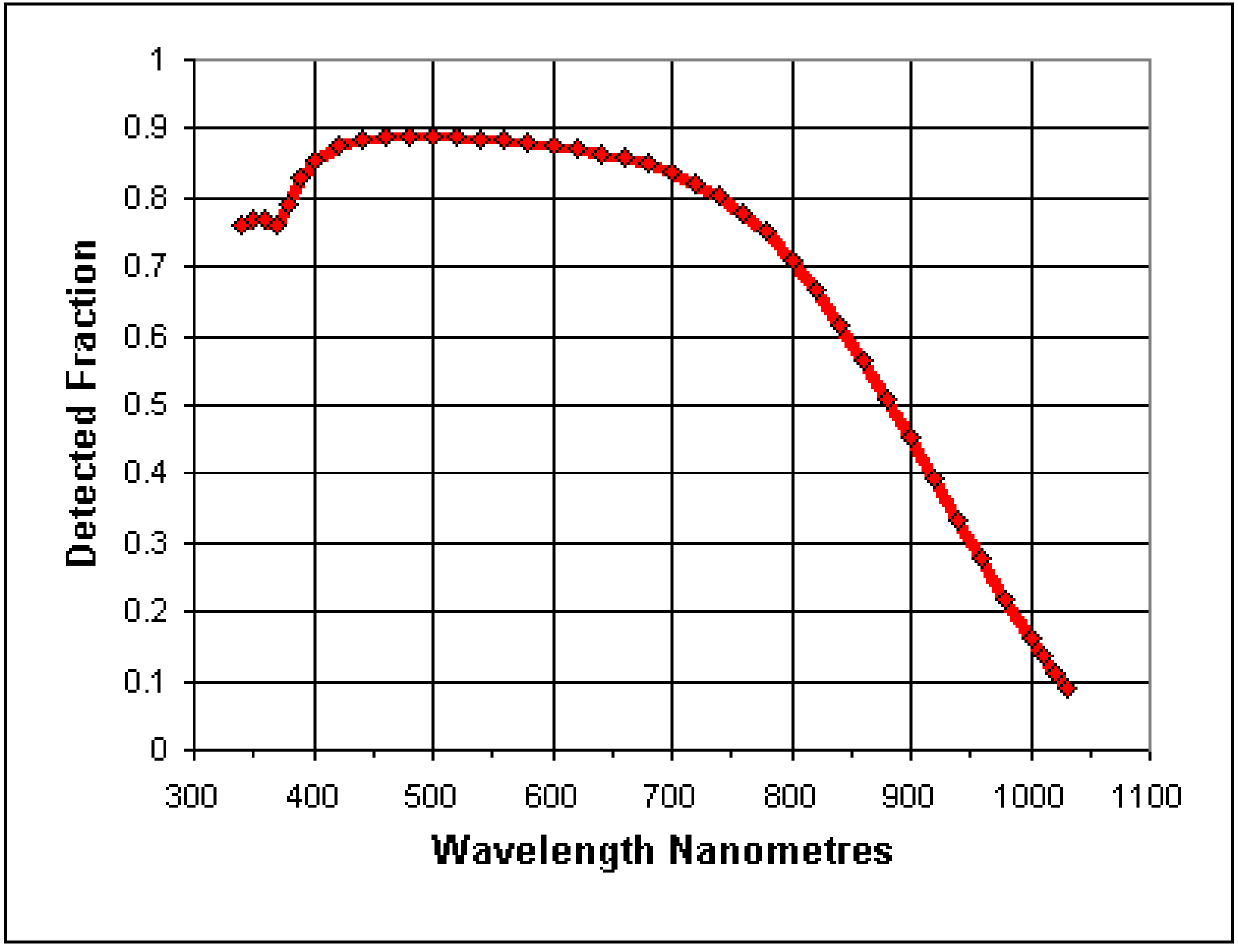
An incoming photon can interact with an electron and transfer its energy.

If $E_{ph} > E_{gap}$, the electron can jump to the conduction band.

For silicon, $E_{ph} > 1.2$ eV or equivalently $\lambda_{ph} < 1.1$ μm.

Silicon is great for optical wavelengths but terrible for NIR!

Quantum efficiency

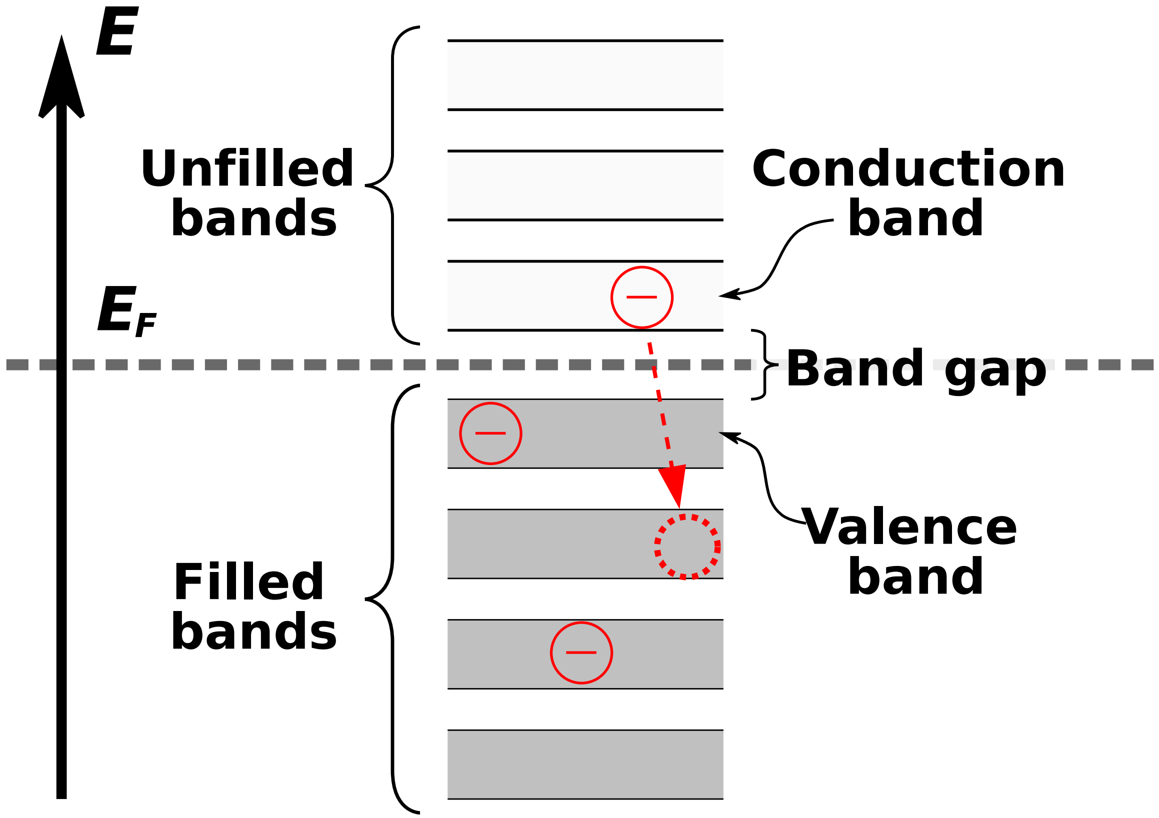


The ability of a CCD to “convert” an incoming photon into a (photo)electron is called

Quantum Efficiency

Notice how the efficiency drops for longer wavelengths!

Photoelectric effect



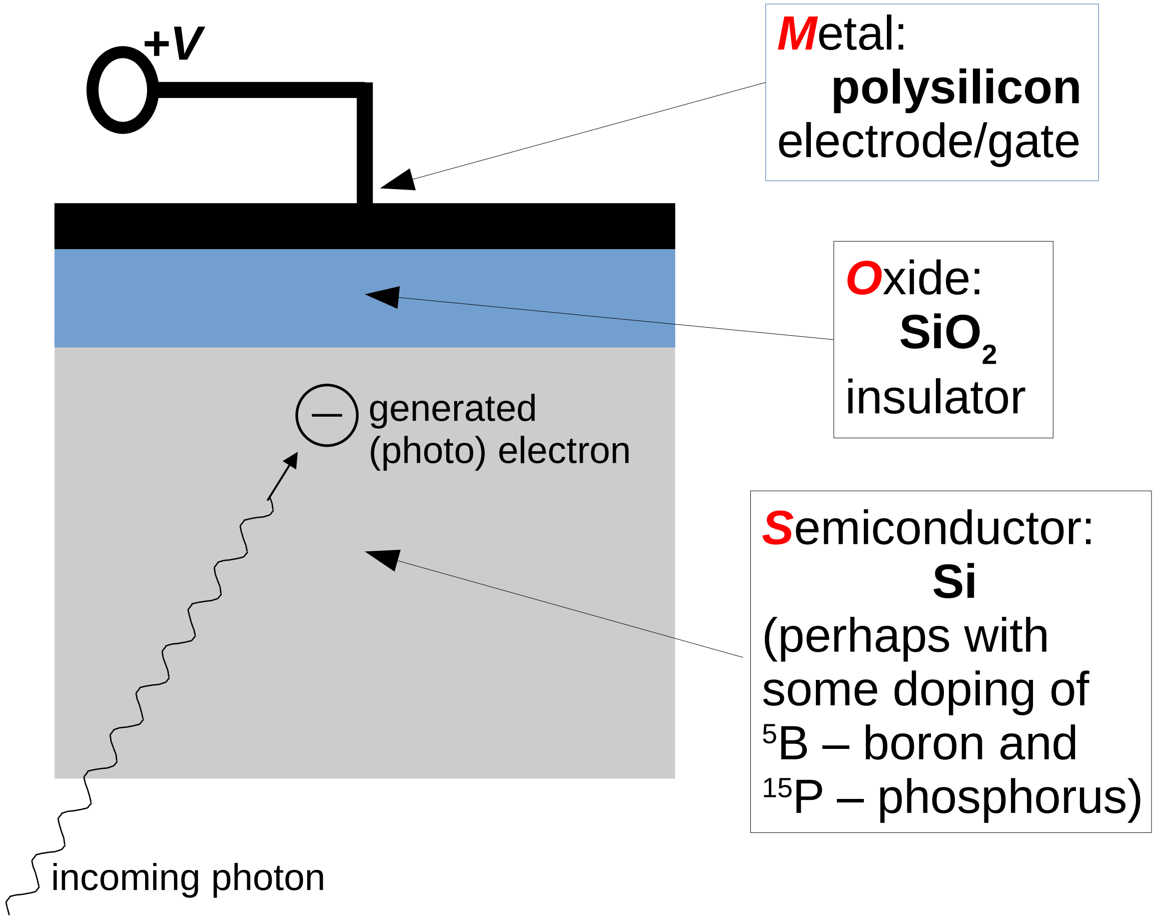
Because the conduction band is usually empty, having an electron there (usually) means that it interacted with a photon.

In CCD language, these are called *photoelectrons.*

However, normally, this electron *would* simply jump back and *recombine.*

In order for a CCD to work properly, we need a way to ***"trap"*** the electron.

The pixel



The main function of a pixel is to accumulate and store the electrons generated during an exposure.

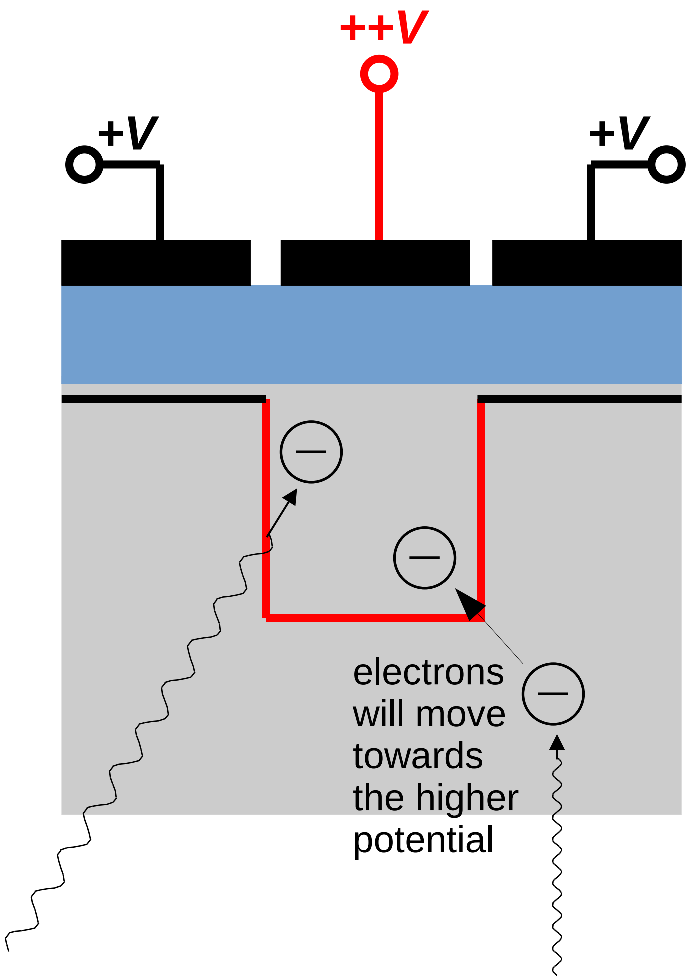
The pixel acts as a ***MOS capacitor***.

