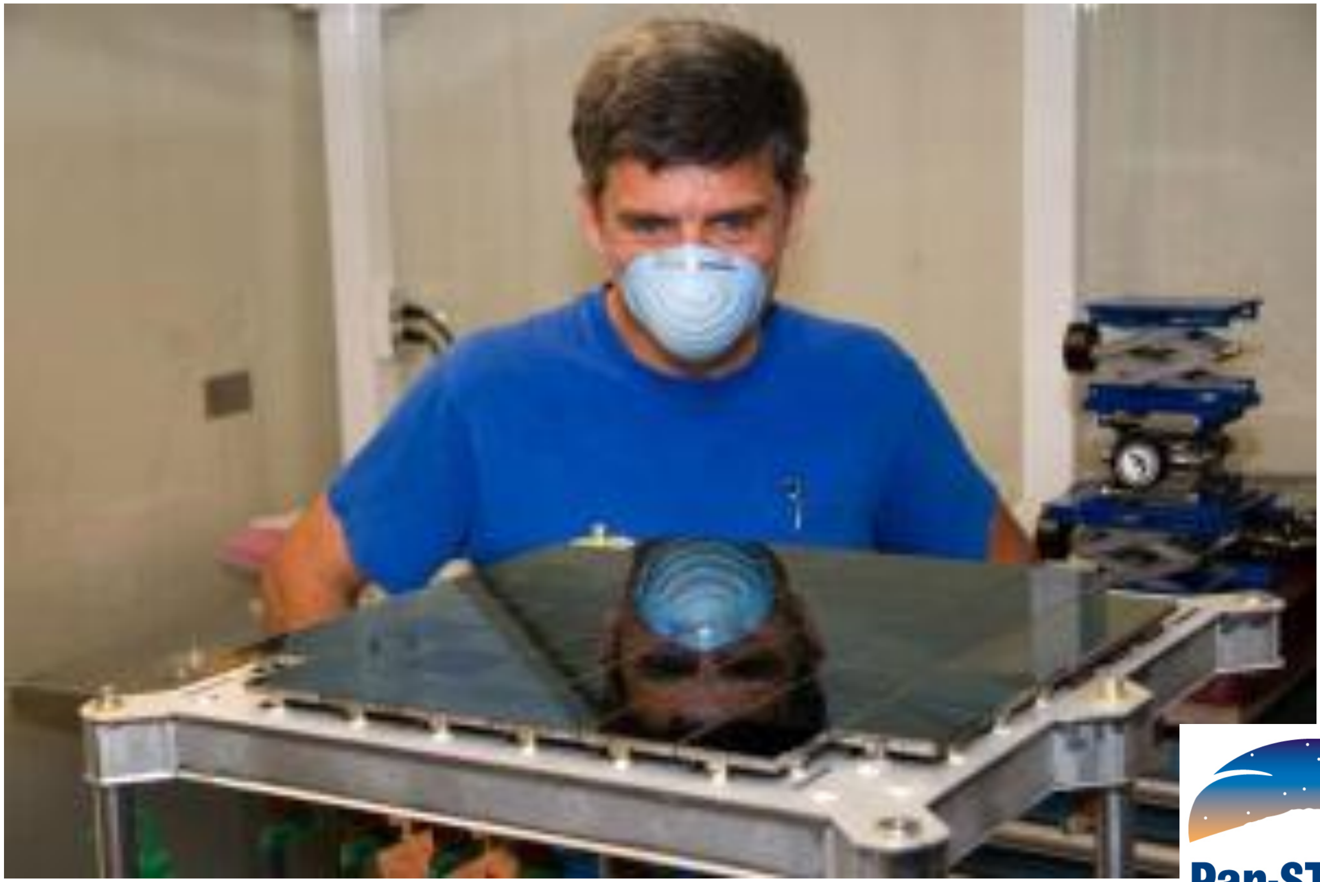
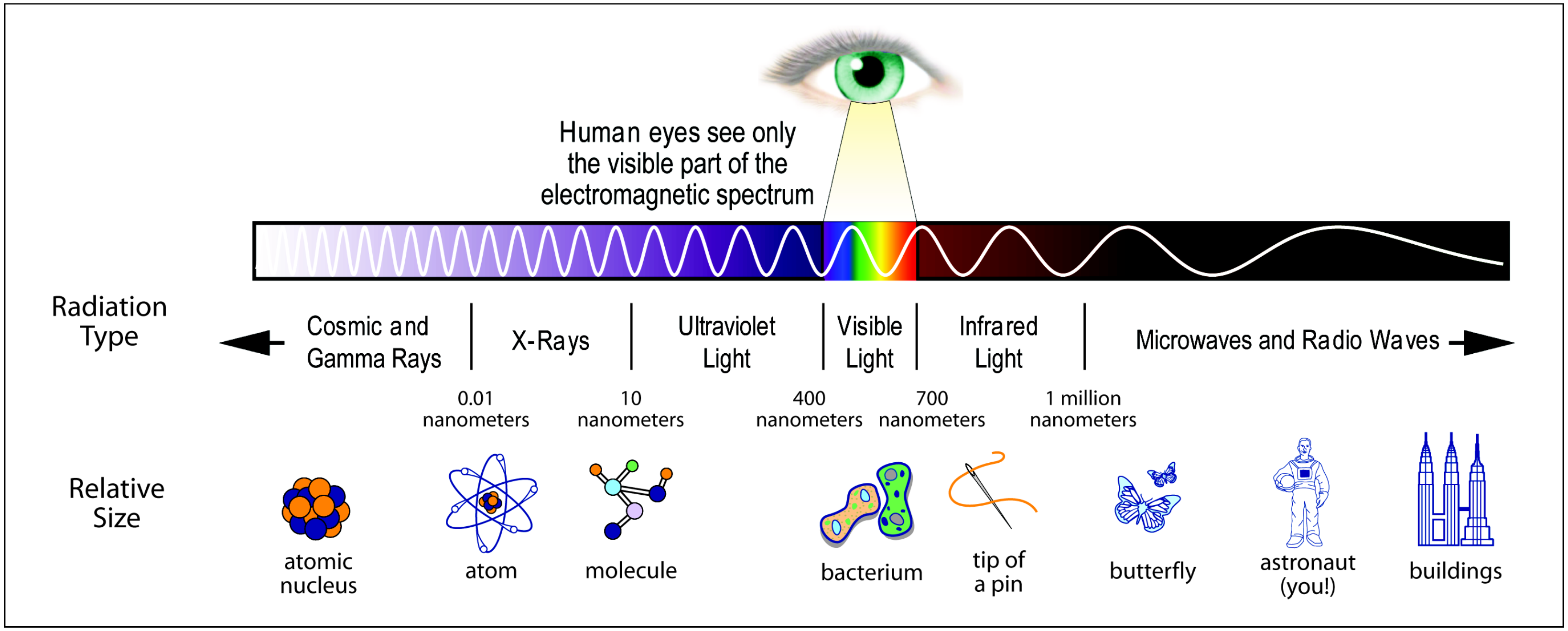
An Introduction to CCDs.

The basic principles of
CCD Imaging is explained.



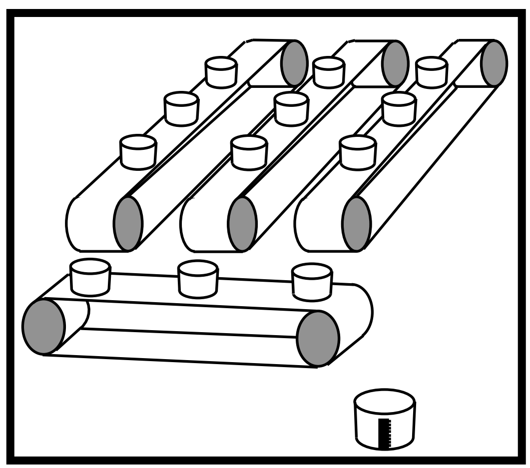
Pan-STARRS

Morning Brain Teaser



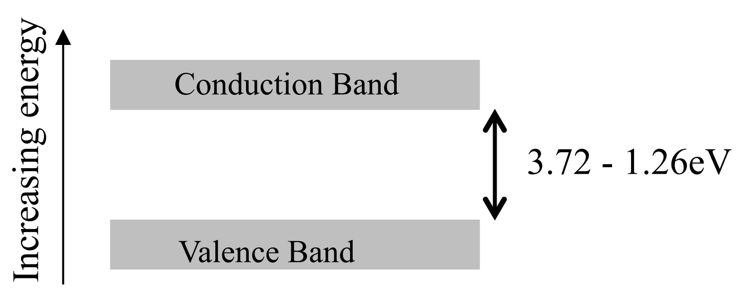
What is a CCD ?

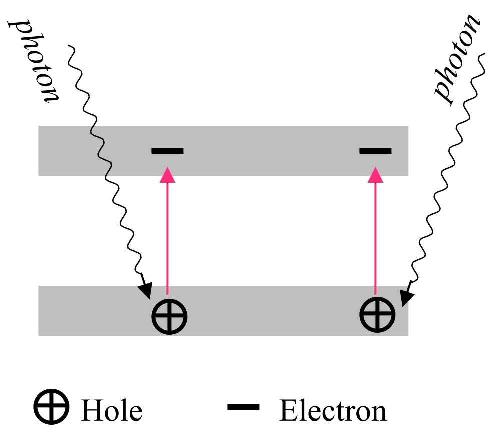
- Charge Coupled Devices (CCDs), invented in the 1970s as memory devices.
- They improved the light gathering power of telescopes by almost two orders of magnitude.
- CCDs work by converting light into a pattern of electronic charge in a silicon chip.
- This pattern of charge is converted into digital form by the analog to digital converter



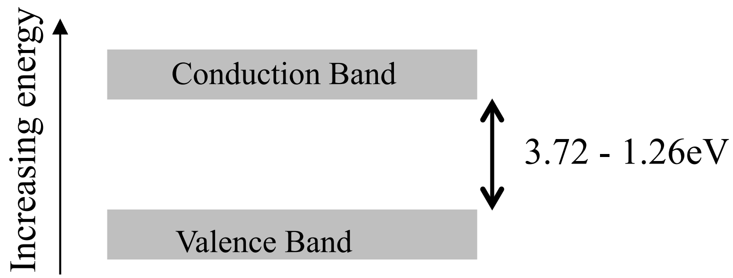
Photoelectric Effect

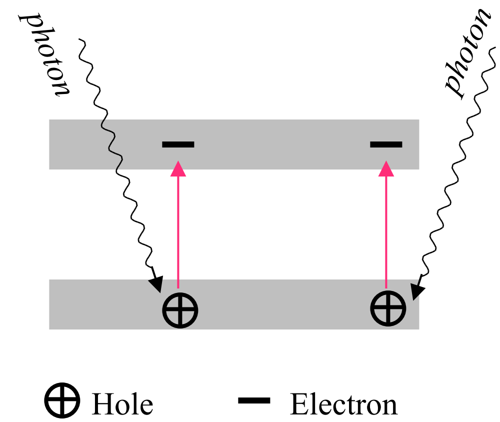
- Atoms in a silicon crystal have electrons arranged in discrete energy bands.
- Valence Band and Conduction Band.
- Heating or the absorption of a photon excites electrons from the Valence band into the conduction band.
- The energy required for this transition is between 3.72 and 1.26 electron volts.
- The electron leaves behind a ‘hole’ and the valence band acts like a positively charged carrier.
- In the absence of an external electric field the hole and electron will quickly re-combine and be lost.
- A CCD uses an electric field to sweep these charge carriers apart and prevent recombination.





Photoelectric Effect



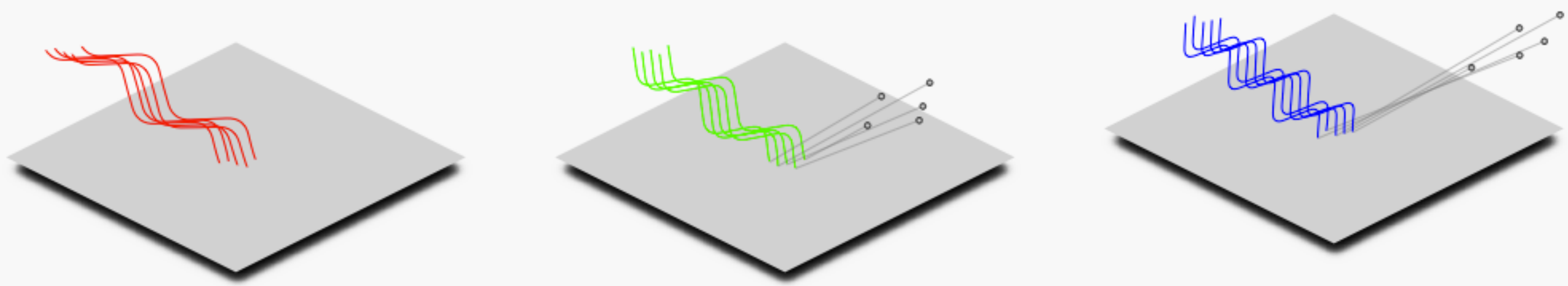


- Thermally generated electrons are indistinguishable from photo-generated electrons . They constitute a noise source known as 'Dark Current' and it is important that CCDs are kept cold to reduce their number.

- 3.72-1.26eV corresponds to the energy of light with wavelengths between 0.33 and 1μm. Beyond 1μm silicon becomes transparent and CCDs constructed from silicon become insensitive. Thinning and coating allows detection shorter wavelengths.

Photoelectric Effect

- Classical physics would predict that a more intense beam of light would eject electrons with greater energy than a less intense beam *no matter what the frequency*.
- Given that it is possible to move electrons with light and based on the concept of the wave model of light that the energy in a beam of light is related to its intensity,



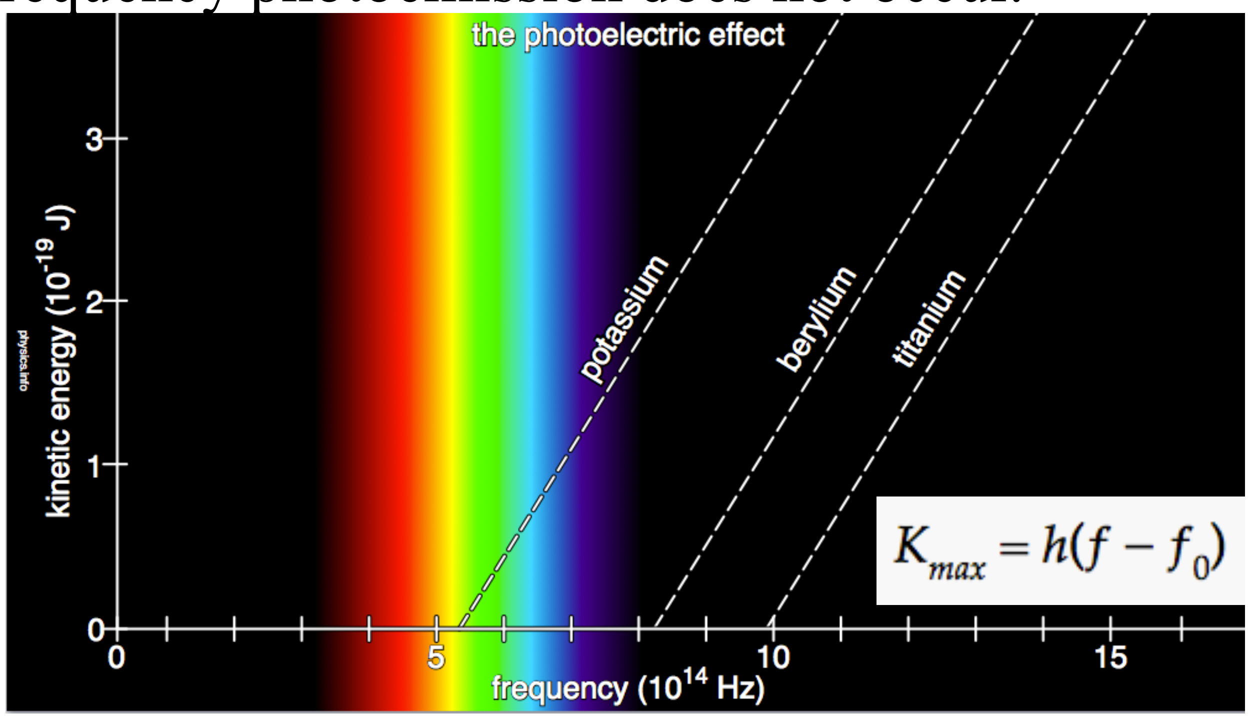
Red light does not eject photoelectrons (even if it is very bright).