MOS stands for:

*M*etal – *O*xide - *S*emiconductor

and describes the basic structure of a pixel.

The potential well



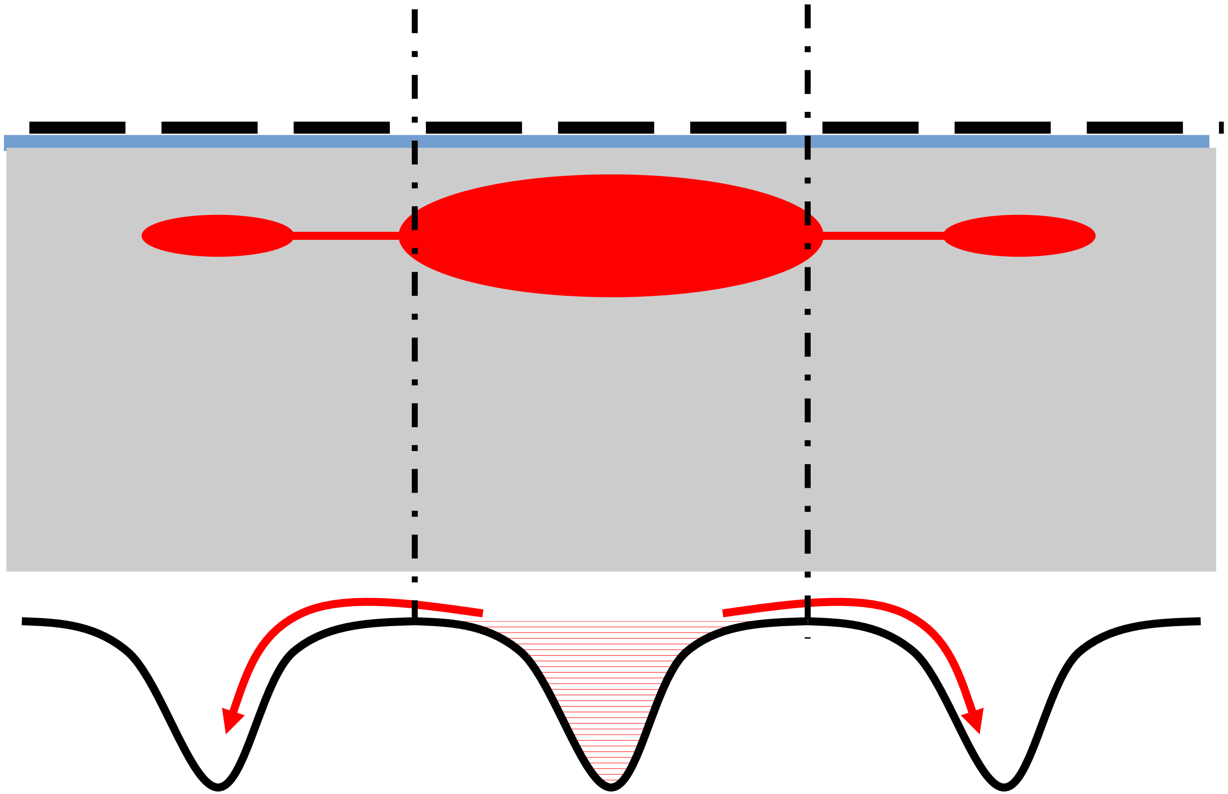
The polysilicon gate is responsible for creating a potential well in order to trap and store the electrons.

In fact, each gate is actually a ***triplet*** of electrodes.

The maximum number of electrons that can be stored in the potential well, is called ***Full Well Capacity.***

The FWC is of the order of 150k e^-

FWC saturation

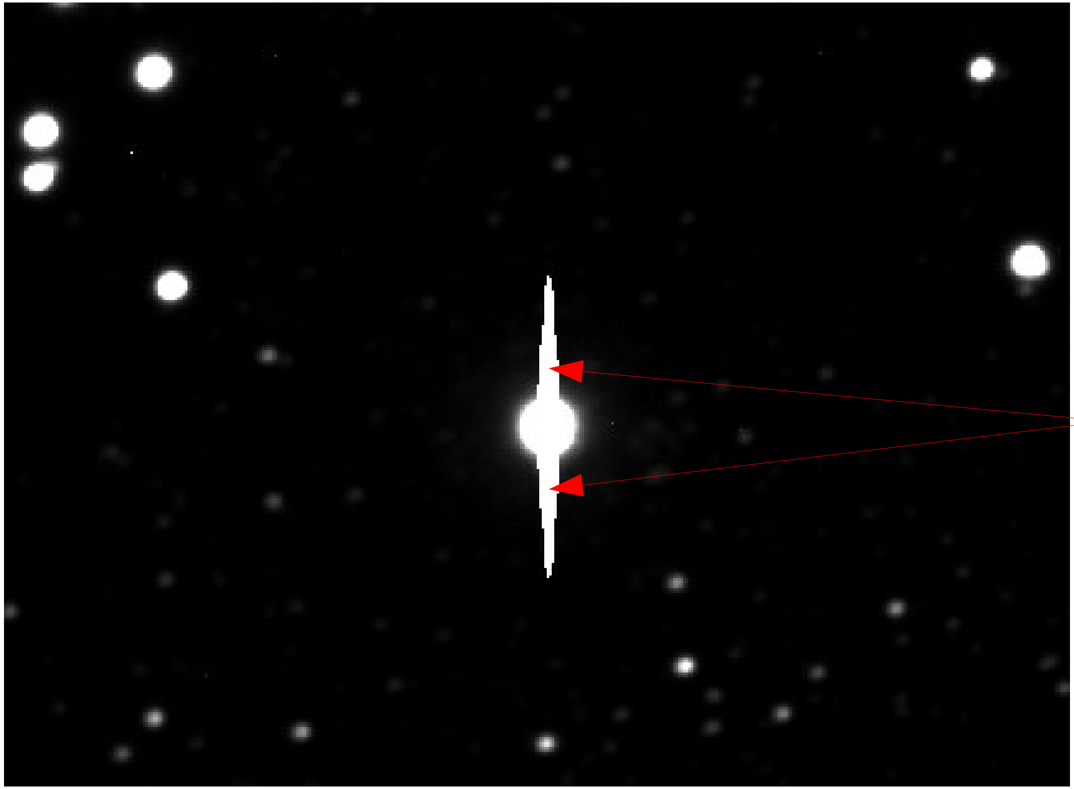


Pixels have finite well capacity!

If the number of (photo)electrons generated exceeds that capacity, then the well is ***saturated***.

In this case, charge will start spilling over to neighbouring pixels.

Blooming

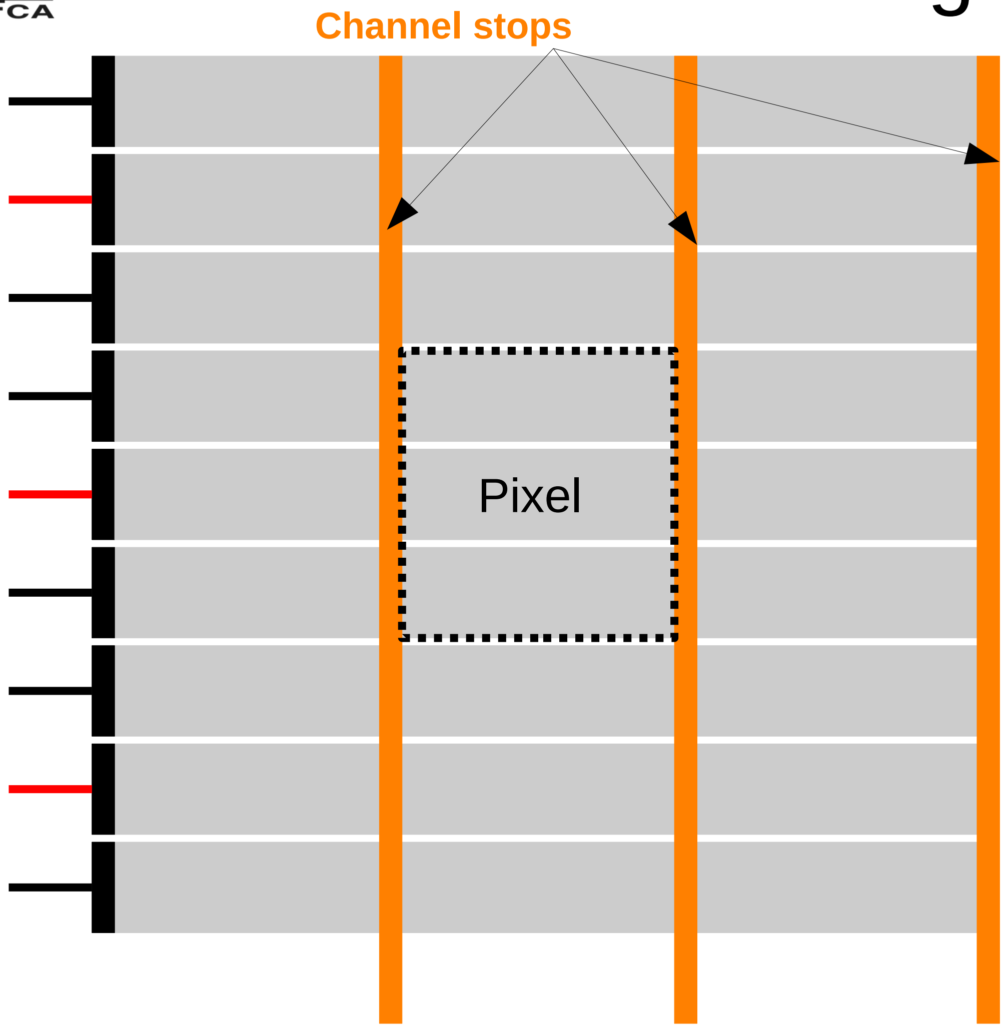


The net effect of well capacity saturation on an astronomical image is called ***blooming.***

Charge spilling over adjacent pixels causes the characteristic elongated streaks.

Notice how blooming occurs in *only one* direction!

Making a CCD

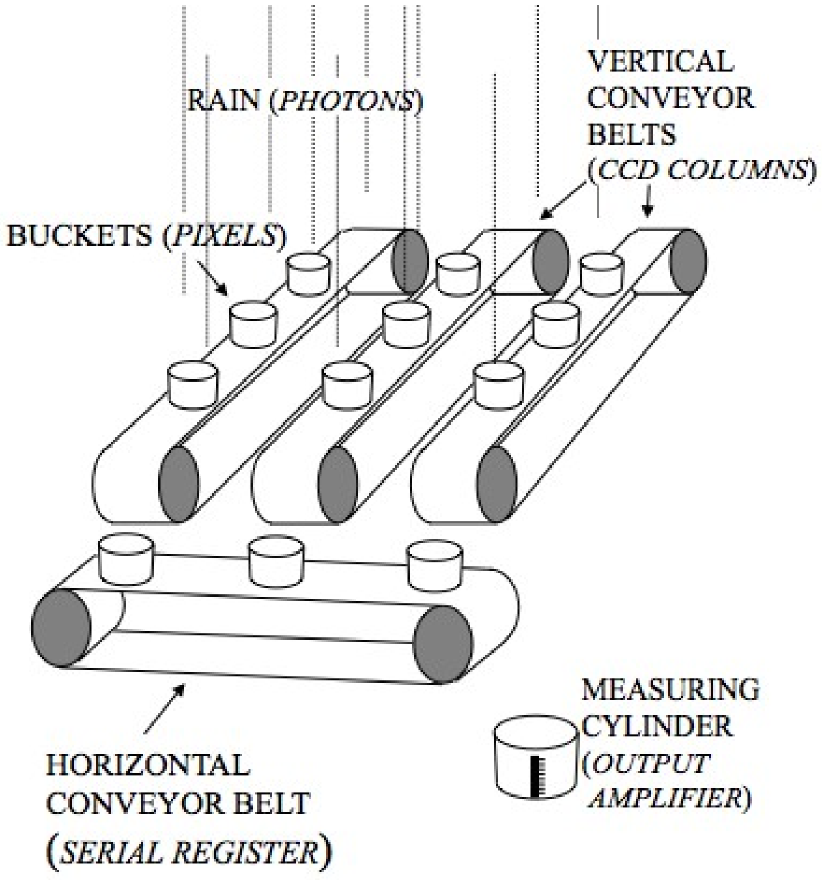


The electrode triplet defines the pixel in one direction (here: vertical).

In the other direction (here: horizontal) the pixels are delineated with insulator strips called ***channel stops***.

In this example, the insulating channel stops prevent charge from moving horizontally.

CCD operation

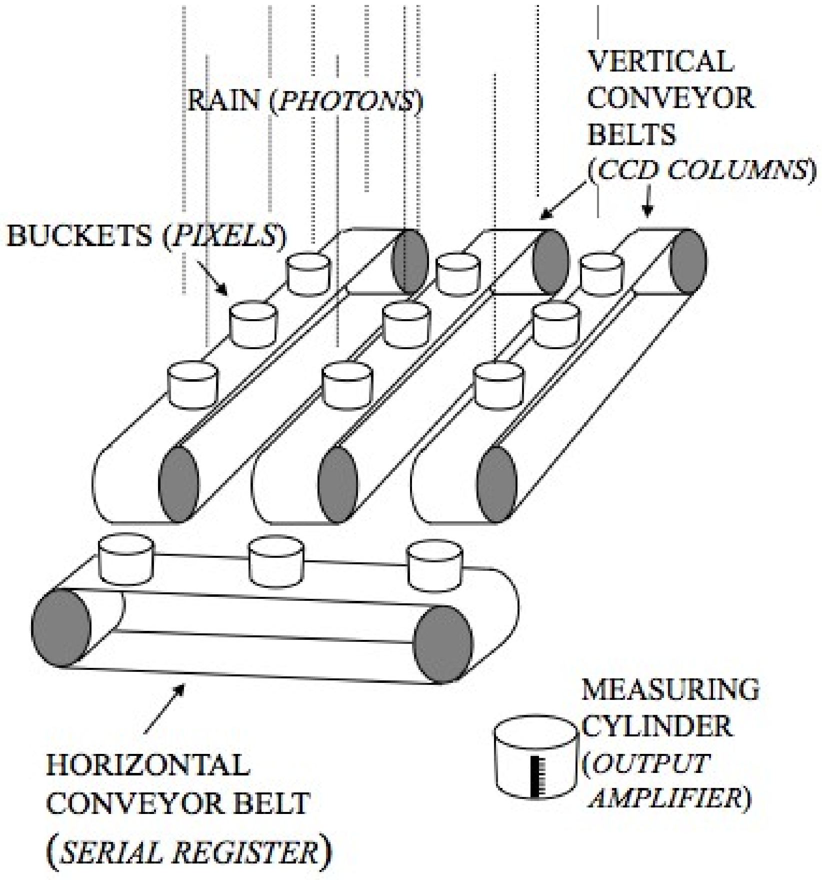


In many textbooks, the basic CCD operation is described as a *bucket-brigade.*

In this context, we have buckets (= pixels) on a field (= CCD chip) and it is raining (= incoming photons).

During an exposure, the buckets (= pixels) are gathering rain (= photoelectrons).

CCD linearity



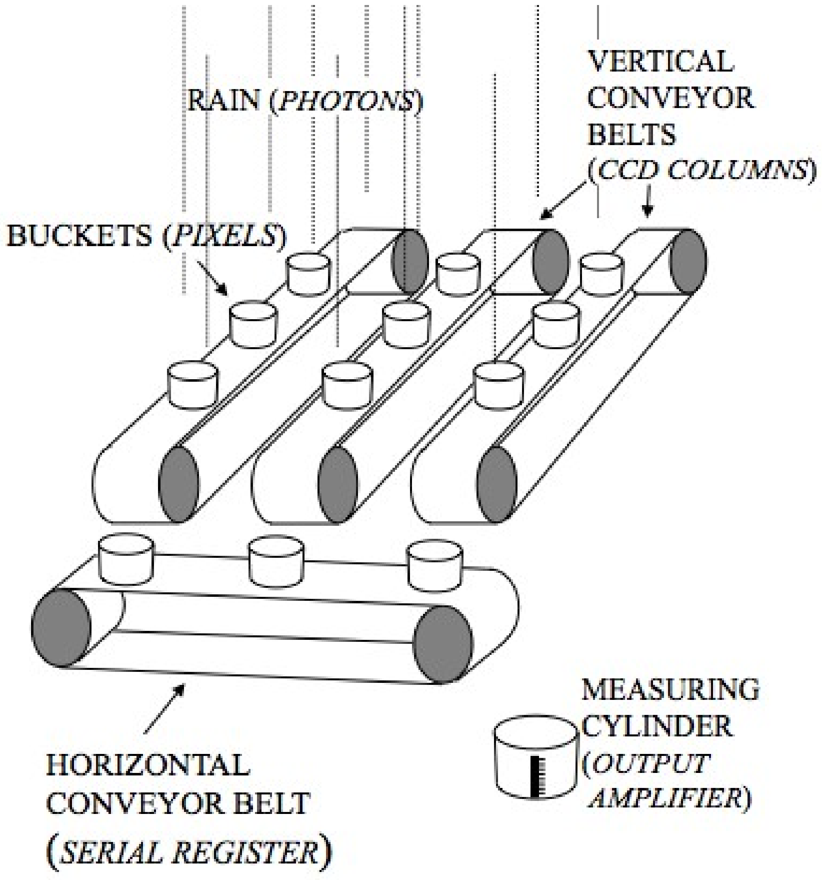
One of the main advantages of a CCD, and one of the main reasons that they have become the standard detector for astronomical observations is that they show ***linear*** behaviour.

This means that if during an exposure of time t_{exp} a pixel gathers a total number of N_e photoelectrons, then for *any* multiple n of the exposure time we will have

$$\boxed{t_{exp} \sim N_e \longrightarrow n*t_{exp} \sim n*N_e}$$

e.g double the exposure time, double the number of photoelectrons

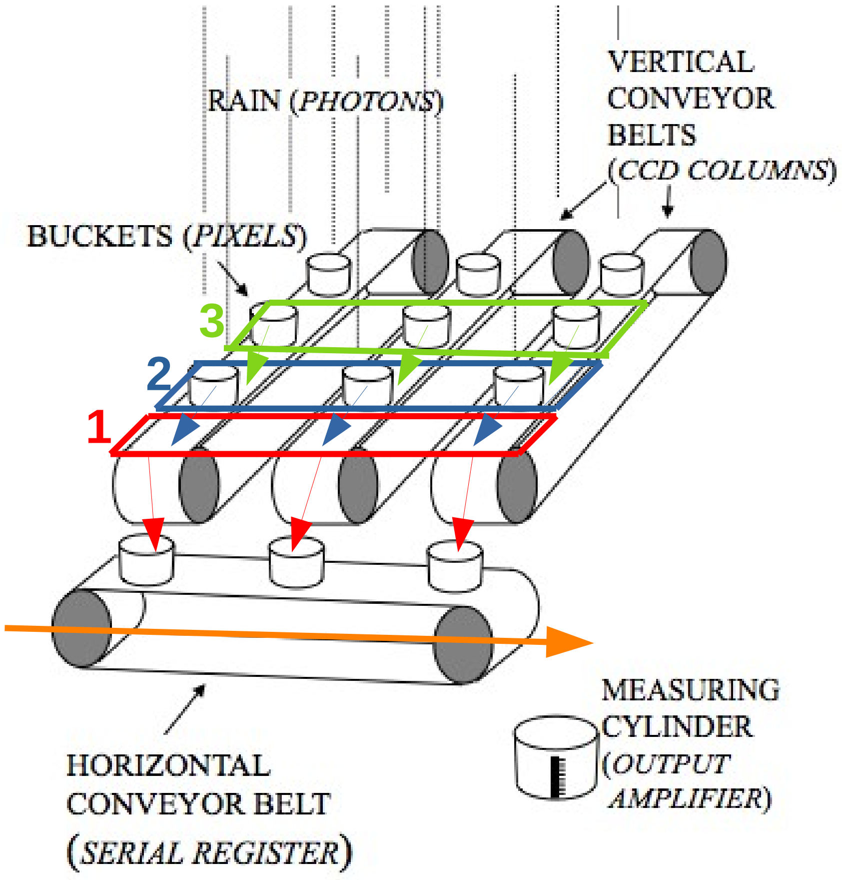
CCD operation



At the end of the exposure, the amount of rain (= photoelectrons) in each bucket (= pixel) has to be measured.

This begins the CCD ***readout*** process.

Readout #1 - charge transfer



1 — The charge of the pixels in Row 1 is transferred to the serial register.

2 — The charge of the pixels in Row 2 is transferred to the empty Row 1.

3 — The charge of the pixels in Row 3 is transferred to the empty Row 2 etc etc...

The charge of the pixels in the serial register is transferred to the readout electronics.

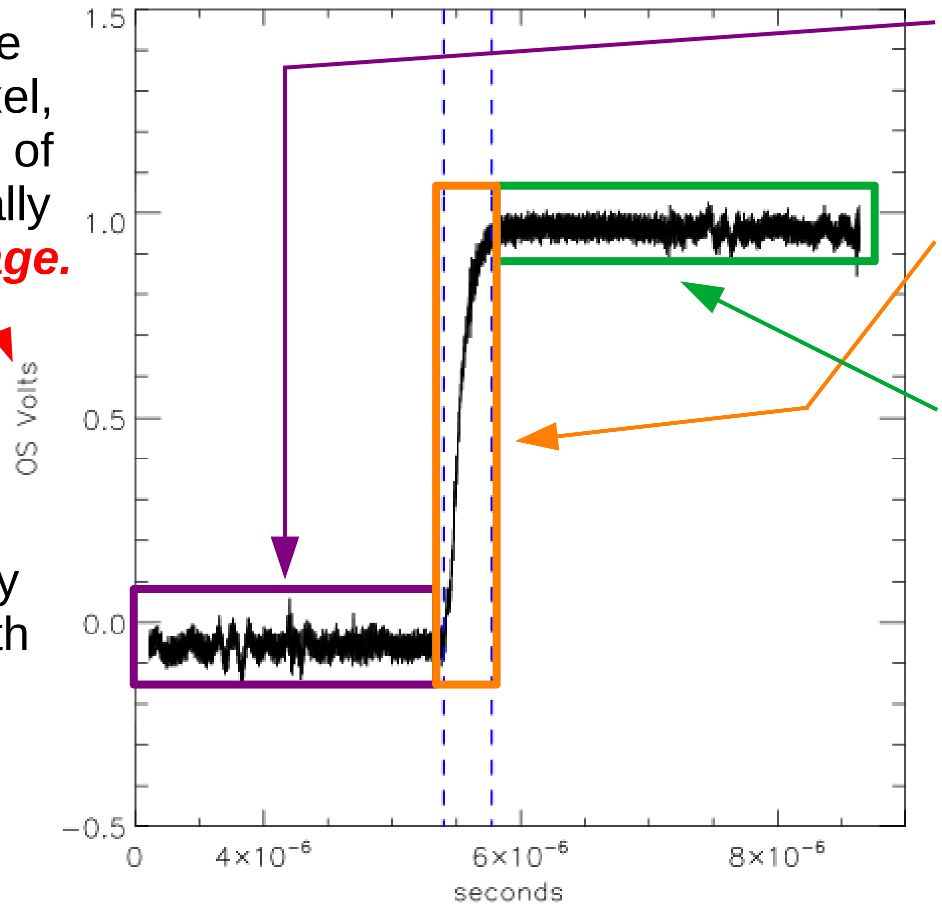
With the serial register empty, the process begins again...

Readout #2 - charge measurement

To measure the *charge* in a pixel, the electronics of the CCD actually measure ***voltage.***

To do that, they use circuits with *capacitors*.

$\boxed{Q = C*V}$



Step 1: a reference voltage at the output of the *empty* capacitor, V_R, is established.

Step 2: the charge of a pixel is deposited on the capacitor.

Step 3: the new signal output voltage, V_S, is measured.

The voltage difference

$$\Delta V = V_S - V_R$$

allows us to establish the charge deposited.