Green light does eject photoelectrons (even if it is very dim).

Blue light ejects photoelectrons with more energy than green light (even if it is very dim).

Photoelectric Effect

- Einstein realized that light was behaving as if it was composed of tiny particles (photons) and that the energy of each particle was proportional to the frequency of the electromagnetic radiation.
- electron energy increases with frequency in a simple linear manner above the threshold (slope equal to Planck's constant).
- Below a threshold frequency photoemission does not occur.
- Each curve has a different intercept on the energy axis, which shows that threshold frequency is a function of the material.



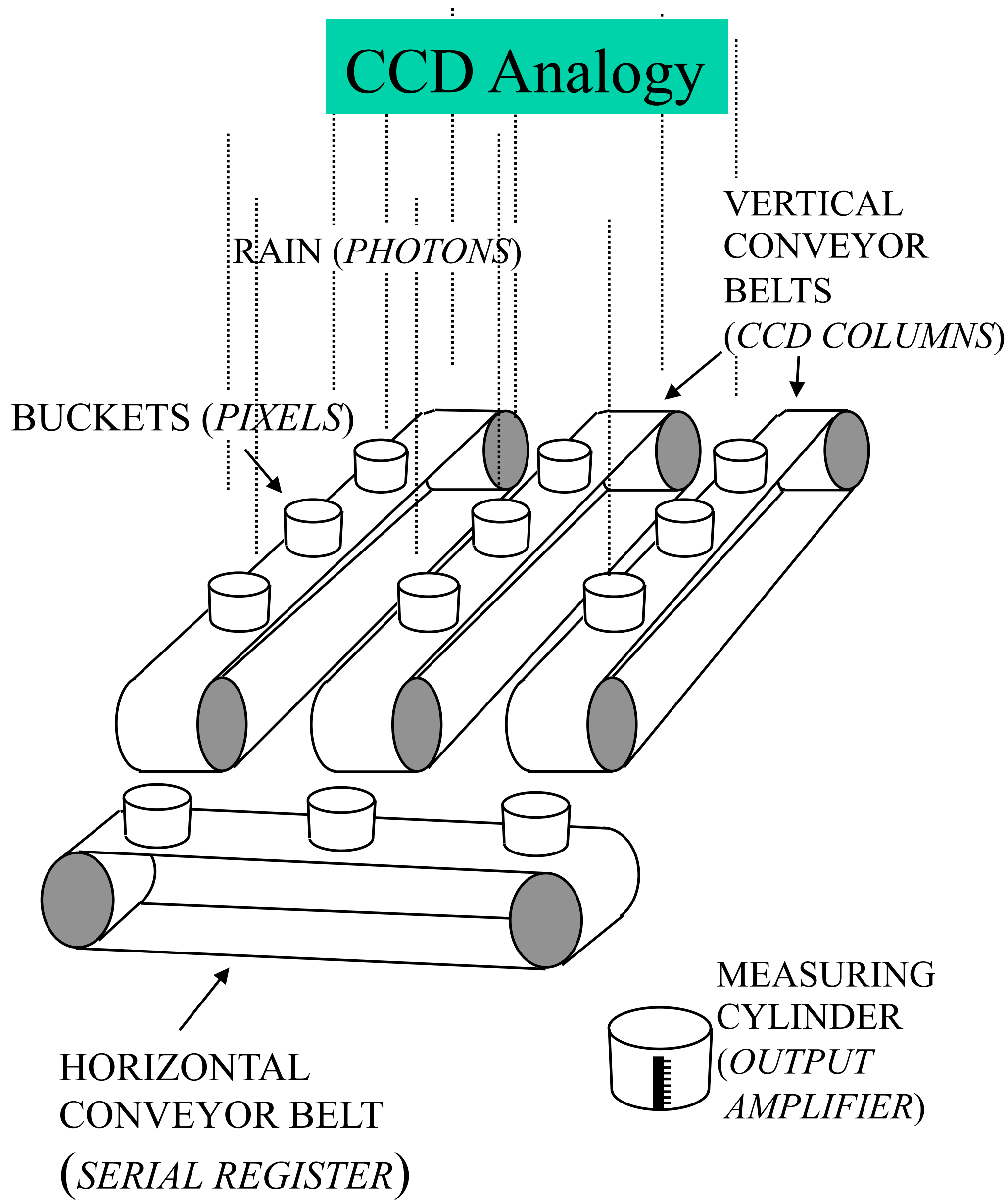
CCD Analogy

A common analogy for the operation of a CCD is as follows:

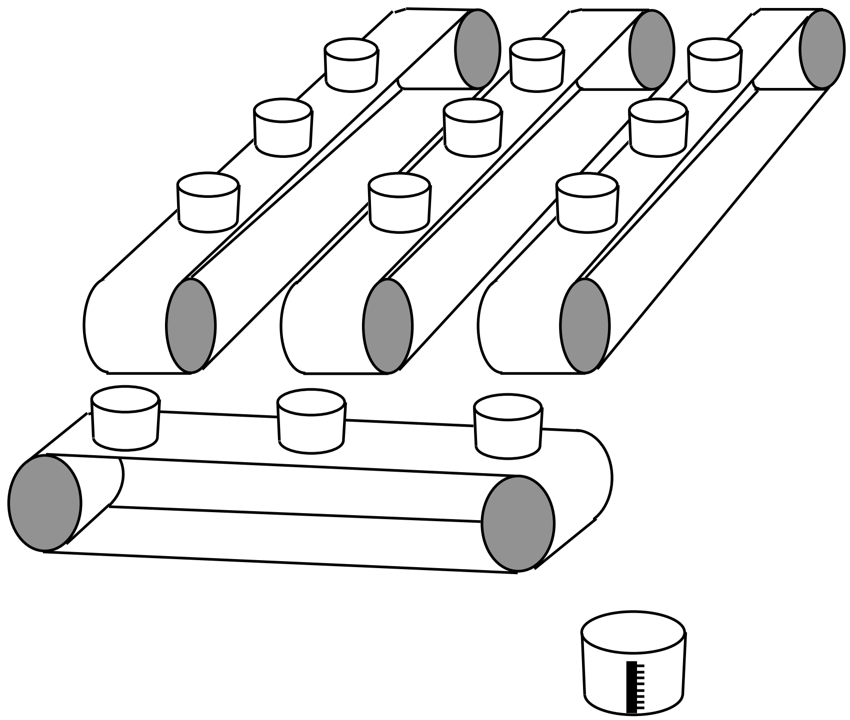
- Pixels/buckets are distributed across a field (Focal Plane of a camera/telescope).
- The buckets are placed on top of a series of parallel conveyor belts and collect rain fall (Photons) across the field.
- The conveyor belts are initially stationary, while the photos fill the
- buckets (During the course of the exposure/integration time).
- Once the The camera shutter "closes" the conveyor belts start turning and transfer the buckets of rain , one-by-one, to a measuring cylinder
- Electronic Amplifier at the corner of the field (at the corner of the CCD)
- Electronic signal (current) is read out into a digital number using an analog to digital converter with a certain gain state (electrons per DN)

The animation in the following slides demonstrates how the conveyor belts work.

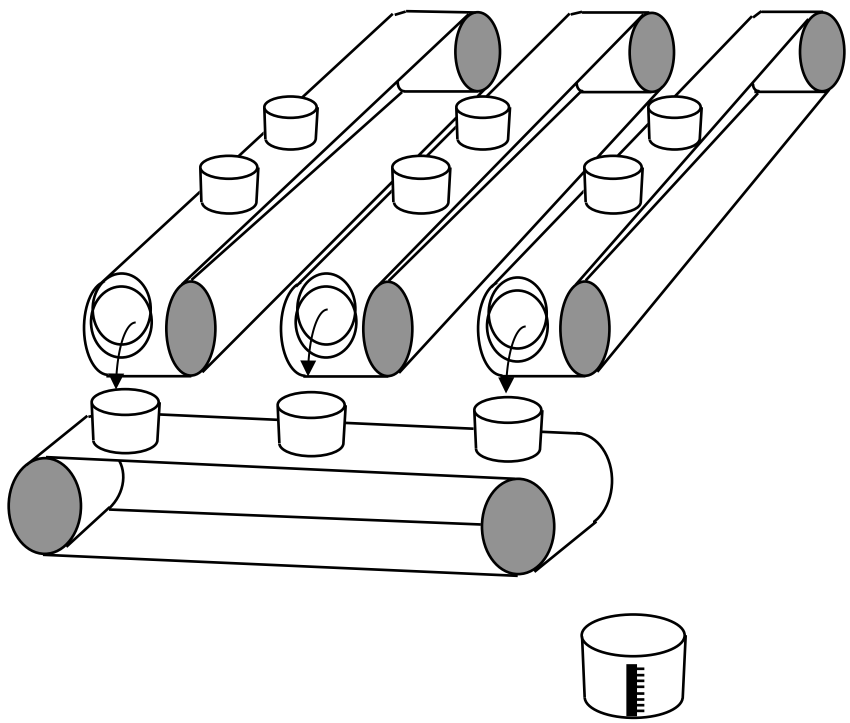
CCD Analogy


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

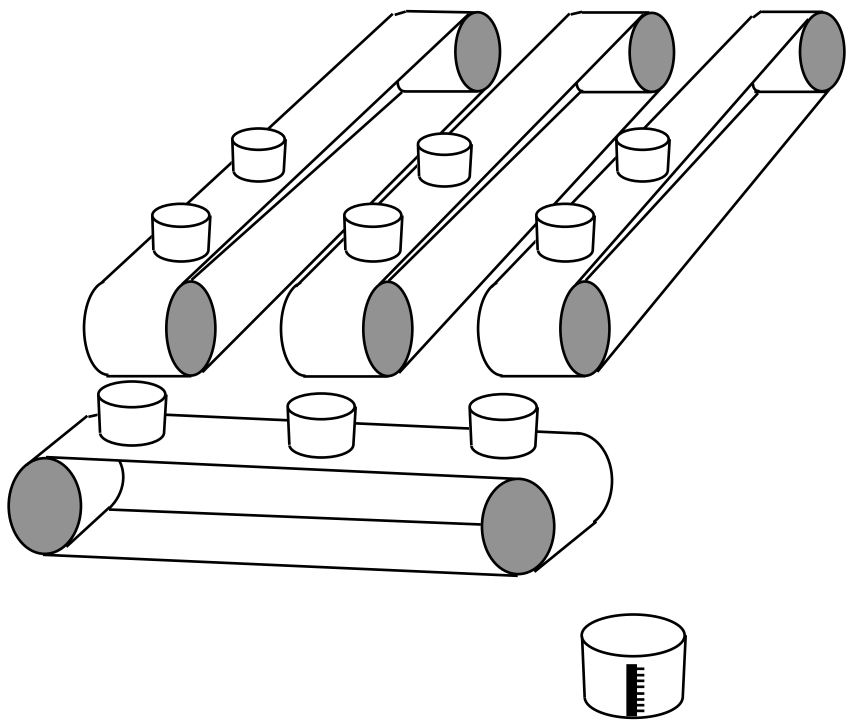
Exposure finished, buckets now contain samples of rain.



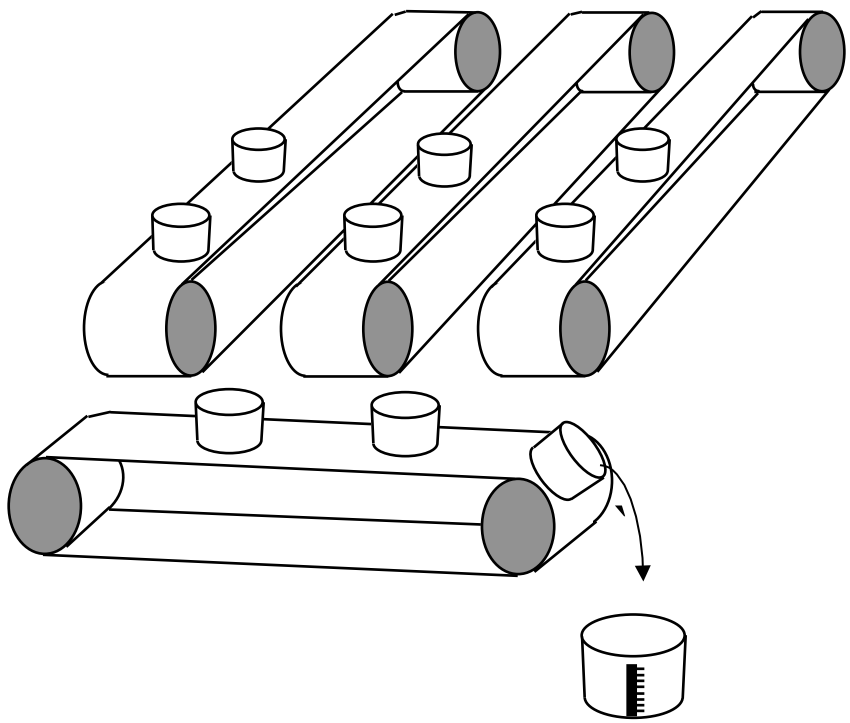
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.