Readout #3 - charge digitisation

Readout electronics

n_e

ADC

$$ADU = \frac{n_e}{gain}$$

n_e = 10000, gain = 1 ► 10000 ADU

n_e = 10000, gain = 2 ► 5000 ADU

n_e = 10000, gain = 1.2 ► ~~8333.33~~ ADU

► 8333 ADU

The CCD readout electronics measure the number of electrons stored in each pixel.

The final output value for a pixel is a ***digital integer*** value, called ***A***nalog-to-***D***igital ***U***nit, or ***ADU***.

The circuit responsible for ***digitising*** the number of electrons is called the ***A***nalog-to-***D***igital ***C***onverter, or ***ADC***.

In this process, the CCD ***gain*** plays a crucial role.

The gain is a quantity that defines *"how many electrons are required to obtain one ADU"*.

The binary system

We read right to left

Bit-3	Bit-2	Bit-1
2^2	2^1	2^0

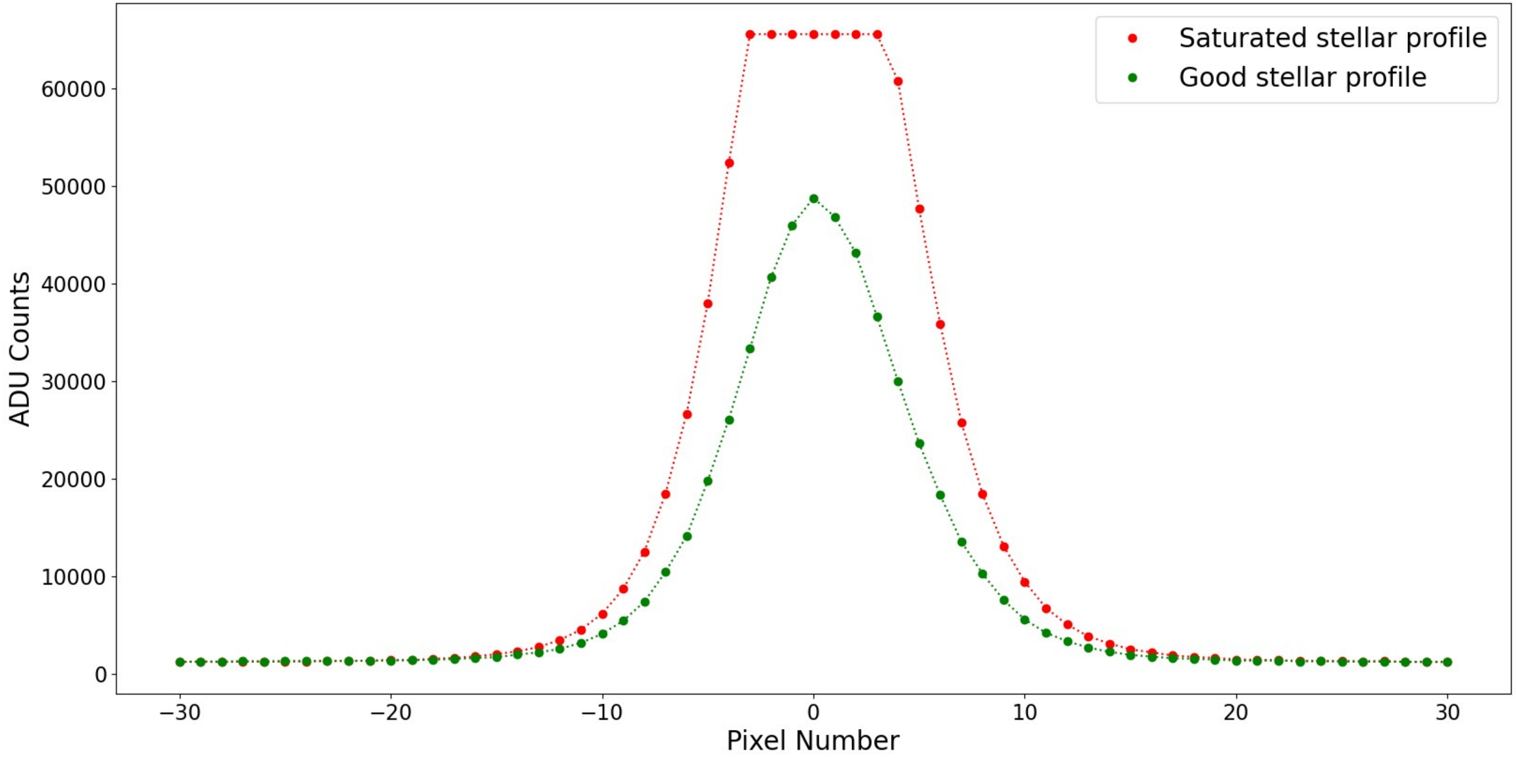
The first power is 0

$$000 = 000 = 0*2^0 + 0*2^1 + 0*2^2 = 0$$
$$001 = 001 = 1*2^0 + 0*2^1 + 0*2^2 = 1$$
$$010 = 010 = 0*2^0 + 1*2^1 + 0*2^2 = 2$$
$$011 = 011 = 1*2^0 + 1*2^1 + 0*2^2 = 3$$
$$100 = 100 = 0*2^0 + 0*2^1 + 1*2^2 = 4$$
$$101 = 101 = 1*2^0 + 0*2^1 + 1*2^2 = 5$$
$$110 = 110 = 0*2^0 + 1*2^1 + 1*2^2 = 6$$
$$111 = 111 = 1*2^0 + 1*2^1 + 1*2^2 = 7$$

- With **3** bits we can represent $2^3 = $ **8** values, ranging from **0** to **7**
- With a standard 16-bit astronomical CCD: $2^{16} = 65536$, ranging from **0** to ***65535***

Digital saturation

If the ADU counts exceed the value of 65535, the ADC ***cannot*** represent them in the binary system and it ***saturates***, returning the same value of 65535 regardless of the *actual* value



Readout Process Summary

- **STEP 1:** Charge transfer to readout electronics
- **STEP 2:** Measurement of charge (actually a voltage difference)
- **STEP 3:** Convertion to ADU (using the gain) and digitisation

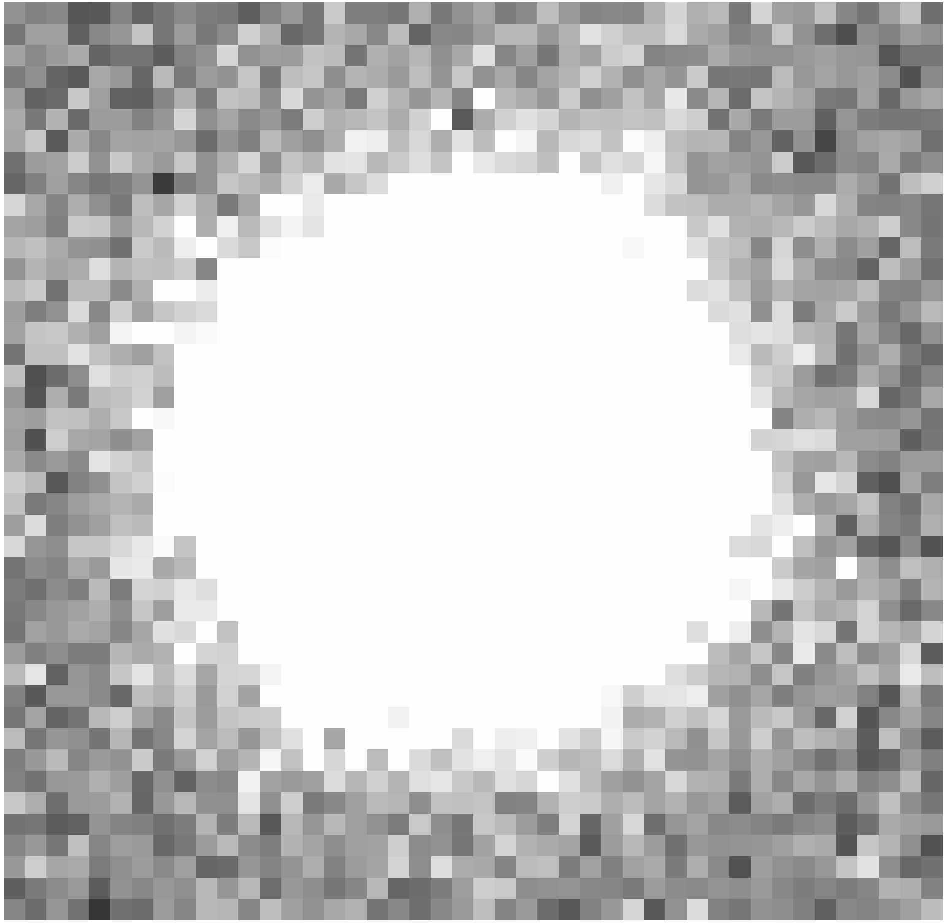
Note: many CCDs offer different speeds for the readout process. For example the GT80 CCD offers two options: (i) 500 kHz and (ii) 3 MHz. A higher frequency option means that readout is faster, but usually this comes with higher noise.

- After the readout process is complete, our image is downloaded to the computer and we can finally see it!

An actual astronomical image...

140	155	157	158	187	180	187	190	218	172	207	199	218	221	205	216	193	196	185	172	146	148	159	154	161
139	160	142	176	190	212	198	228	240	254	247	247	251	255	258	240	216	185	203	174	159	167	167	170	142
144	161	162	172	204	209	236	264	303	285	290	320	333	311	312	297	257	262	220	242	194	190	164	158	150
161	160	190	186	223	252	283	312	351	382	405	429	454	421	392	346	323	297	279	233	204	185	177	182	152
180	154	197	198	245	271	332	393	473	522	569	612	582	532	500	511	431	361	335	291	261	209	208	164	182
169	183	197	236	290	328	396	522	590	775	844	820	937	873	757	690	604	506	416	313	265	240	211	197	183
164	190	217	257	321	418	548	735	893	1141	1330	1448	1501	1399	1263	1037	758	688	523	390	335	283	225	202	192
191	202	224	293	402	535	733	998	1450	1833	2189	2460	2472	2265	1998	1530	1201	879	667	496	382	335	277	247	207
199	197	287	336	476	691	1008	1453	2188	3088	3948	4377	4343	3889	3233	2459	1747	1282	902	660	517	390	286	247	203
186	245	320	408	557	845	1342	2155	3338	5079	6892	7940	7792	6805	5460	3869	2610	1734	1103	842	599	409	317	247	208
203	253	339	450	689	1035	1669	2972	5157	8275	11696	13777	13464	11300	8419	5766	3725	2320	1460	966	701	456	346	266	221
228	246	360	481	699	1218	2085	3885	7044	11843	17738	21638	20549	16644	11974	7783	4915	2851	1725	1140	757	525	367	286	253
220	278	352	487	775	1316	2326	4305	8404	14919	22477	26194	24628	19709	13871	9370	5602	3300	1994	1262	783	568	360	289	221
206	292	337	501	766	1295	2328	4286	8225	14797	22034	25366	23374	18267	13222	9199	5574	3346	1995	1287	840	573	391	326	235
226	250	323	498	678	1218	2024	3741	6852	11673	16734	18833	17846	14049	10527	7184	4837	2898	1847	1118	724	500	364	313	249
206	236	299	410	589	974	1606	2798	4721	7392	10245	11673	11018	9130	6894	5029	3454	2256	1431	960	645	453	356	232	198
209	240	275	383	524	806	1178	1937	2909	4376	5662	6448	6295	5345	4307	3190	2283	1608	1132	786	512	388	308	257	205
179	216	268	326	425	586	832	1241	1785	2429	3039	3500	3452	3032	2495	2007	1540	1072	783	589	463	325	255	220	227
175	213	232	272	352	454	591	768	1066	1369	1671	1823	1835	1792	1537	1255	1011	773	606	445	364	298	240	177	183
163	181	217	286	278	349	467	549	665	865	1011	1023	1108	1072	917	788	665	572	480	353	283	248	217	195	163
170	188	219	207	260	265	336	415	491	546	612	683	675	610	608	550	474	419	344	309	251	216	196	164	166
132	182	182	230	215	255	274	289	325	393	408	439	439	451	431	385	348	318	289	249	220	198	176	177	157
176	163	157	175	208	228	225	248	289	284	322	305	338	340	312	322	251	271	250	207	174	188	178	165	155
146	171	151	165	173	167	192	199	210	229	254	240	248	283	255	247	252	242	193	221	184	179	177	156	165
146	128	143	179	194	169	180	201	197	217	201	223	229	233	207	205	216	176	214	187	191	163	154	153	146

Visualising an actual astronomical image...



Calibration

Frames

Calibration Frames

- When talking about photometric observations, the term ***calibration frames*** refers collectively to ***bias***, ***dark*** and ***flat*** frames

- These frames are required to reduce the science frames and correct various sources of unwanted signal and various imperfections

- They are necessary to use because they are a result of how a CCD is constructed and how it works

BIAS FRAMES

BIAS

- We saw that determining the charge of a pixel depends on measuring a voltage difference $\Delta V = V_S - V_R$

- This process is not perfect, but is affected by ***readout noise***. In practice, this means that even if we measured the *exact same* charge multiple times, the resulting ΔV values would be *slightly different* each time.

- In cases where a pixel contains very little charge or none at all, because of readout noise and the uncertainty in measuring the voltages, it can happen that $V_R > V_S$ and so $\Delta V < 0$. That would propagate as negative n_e and negative ADUs.

- To avoid the need to digitise negative ADU values, a fixed ***bias*** voltage, V_B, is added at the moment of measurement so that $\Delta V' = (V_S - V_R) + V_B$, ensuring that $\Delta V' > 0$ always.

BIAS

- So, the bias level, or simply bias, is a voltage added when the CCD is read out. Of course this propagates as additional ADU counts in the final image.

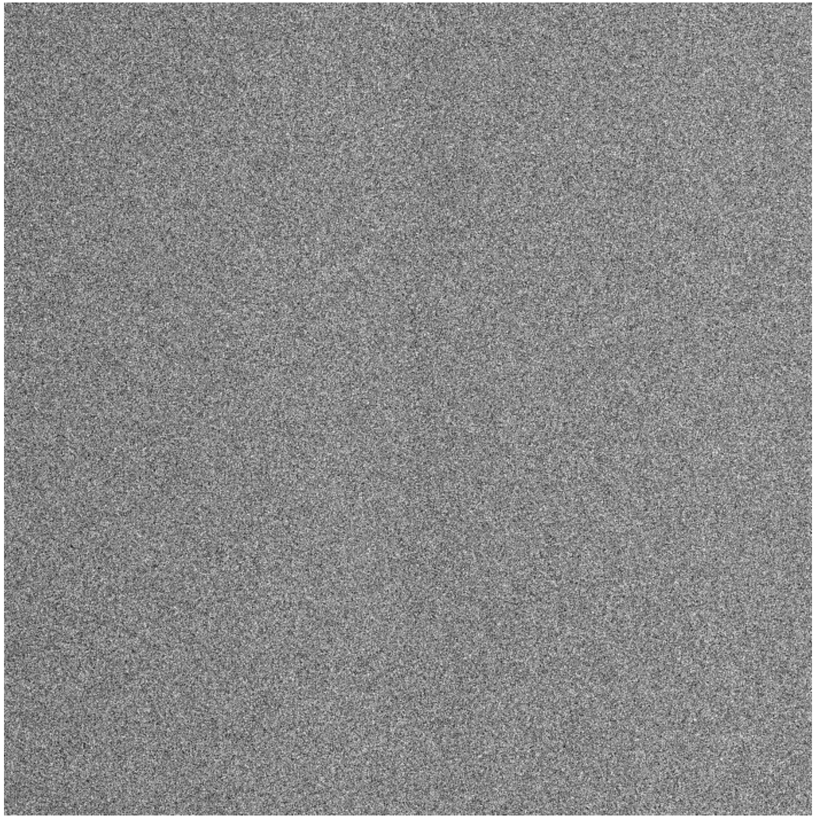
- The bias is added to ***<u>*EVERY*</u>*** image, regardless of image type.

- As the ADU counts of the bias are “fake” we want to remove them from the science images. To do that, we need to use ***bias frames***.

- A bias frame is a zero-time “integration” (t_{exp} = 0); effectively it’s a simple readout of the CCD, with the shutter closed. As such, bias frames are independent of any filter used.