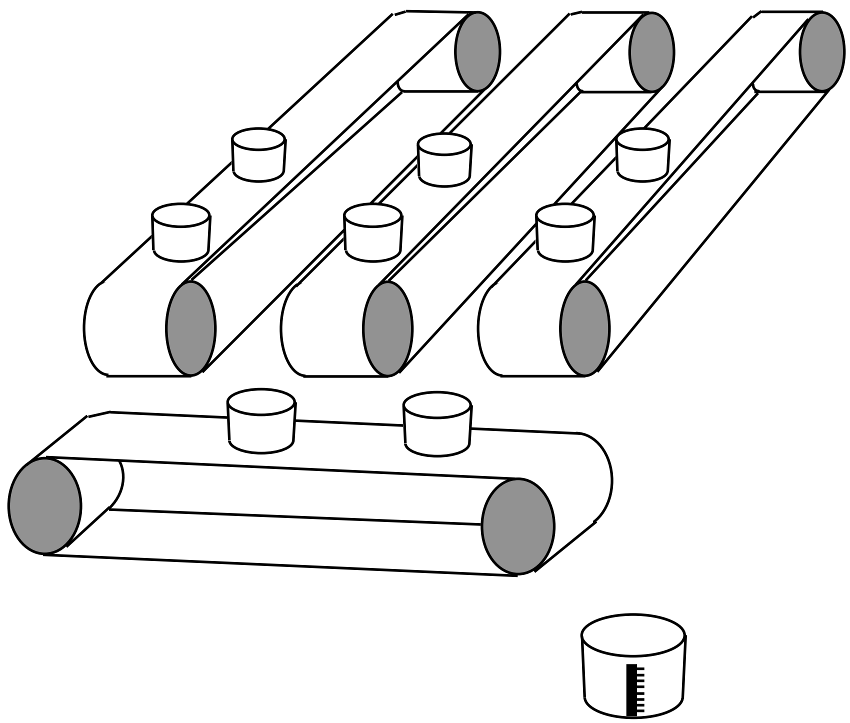


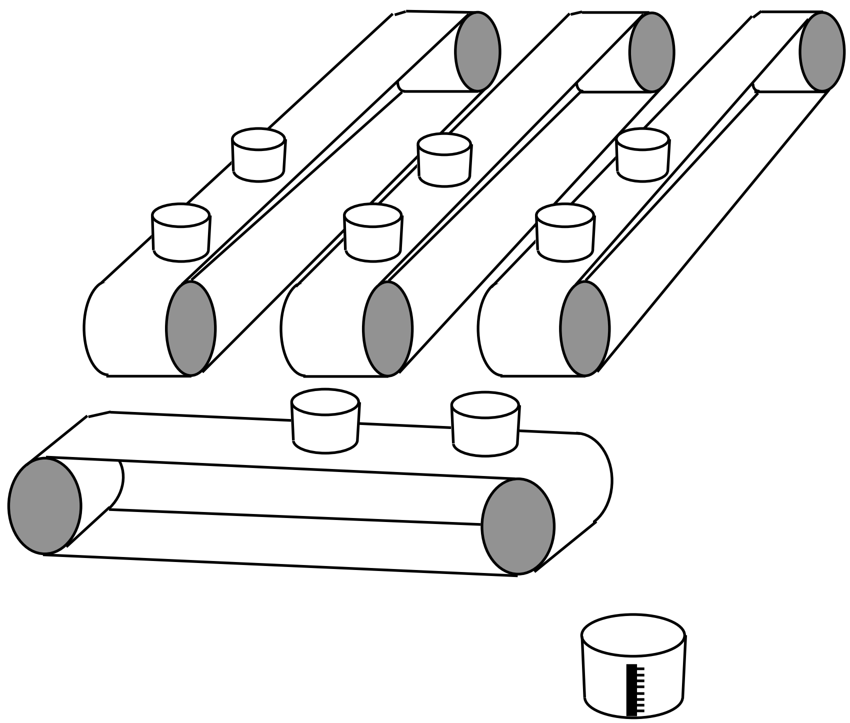
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .

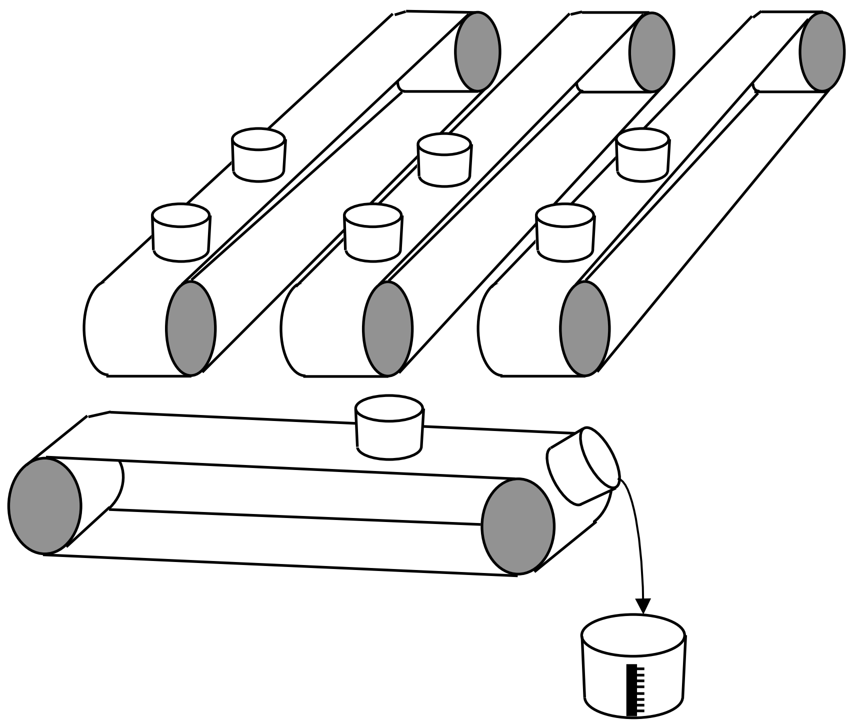


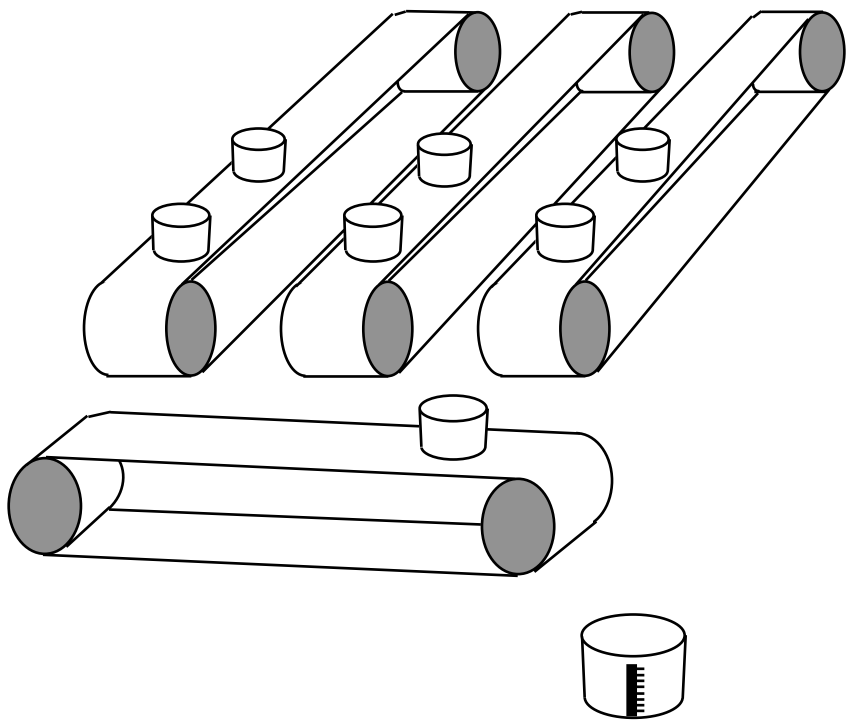
After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.