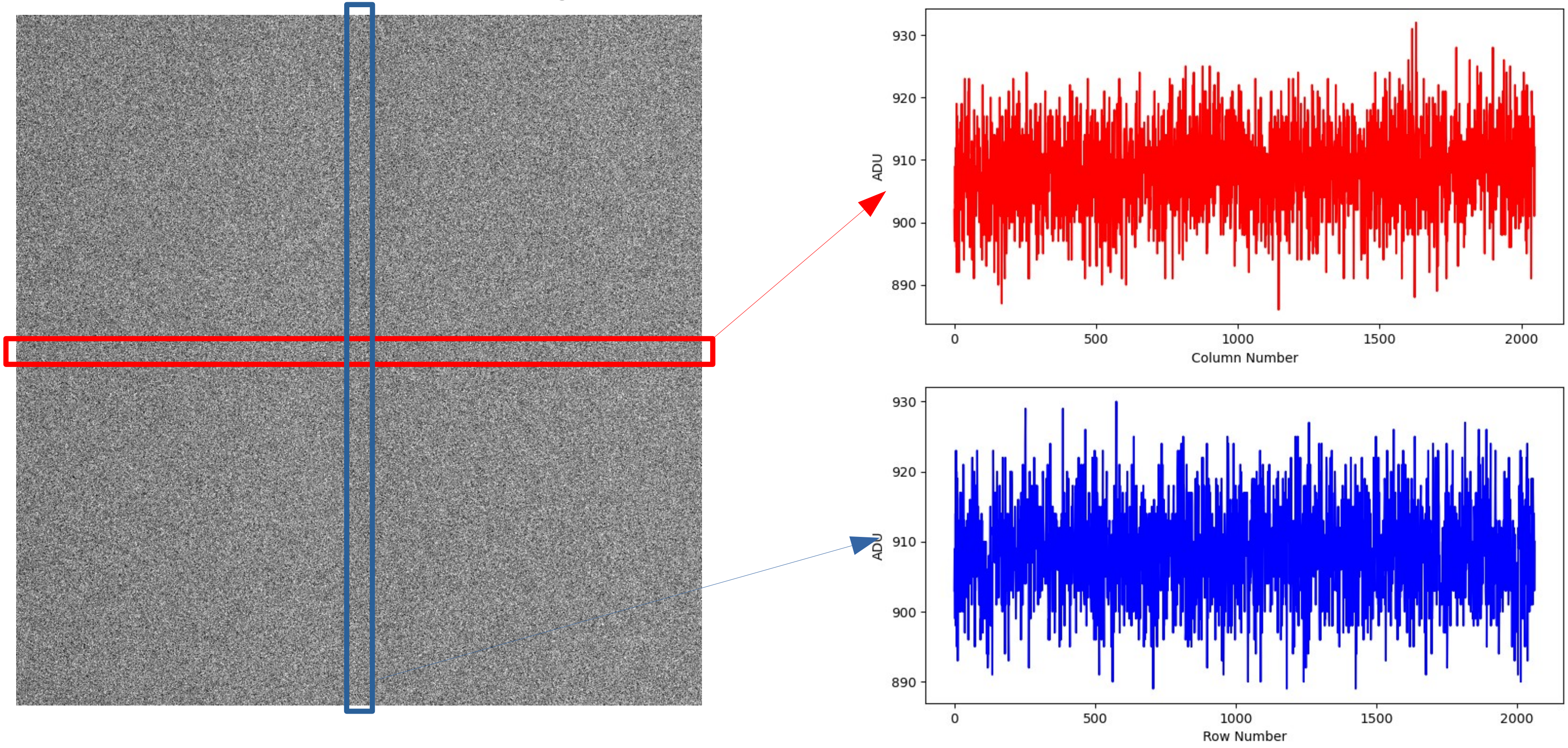
BIAS

Example of a typical bias frame from the GT80 CCD



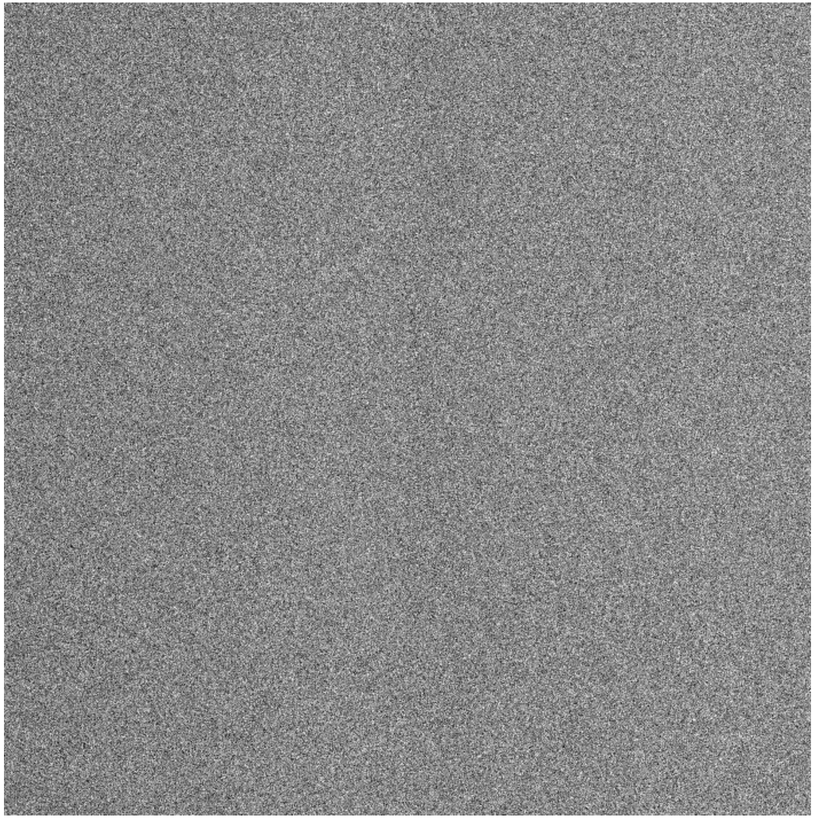
BIAS

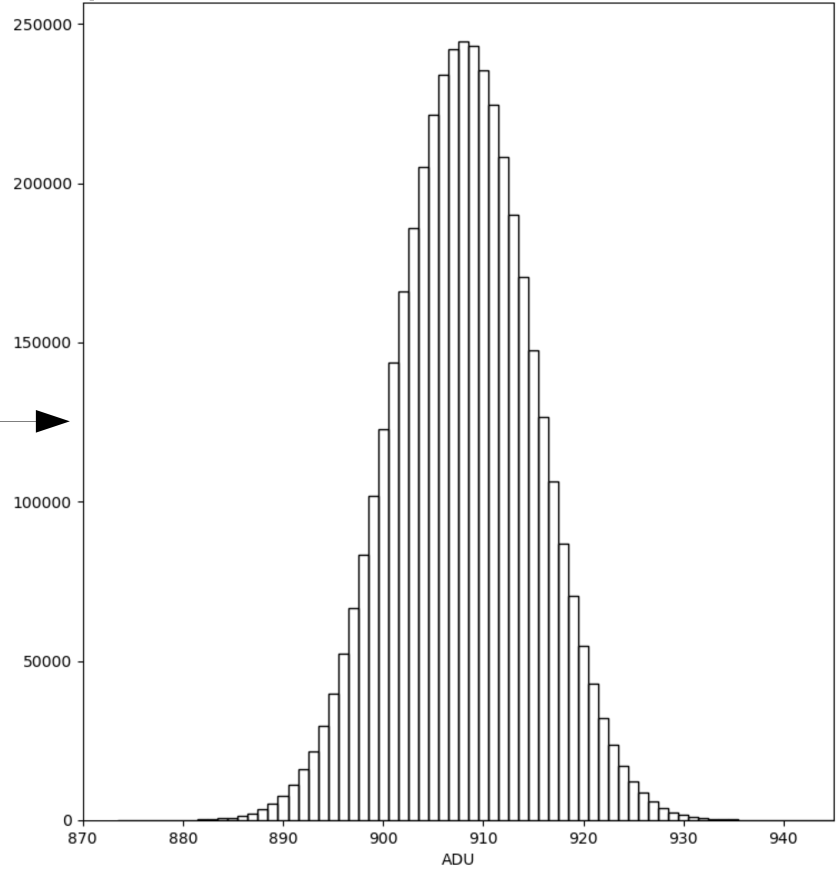
Plotting one **row** and one **column**



BIAS

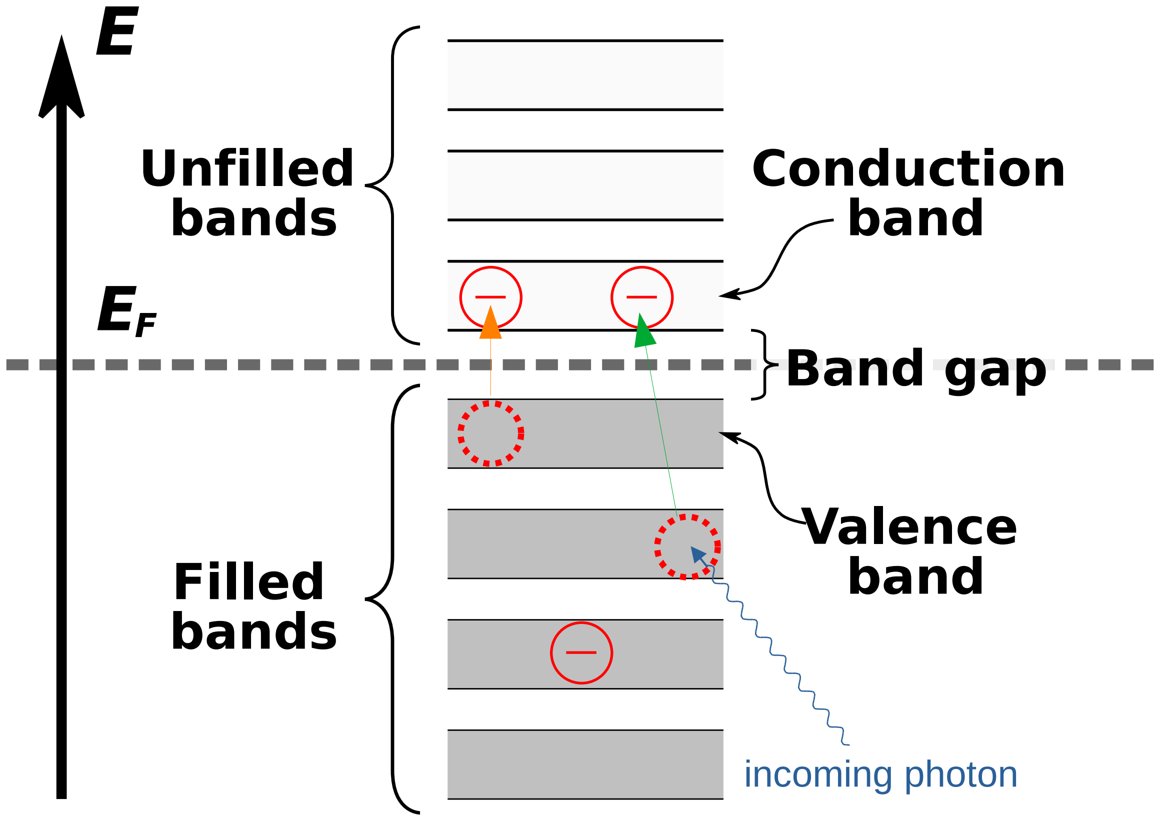
Plotting a histogram of all the pixel values





DARK FRAMES

DARK



Electrons can, some times, *jump* to the conduction band *spontaneously*, due to their thermal energy.

These electrons are called ***thermal electrons*** and are indistinguishable from photoelectrons.

The amount of thermal electrons present in the CCD chip is called ***dark current***.

DARK

- The dark current is described by a constant $C_D(T)$ that depends on the material and the <u>*temperature*</u> of the CCD. For this reason, astronomical CCDs are cooled down, as that makes $C_D(T)$, and dark current in general, *smaller* (down to negligible).

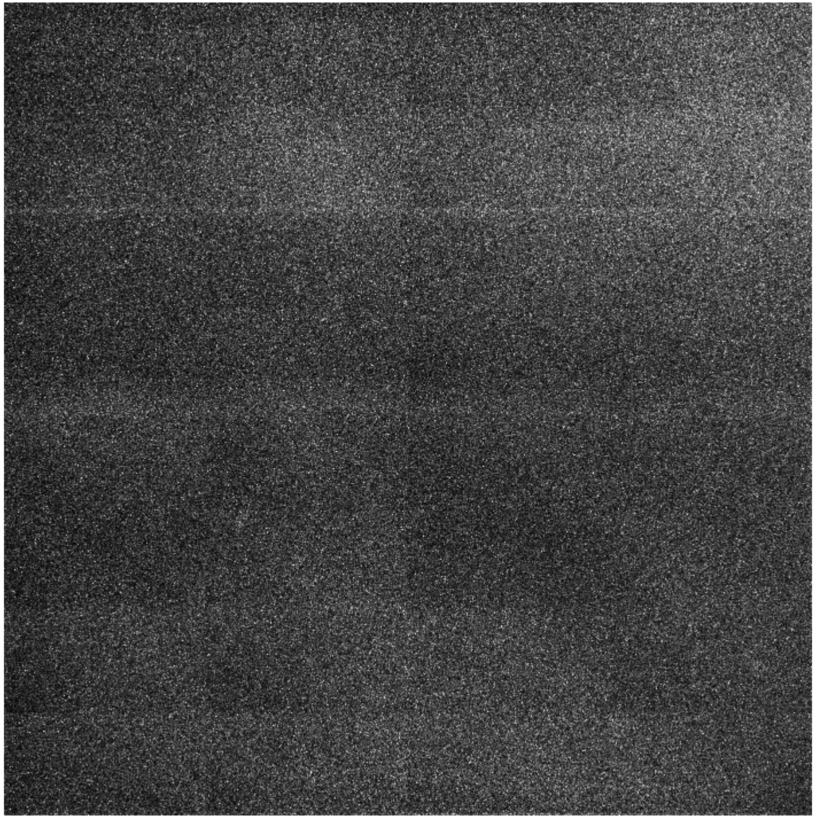
- $C_D(T)$ is usually given in units of [e^-/pix/s]. The [/s] part indicates that the amount of dark current increases with exposure time $C_D(T)*t_{exp}$.

- Thermal electrons are counted together with photoelectrons at the moment of readout, so they introduce additional ADUs. As these ADU counts are "fake", we want to remove them from the science images. To do that, we need to use ***dark frames***.

- A dark frame is an integration (that means $t_{exp} > 0$), but without exposing the chip to light, i.e. with the shutter closed. As such, dark frames are independent of any filter used.

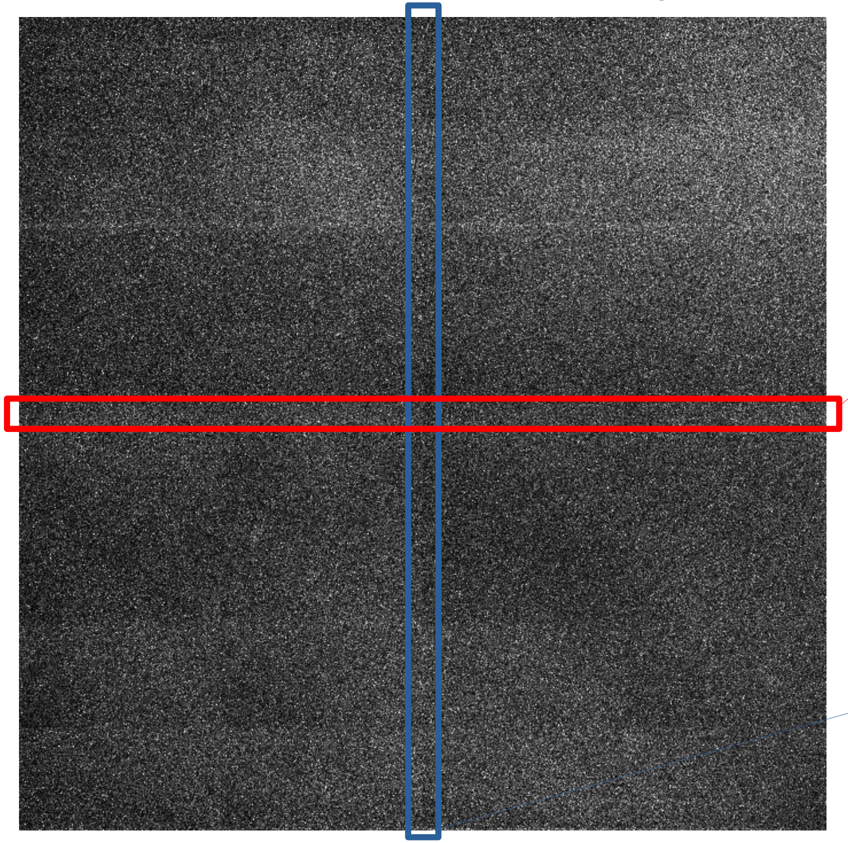
DARK

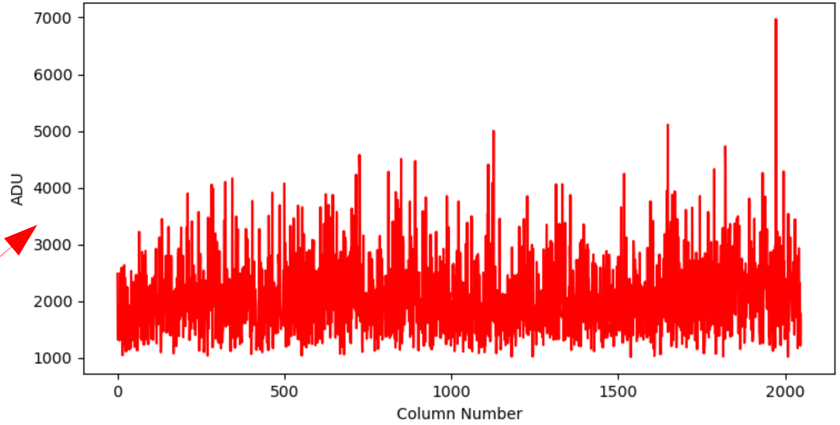
Example of an 1800s dark frame from the GT80 CCD

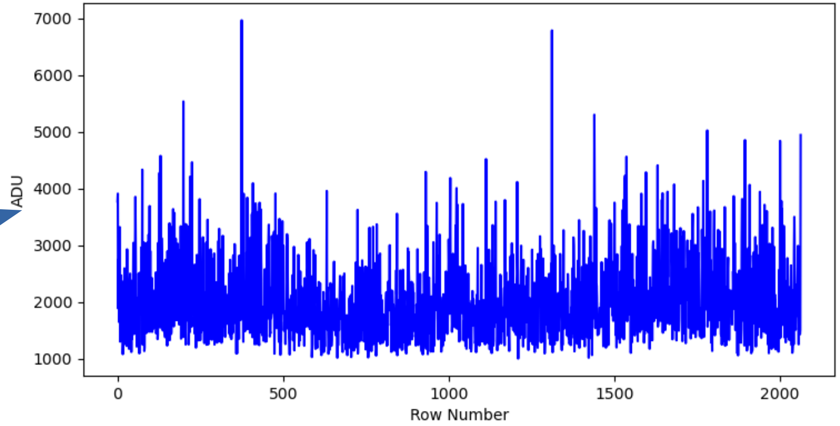


DARK

Plotting one **row** and one **column**

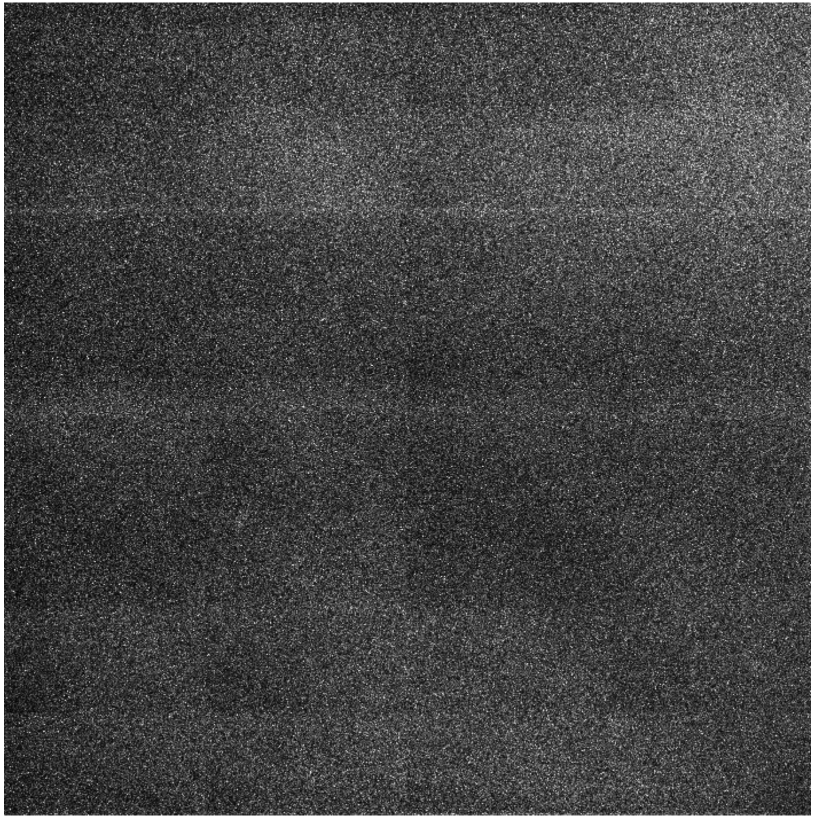


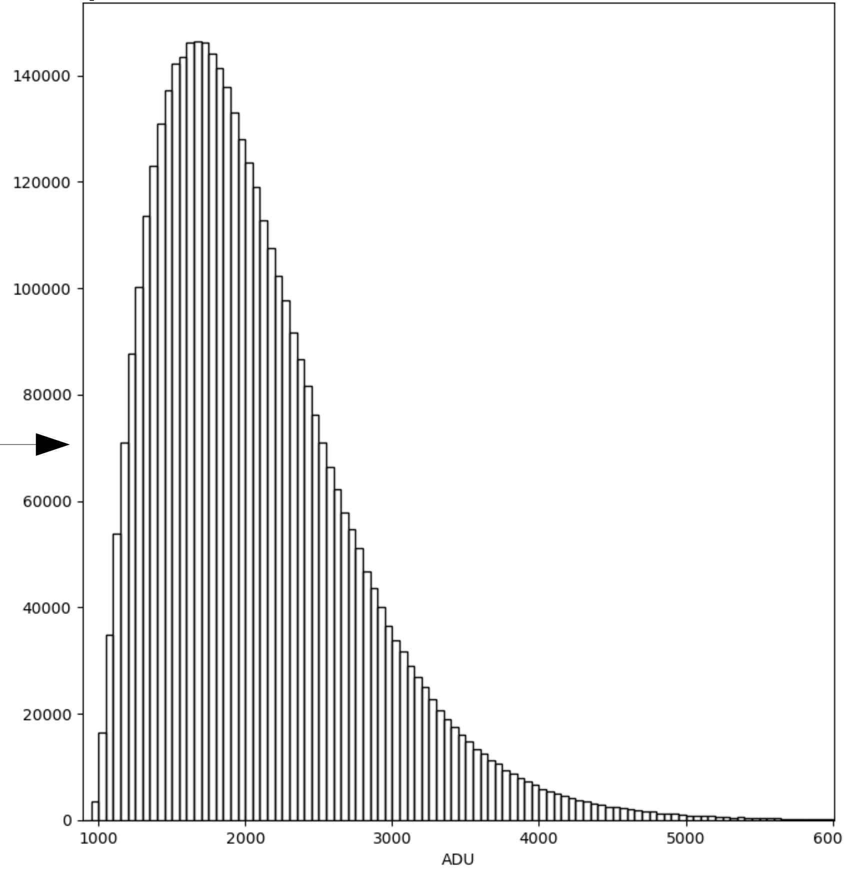




DARK

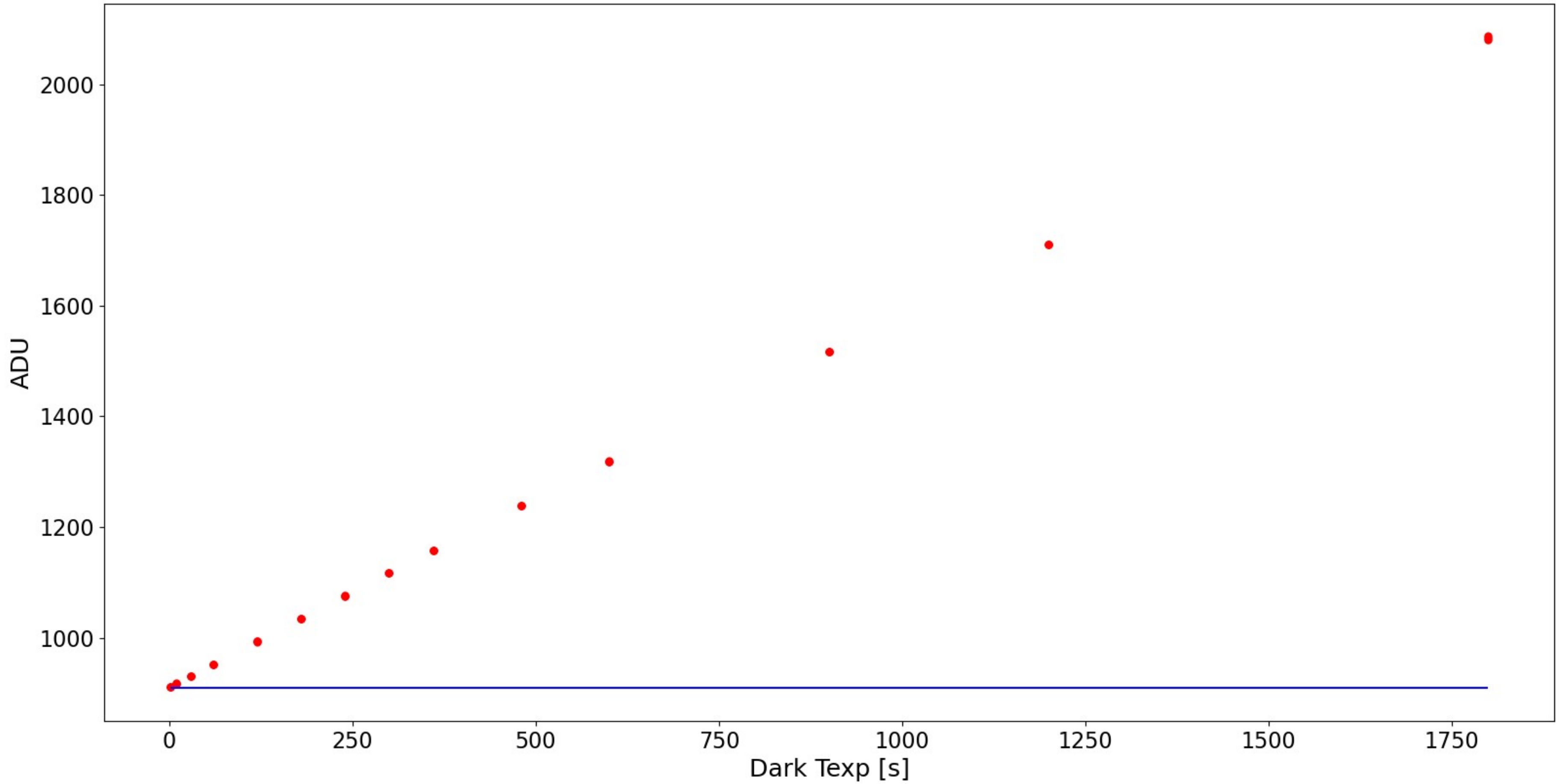
Plotting a histogram of all the pixel values





DARK

As we discussed, the dark signal $C_D(T)*t_{exp}$ will grow with longer integrations



FLAT FRAMES

FLAT

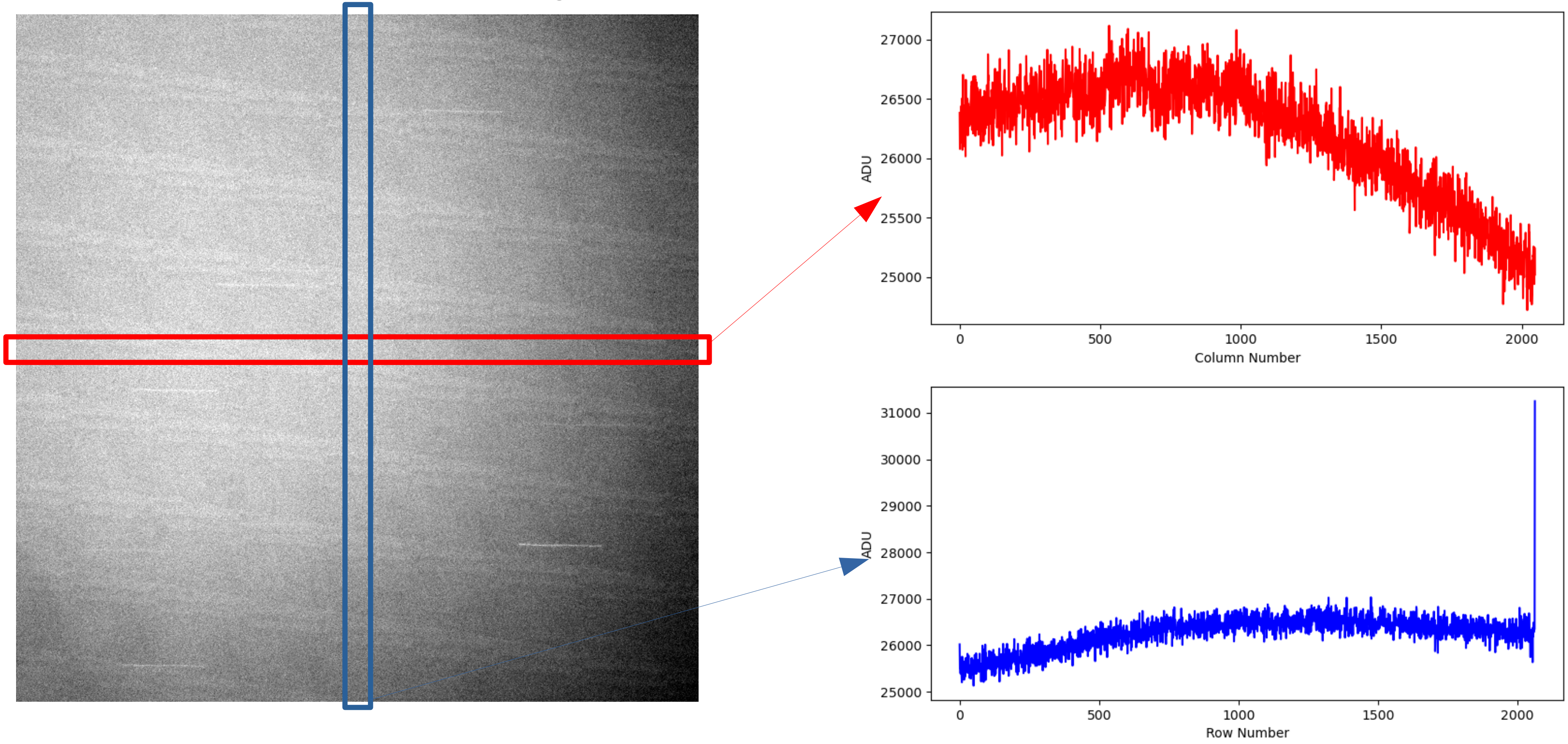
- Flat frames are somewhat different from the bias & dark frames, because they are not used to remove and correct an added signal, like the bias level or the dark current.
- Instead, flat frames are required to correct: (1) imperfections in the optical path (e.g. vignetting, dust motes etc) and (2) differences in pixel sensitivity over the whole chip
- A flat frame is a “proper” exposure, with $t_{exp} > 0$ and ***open*** shutter, i.e. the chip is exposed to light
- As such, a flat frame ***depends*** on the filter that it is taken in!
- It is very common to obtain flat frames by simply pointing the telescope at the dusk or dawn twilight sky.