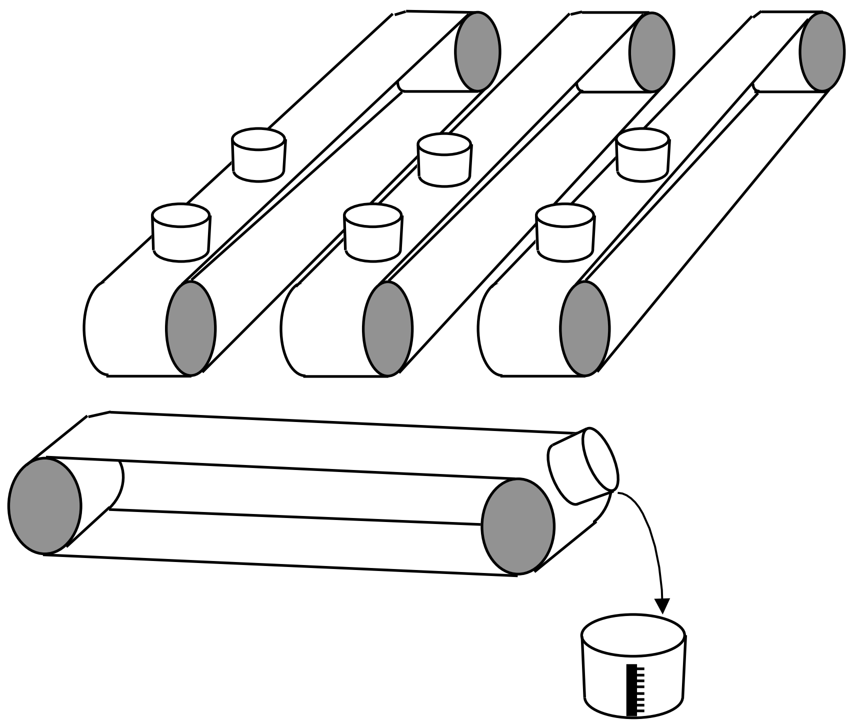


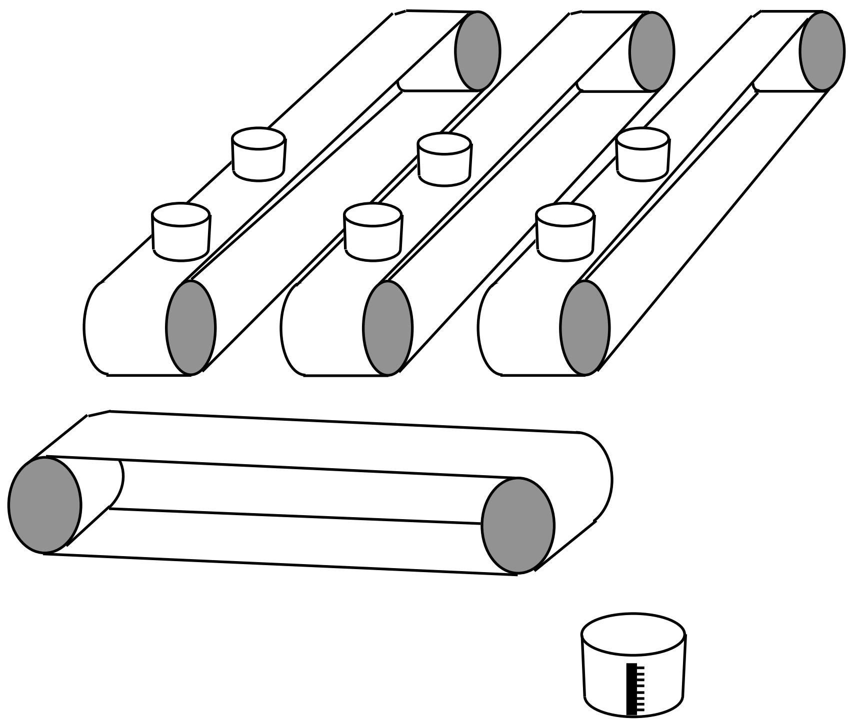




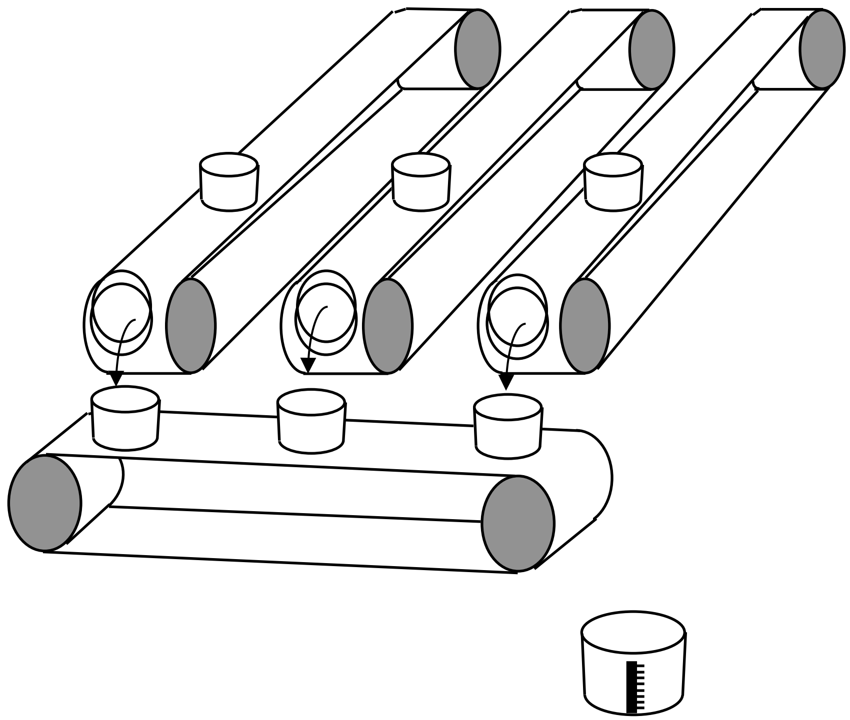


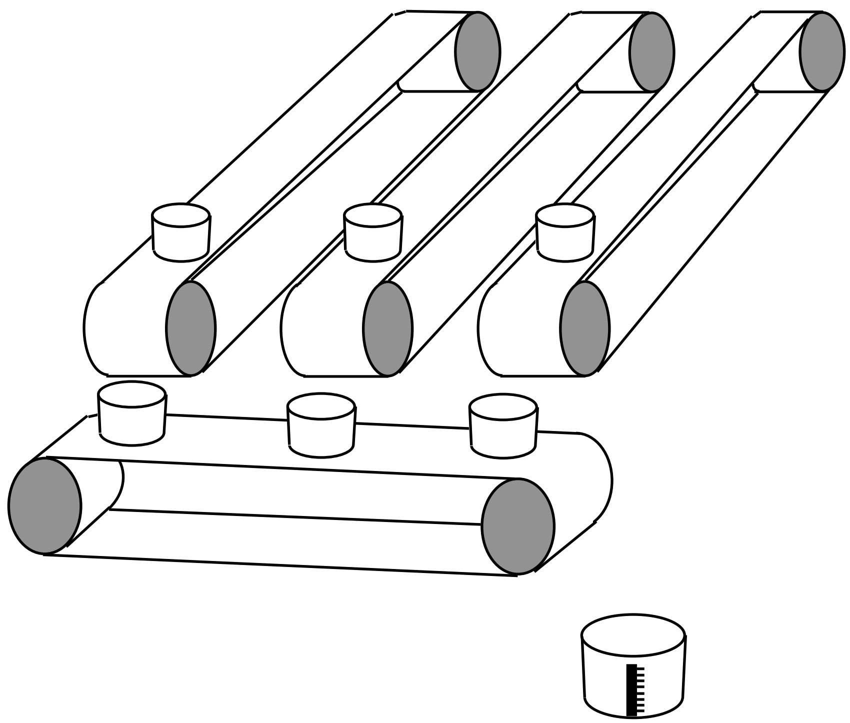


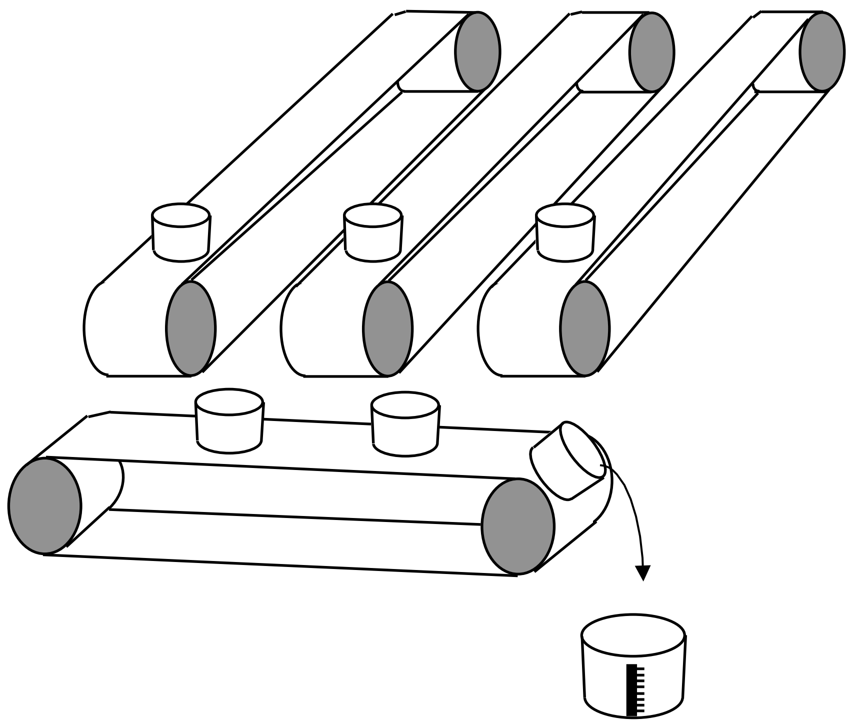


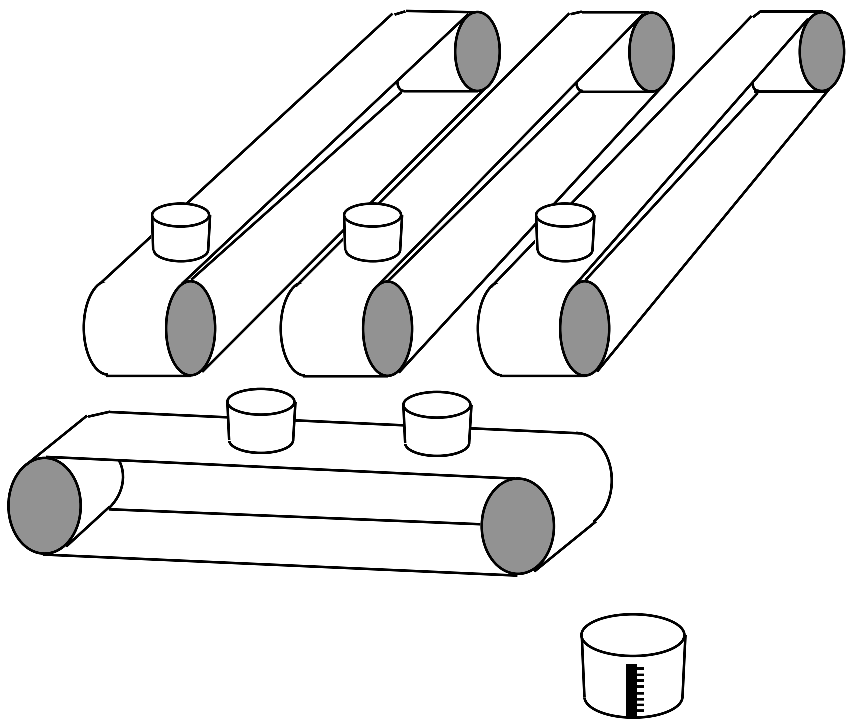


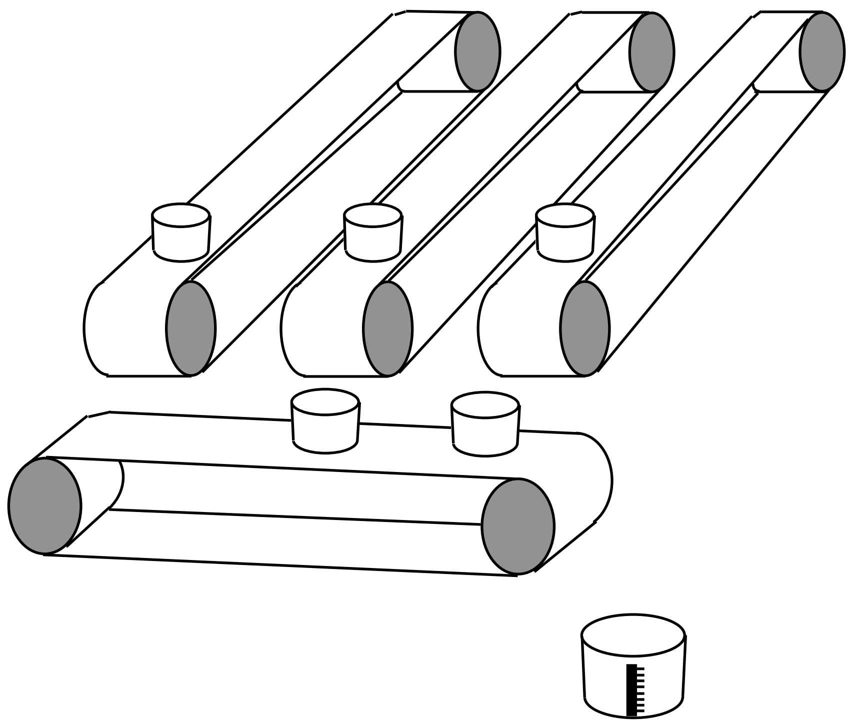
A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.