FLAT

Example of a typical flat frame

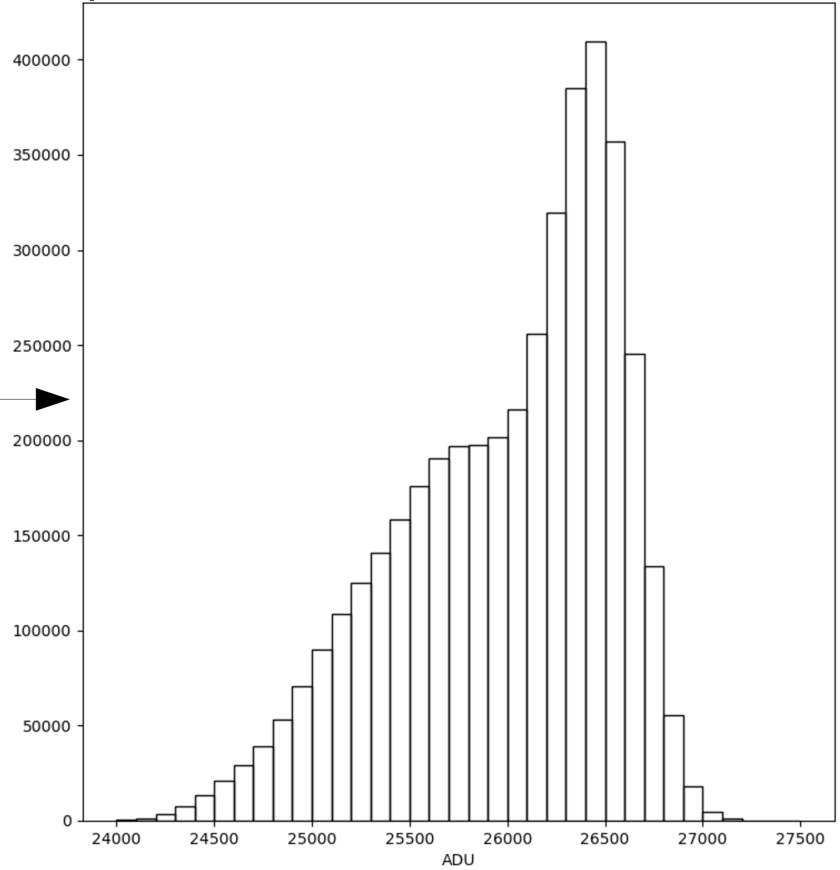
FLAT

Plotting one **row** and one **column**



FLAT

Plotting a histogram of all the pixel values

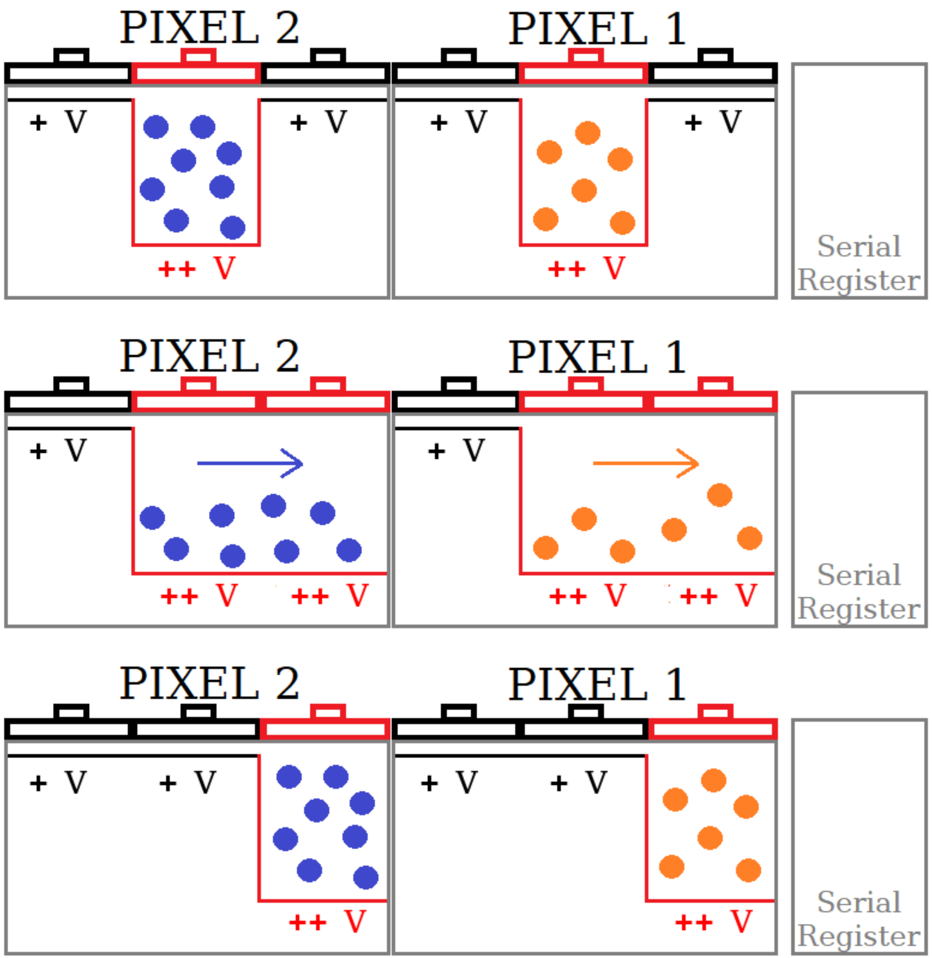


CCD Glossary

- **Photoelectrons** – electrons that have interacted with an incoming photon
- **Thermal electrons** – electrons that jump to the conduction band due to thermal energy
- **Quantum efficiency (QE)** – the ability of a CCD to “convert” photons into photoelectrons
- **Charge transfer efficiency (CTE)** – how well the CCD transfers electrons from pixel to pixel
- **Full Well Capacity (FWC)** – how many electrons a pixel can safely store
- **Analog to Digital Unit (ADU)** / **counts** – the “unit” of the CCD output data
- **Analog to Digital Converter (ADC)** – the circuit that digitises the number of electrons to ADUs
- **Gain** – the number of electrons needed to get one ADU [e^- / ADU]
- **FWC saturation** – happens when the number of electrons in a pixel exceeds the FWC
- **ADC saturation** – happens when the digitised ADUs exceed 2^N-1; for 16 bits = 65535
- **Readout** – the process of transferring and measuring the charge of each pixel
- **Readout noise** – the uncertainty (= “errorbar”) in measuring the charge of a pixel
- **Binning** – grouping together M * N pixels and summing their charge at the moment of readout
- **Blooming** – the effect of FWC saturation on a CCD image
- **Bias level** – an extra voltage applied at the moment of readout, to ensure always positive values
- **Dark current** – the number of thermal electrons present in an exposure; $C_D(T)*T_{exp}$

APPENDIX

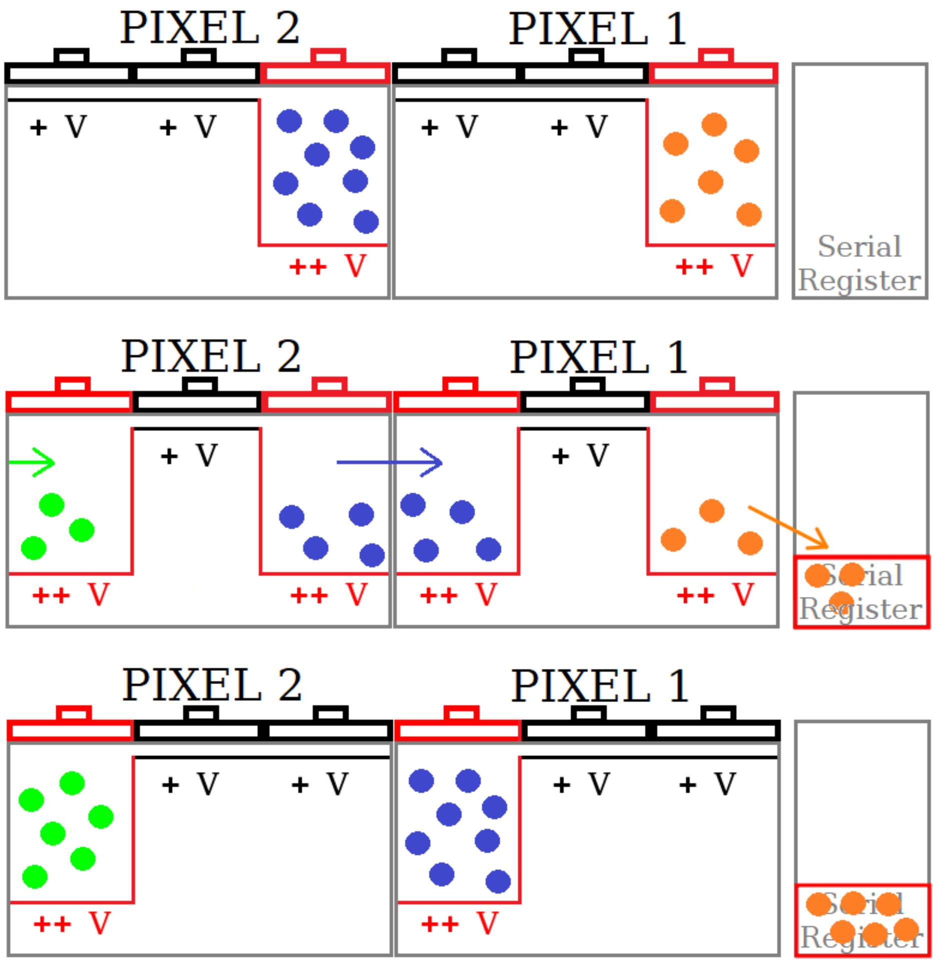
Charge transfer #1



Charge transfer is achieved by cyclically alternating the voltage on the electrodes.

This process is also known as ***clocking***.

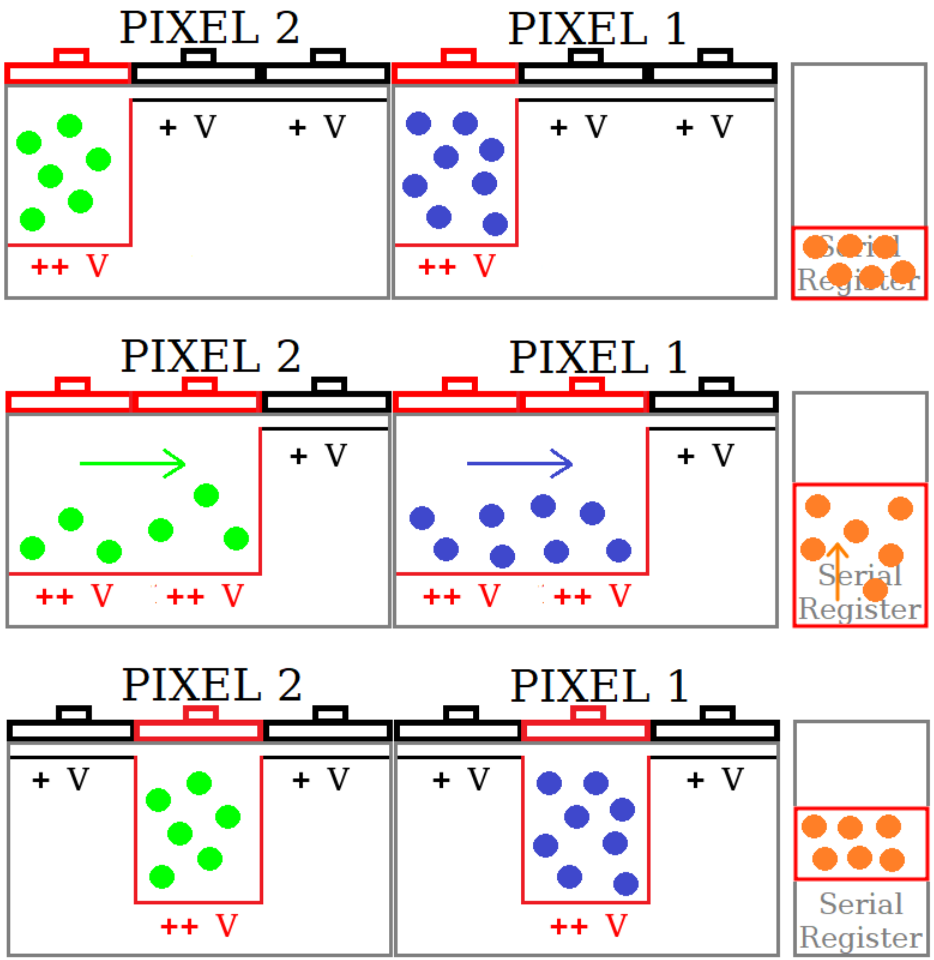
Charge transfer #2



In a CCD with 3 electrodes per pixel, *three* transfers are required to move charge by one pixel.

This ***coupling*** of charge, i.e. the fact that charge is moved from one pixel to the other, is what gives CCDs their name!

Charge transfer #3



Charge transfer is not perfect! If N_0 is the number of electrons under one electrode, and N_t the number transferred to the next, then the Charge Transfer Efficiency is

$$CTE = 1 - \frac{N_0 - N_t}{N_0}$$

If N_{org} is the original number of electrons in one pixel and n is the number of times this packet is transferred until it is read out, then the final number of electrons N_{fin}

$$N_{fin} = N_{org} * CTE^n$$

Charge transfer efficiency

For a CCD with 2048x2048 pixels, the maximum number of transfers is 3*2048+3*2048 = 12288, assuming a three-phase gate design, i.e. three transfers per pixel. An acceptable CTE value is of the order of 99.9999%, that is, a loss of only 1 electron in 1,000,000!