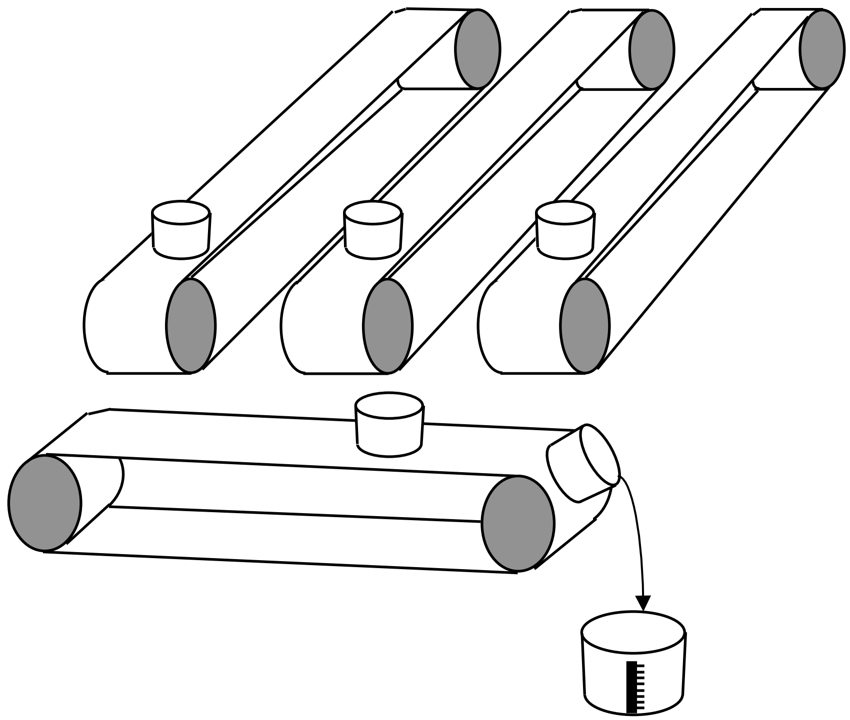


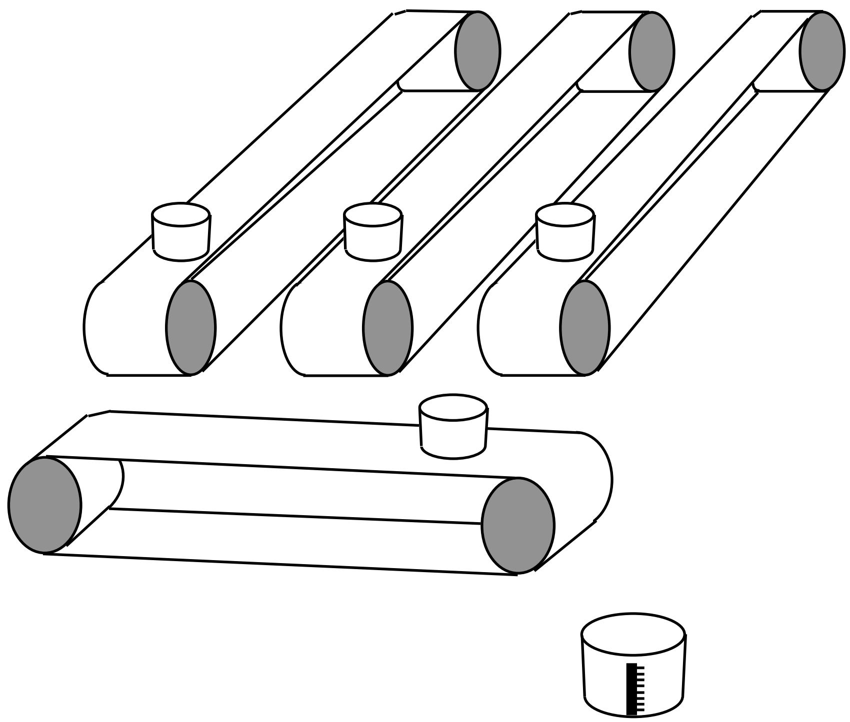


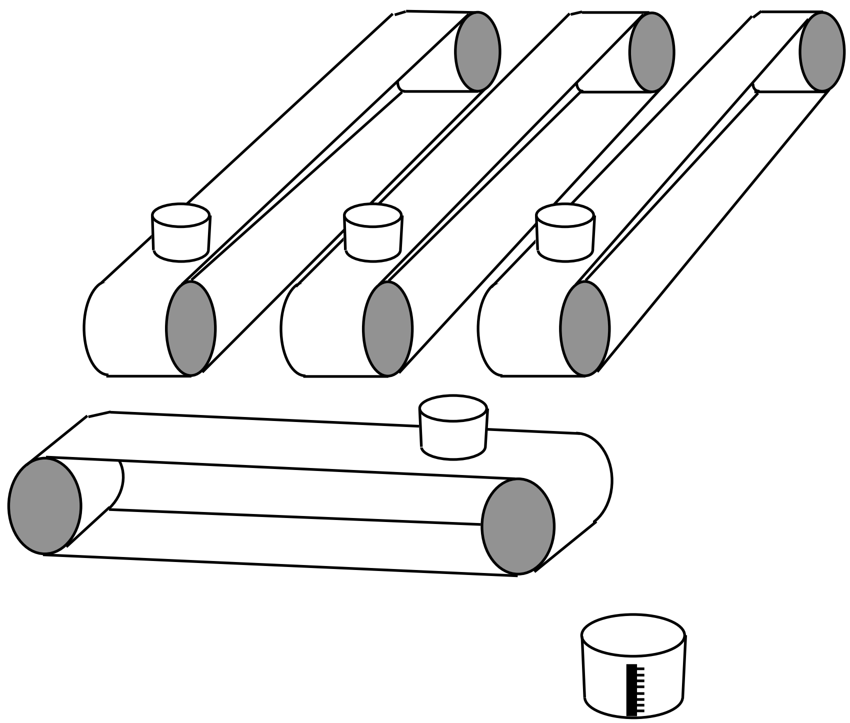


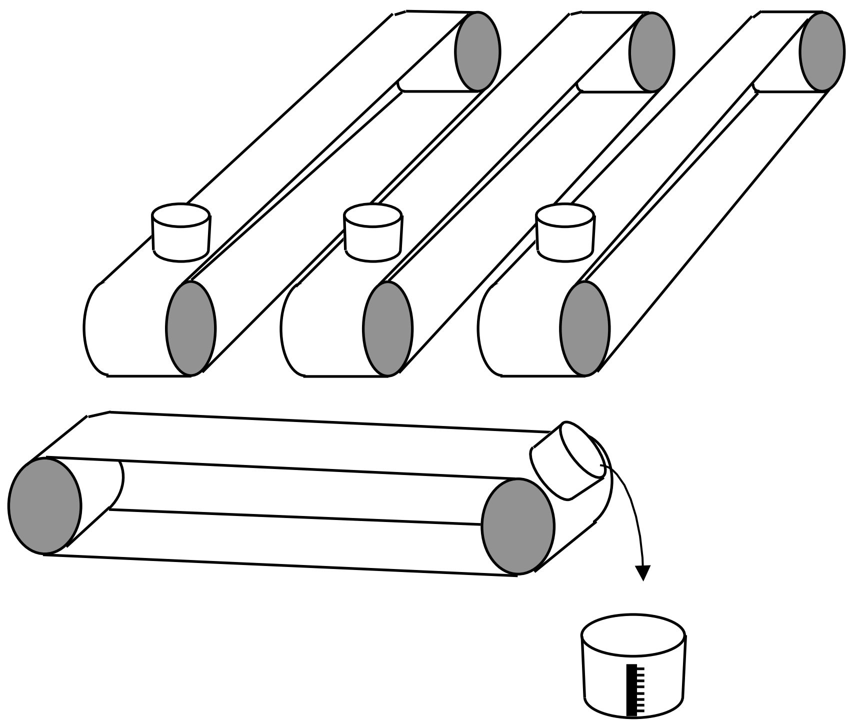


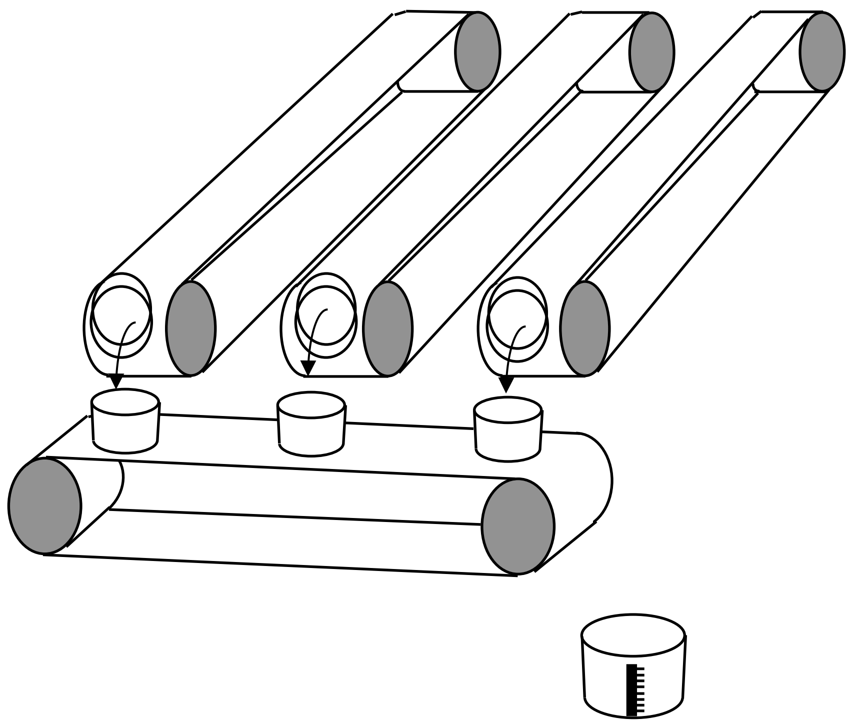


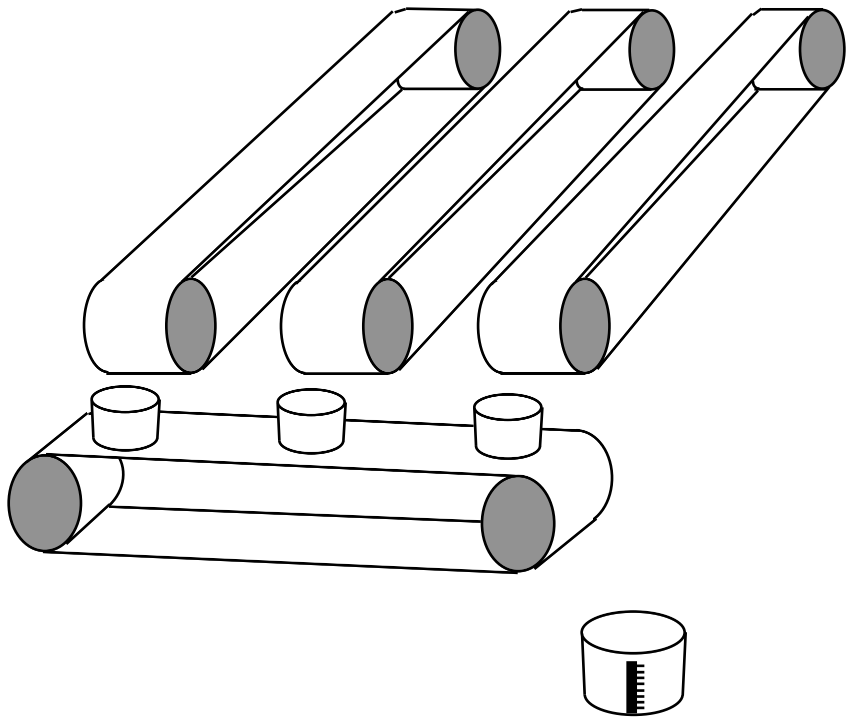


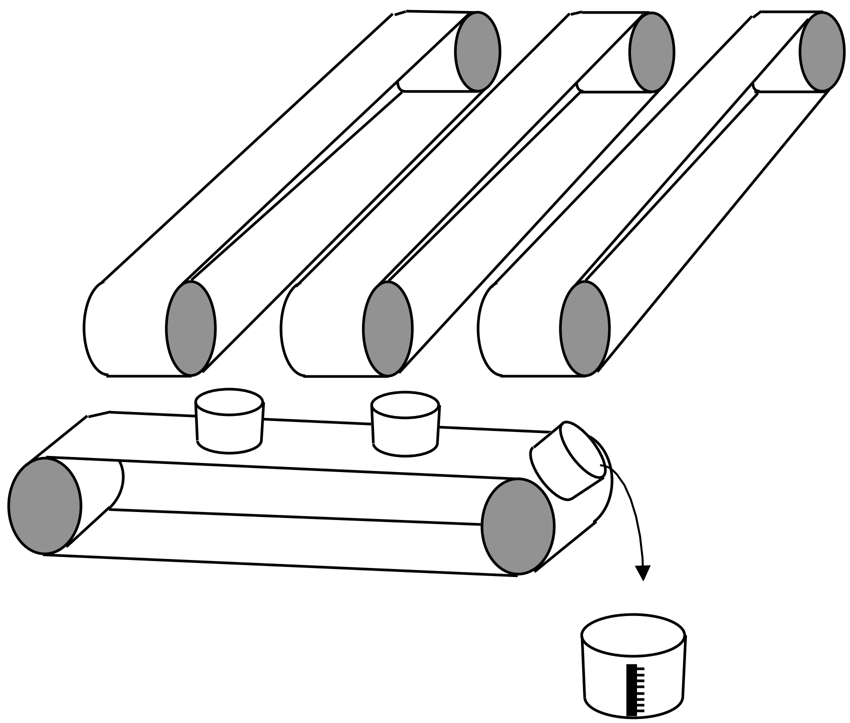


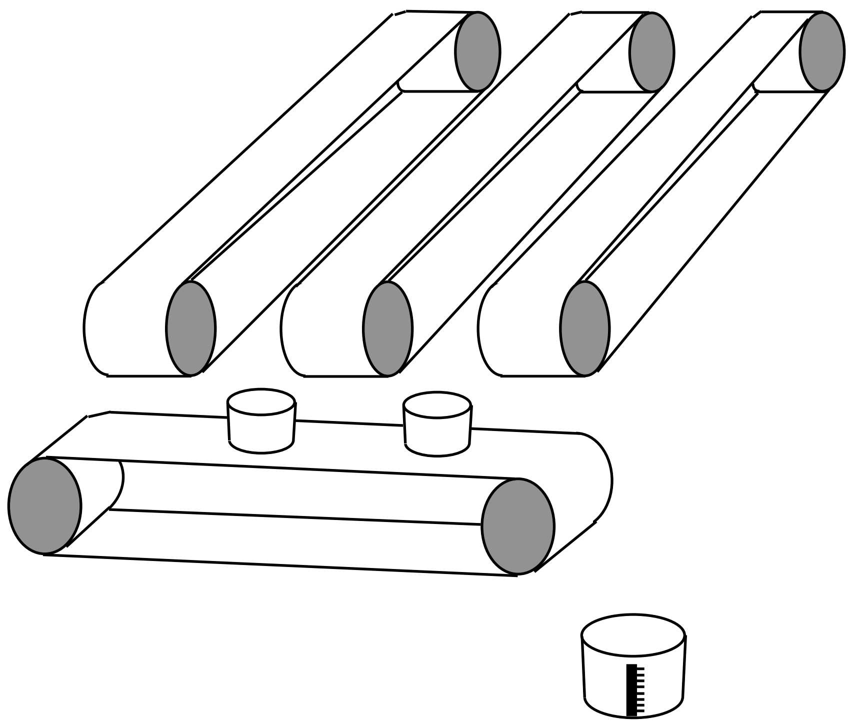


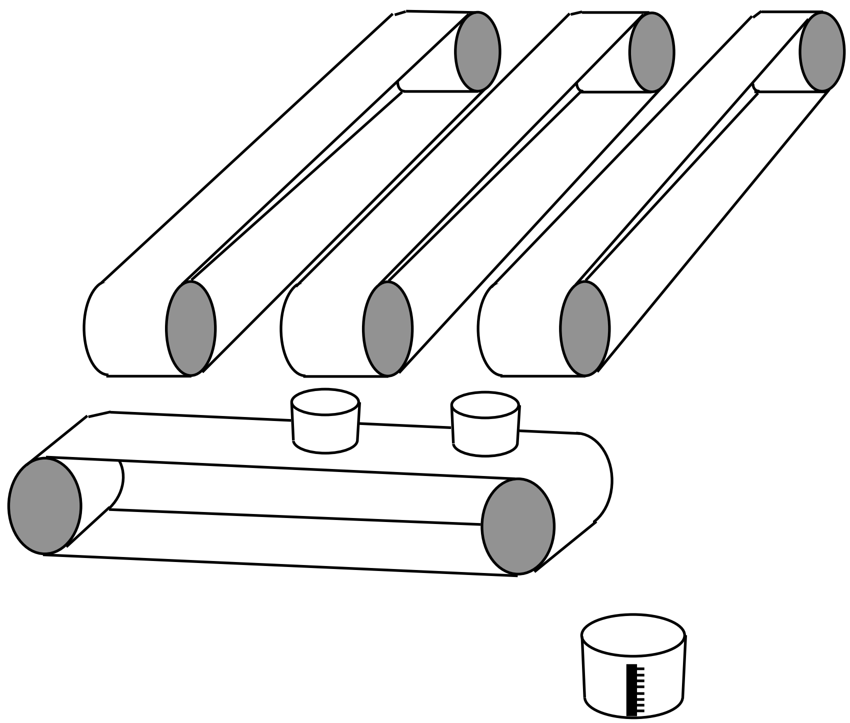


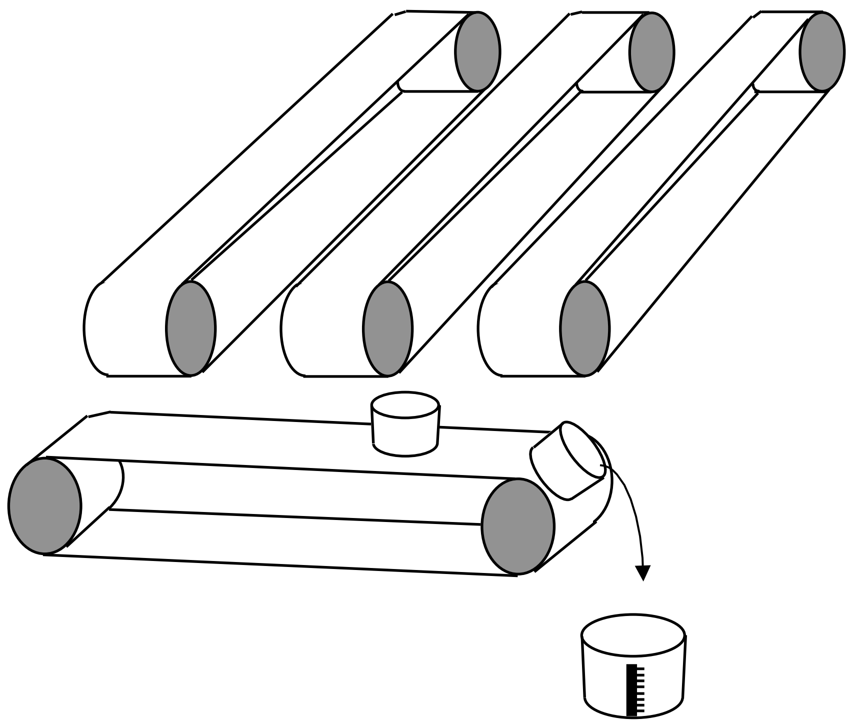


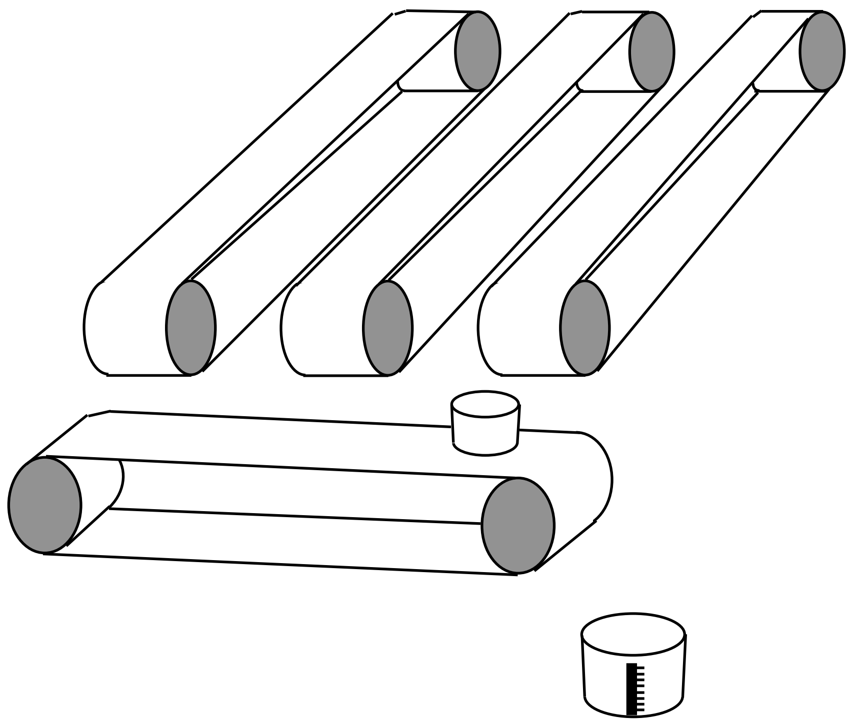


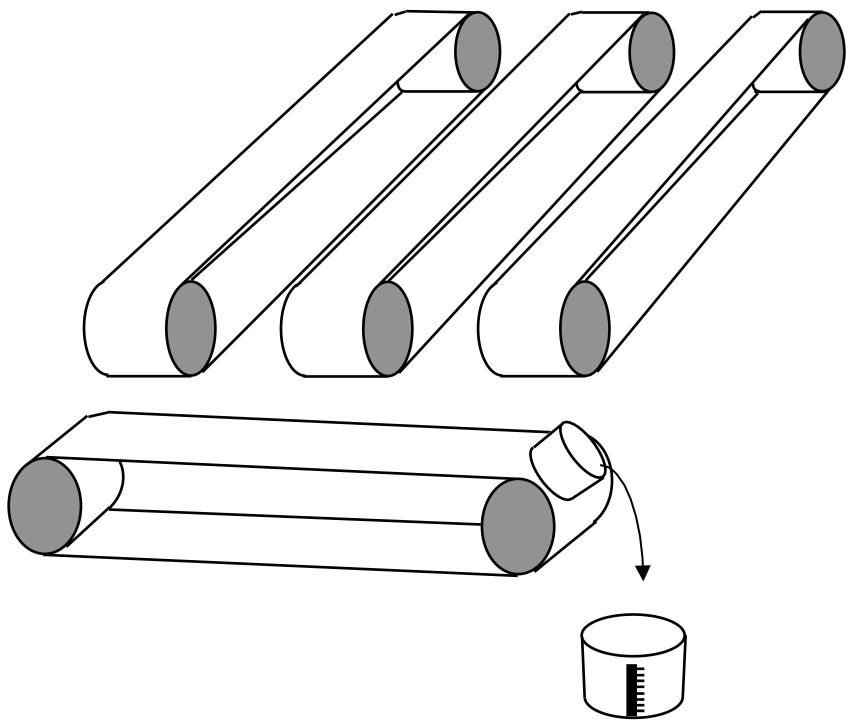




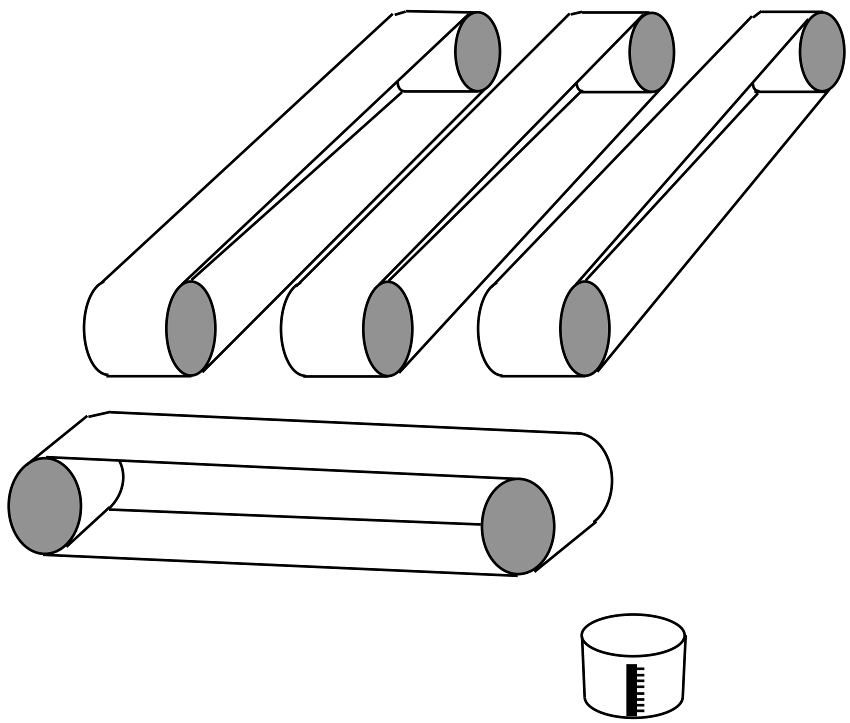






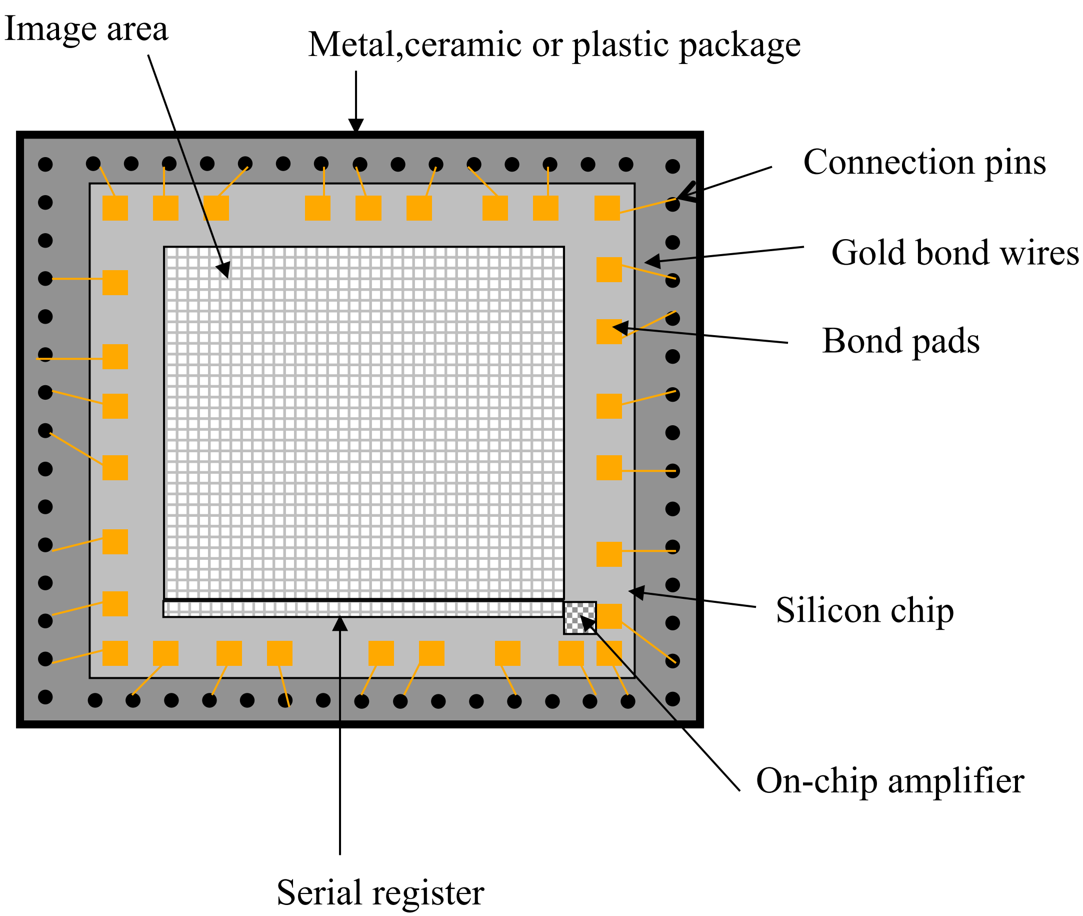


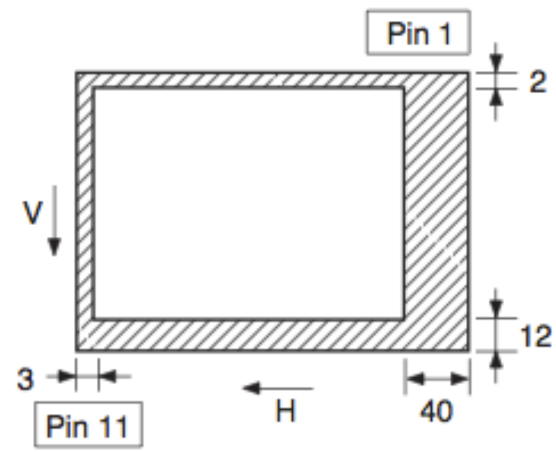
Eventually all the buckets have been measured, the CCD has been read out.



Structure of a CCD

- The image area of the CCD is positioned at the focal plane of the camera.
- An image then builds up that consists of a pattern of electric charge.
- At the end of the exposure this pattern is then transferred, pixel at a time, by way of the serial register to the on-chip amplifier.



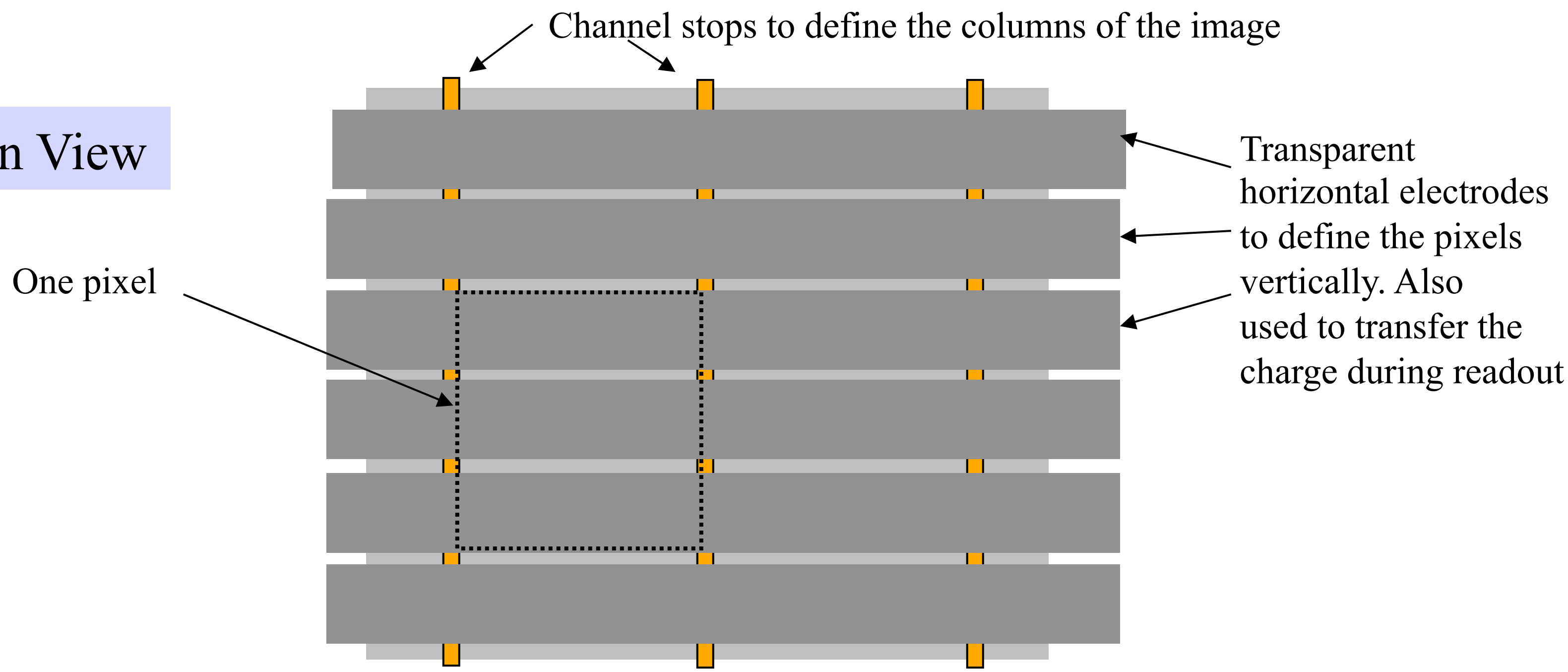


Our CCD is 752x582
But true size is 795x596

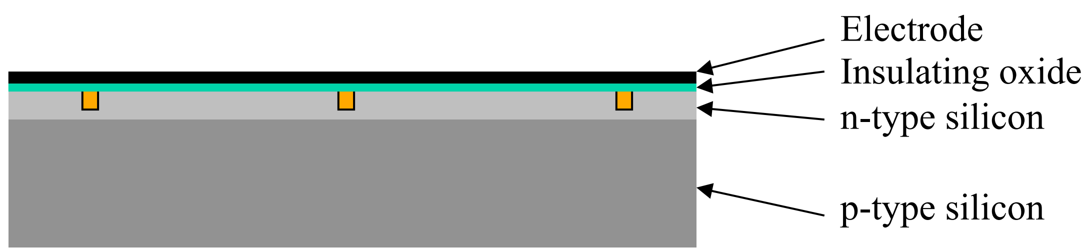
Structure of a CCD

The diagram shows a small section (a few pixels) of the image area of a CCD. This pattern is repeated.

Plan View



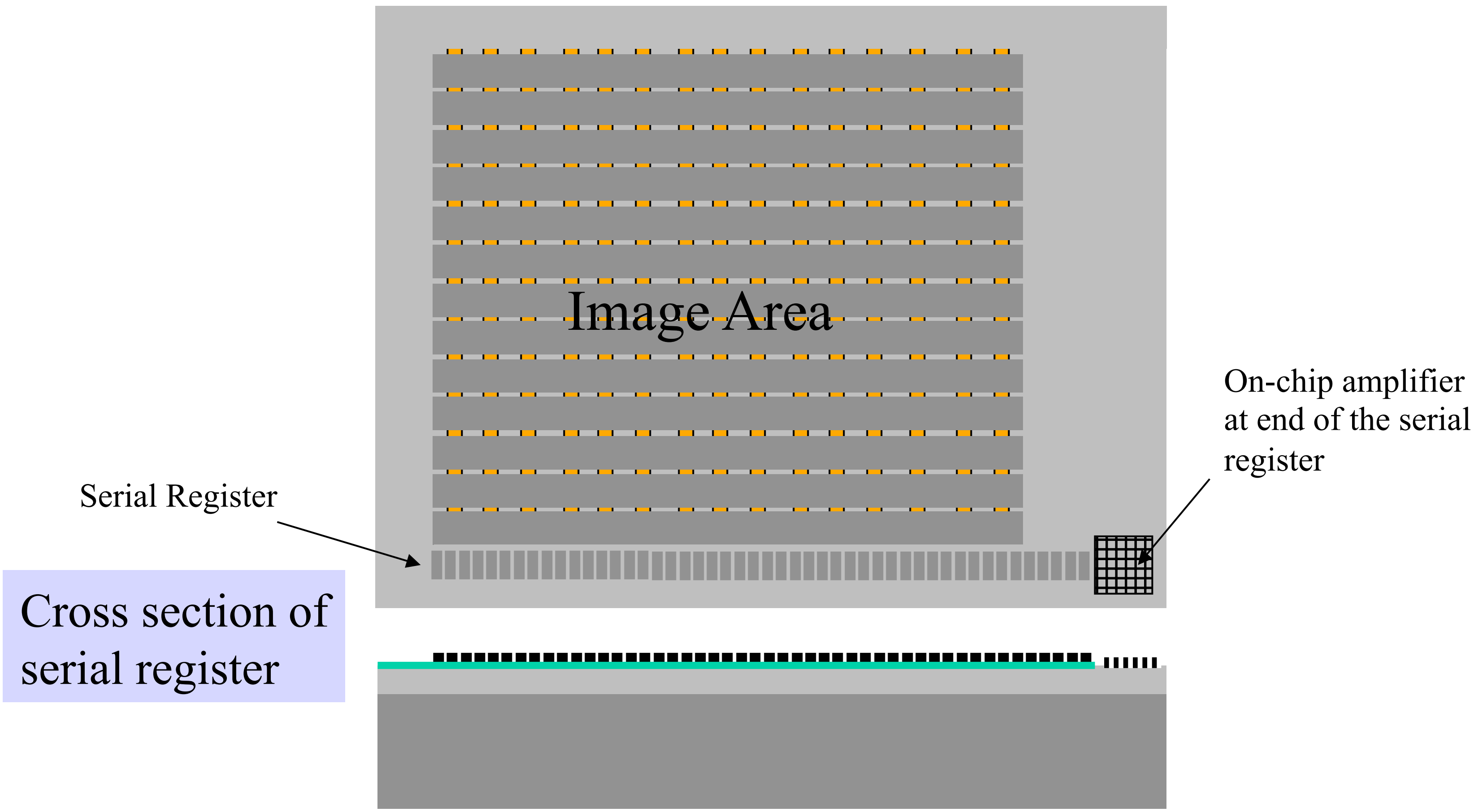
Cross section



Every third electrode is connected together. Bus wires running down the edge of the chip make the connection. The channel stops are formed from high concentrations of Boron in the silicon.

Structure of a CCD

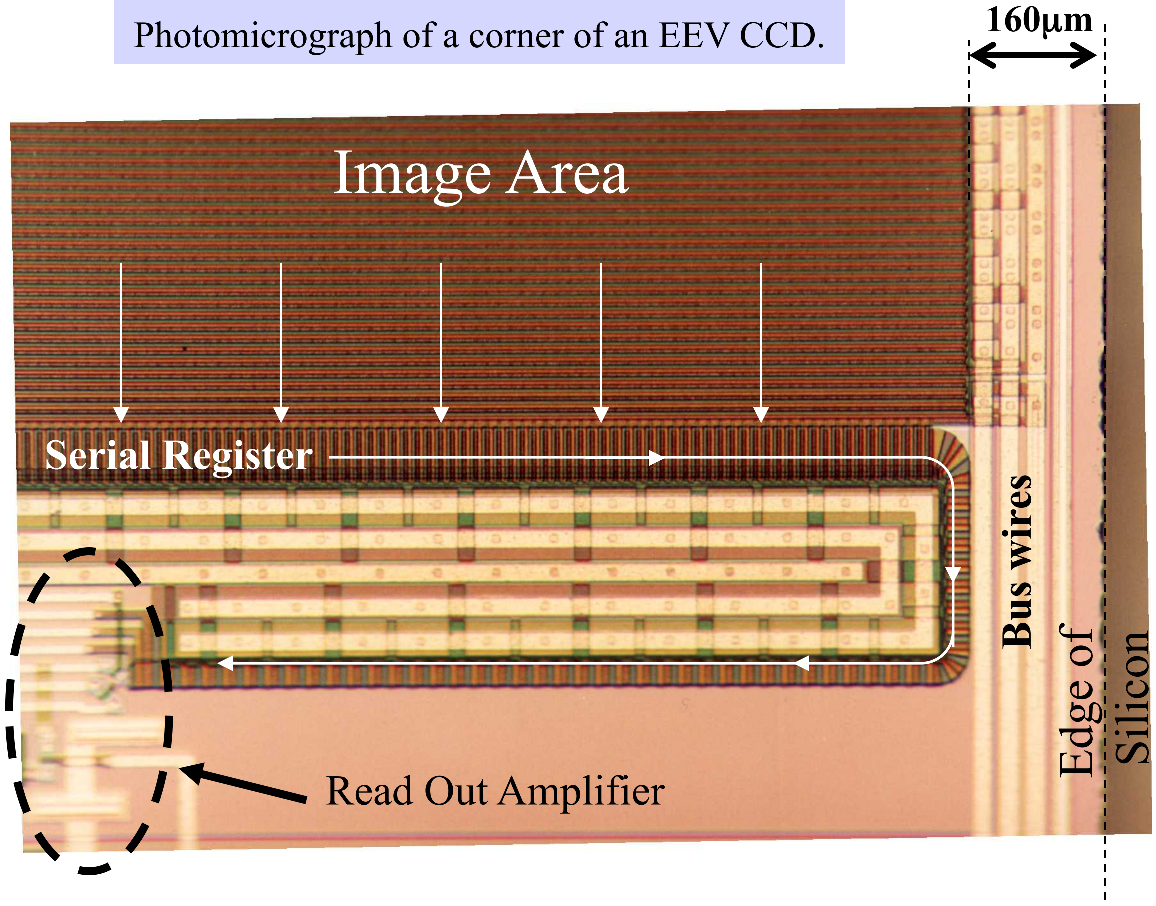
Below the image area (the area containing the horizontal electrodes) is the 'Serial register'. This also consists of a group of small surface electrodes. There are three electrodes for every column of the image area



Once again every third electrode is in the serial register connected together.

Structure of a CCD

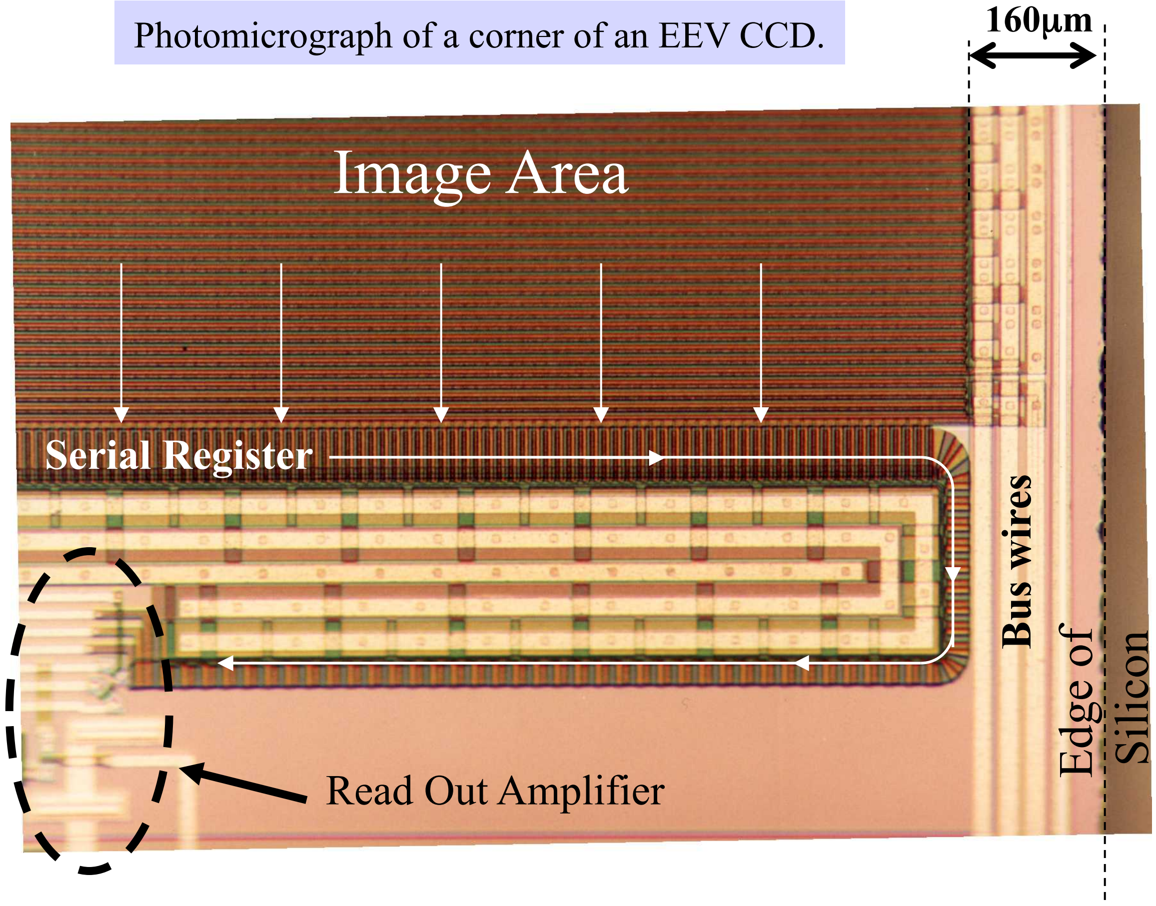
Photomicrograph of a corner of an EEV CCD.



The serial register is bent double to move the output amplifier away from the edge of the chip. This useful if the CCD is to be used as part of a mosaic.The arrows indicate how charge is transferred through the device.

Structure of a CCD

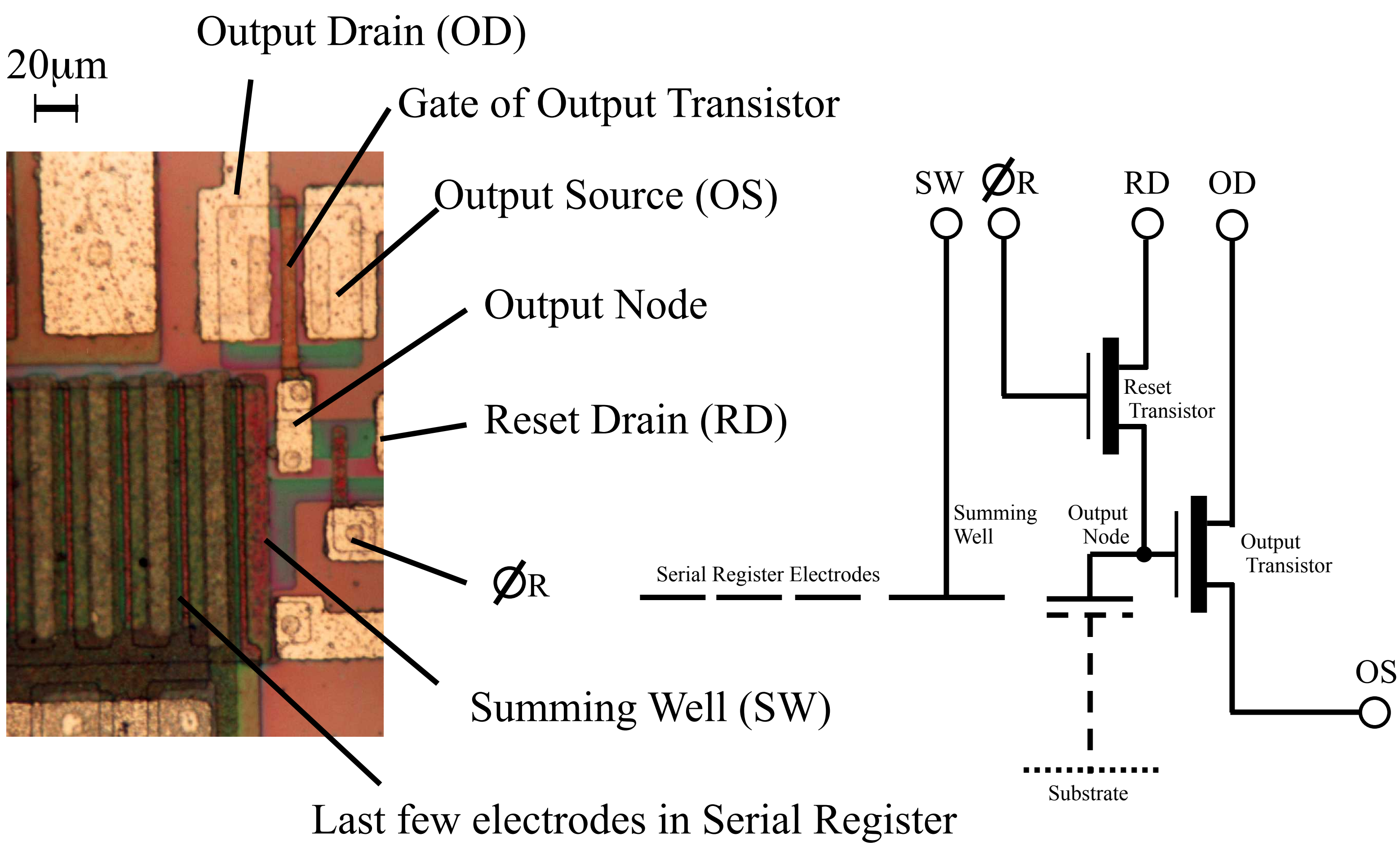
Photomicrograph of a corner of an EEV CCD.



The serial register is bent double to move the output amplifier away from the edge of the chip. This useful if the CCD is to be used as part of a mosaic.The arrows indicate how charge is transferred through the device.

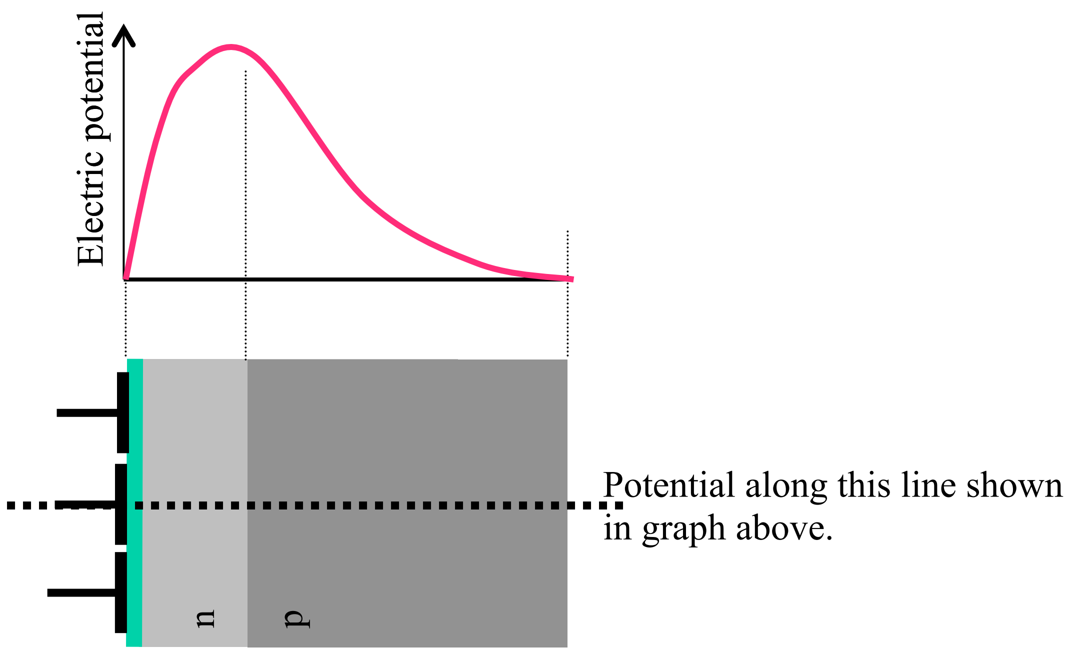
Structure of a CCD

Photomicrograph of the on-chip amplifier of a Tektronix CCD and its circuit diagram.



Electric Field in a CCD

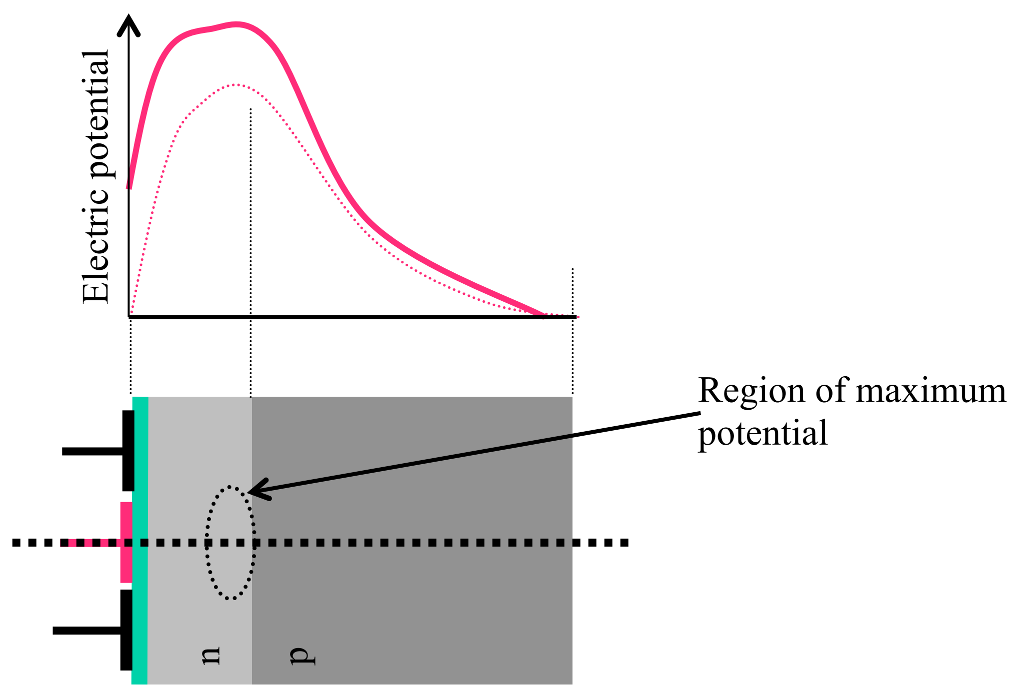
- n-type layer contains an excess of electrons that diffuse into the p-layer.
- p-layer contains an excess of holes that diffuse into the n-layer.
- The diffusion creates a charge imbalance and induces an internal electric field.
- The electric potential reaches a maximum just inside the n-layer, and it is here that any photo-generated electrons will collect.



Cross section through the thickness of the CCD

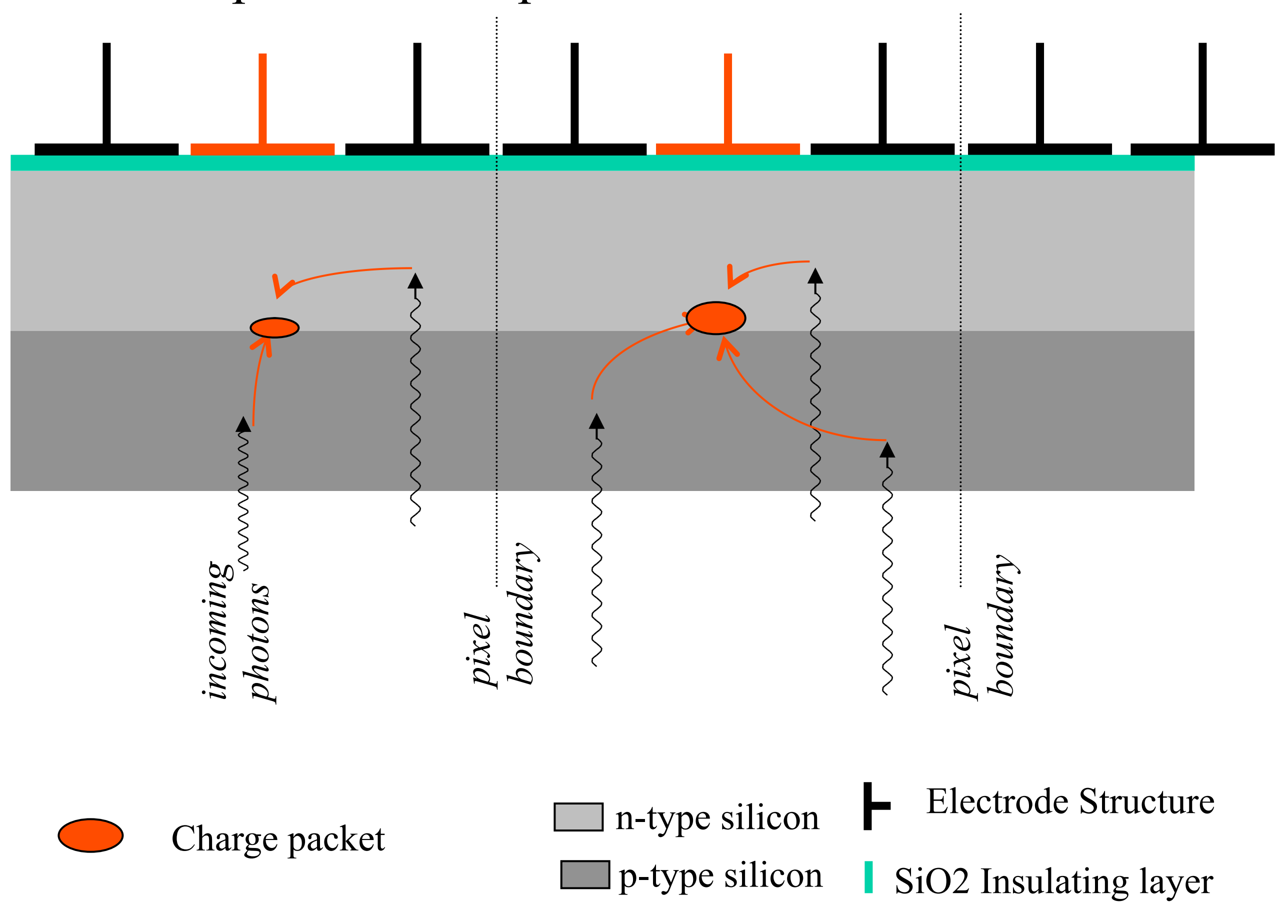
Electric Field in a CCD

During integration of the image, one of the electrodes in each pixel is held at a positive potential. This further increases the potential in the silicon below that electrode and it is here that the photoelectrons are accumulated. The neighboring electrodes, with their lower potentials, act as potential barriers that define the vertical boundaries of the pixel. The horizontal boundaries are defined by the channel stops.



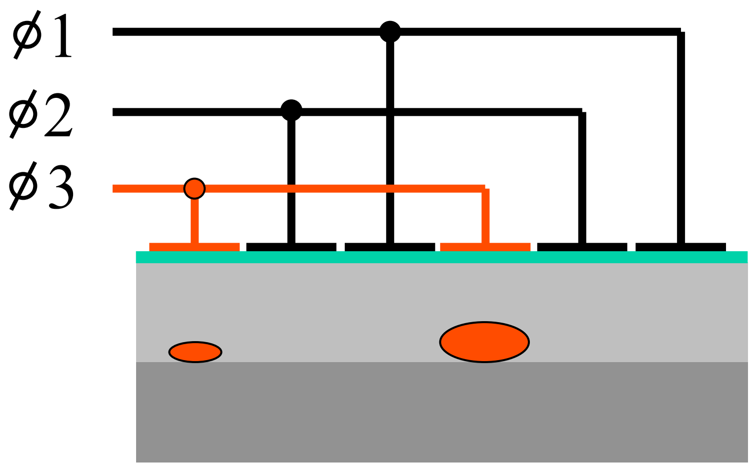
Charge Collection in a CCD

- Photons entering the CCD create electron-hole pairs.
- electrons are then attracted towards the most positive potential in the device where they create 'charge packets'.
- Each packet corresponds to one pixel

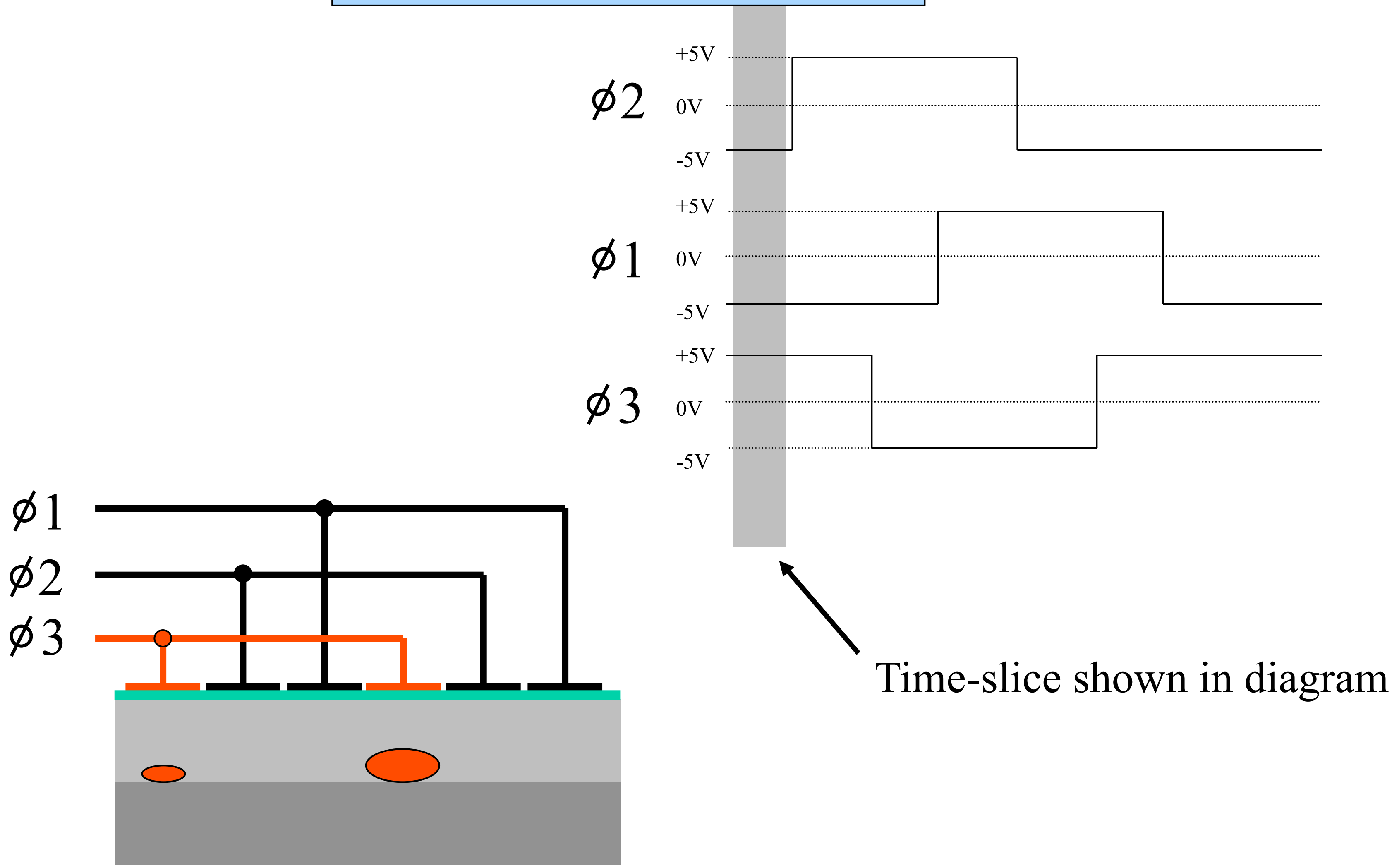


Charge Transfer in a CCD

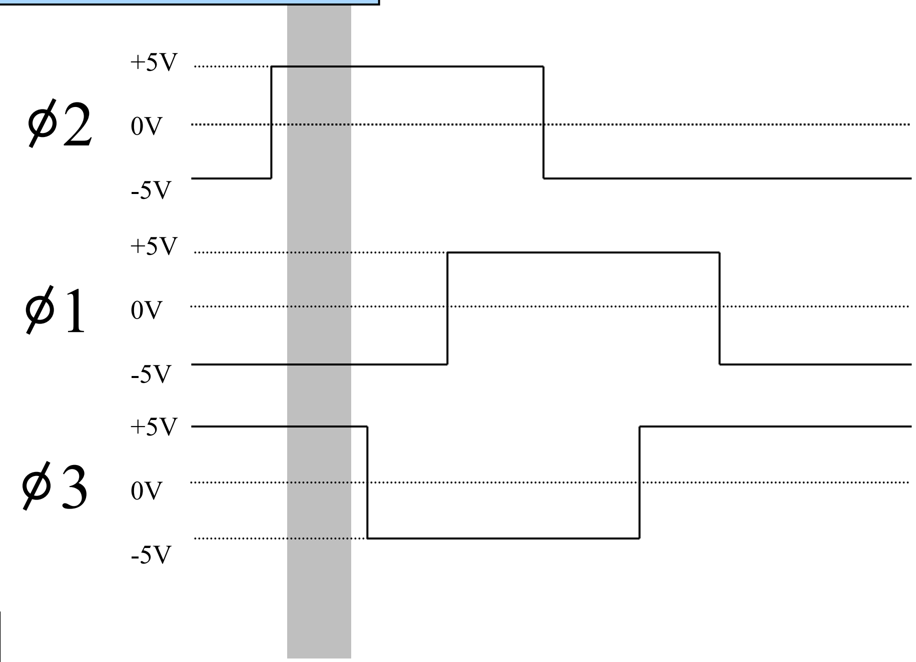
In the following few slides, the implementation of the 'conveyor belts' as actual electronic structures is explained.
The charge is moved along these conveyor belts by modulating the voltages on the electrodes positioned on the surface of the CCD. In the following illustrations, electrodes color coded red are held at a positive potential, those colored black are held at a negative potential.

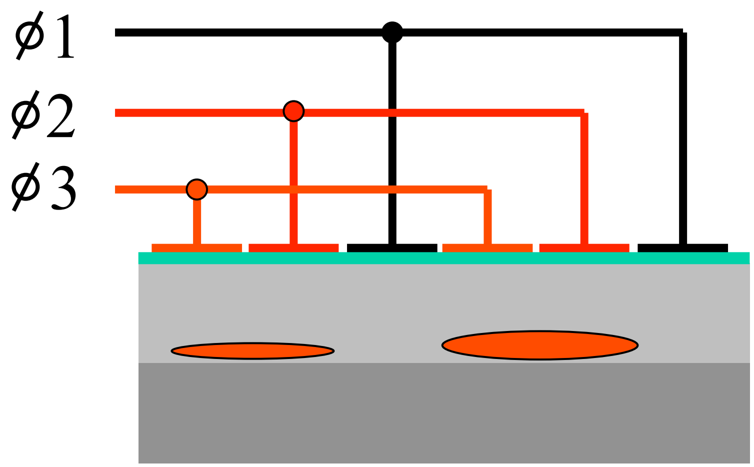


Charge Transfer in a CCD

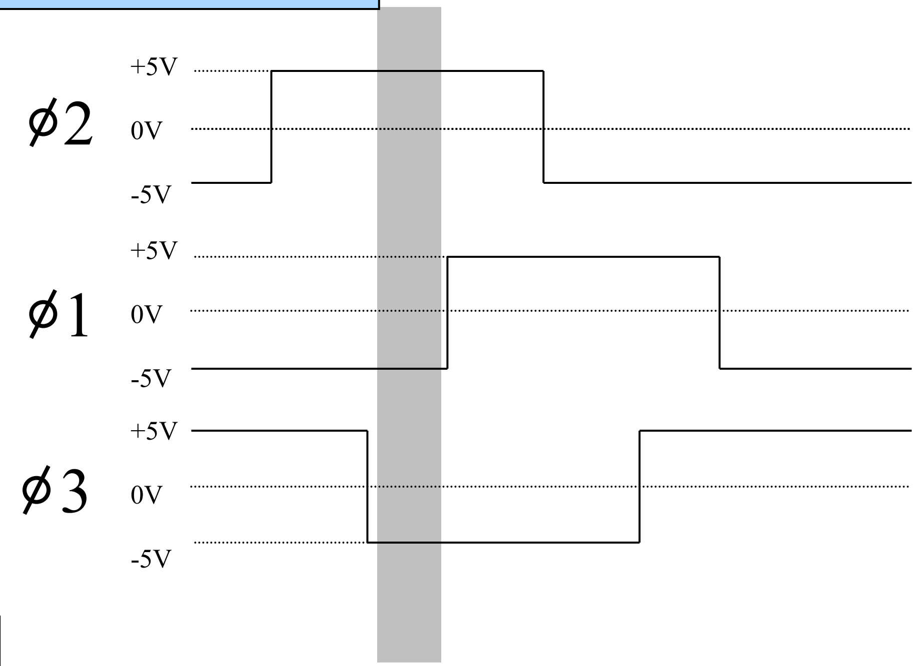


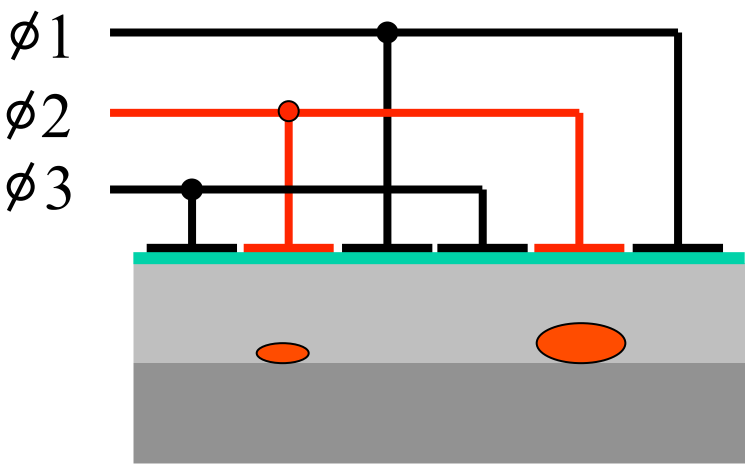
Charge Transfer in a CCD 3.



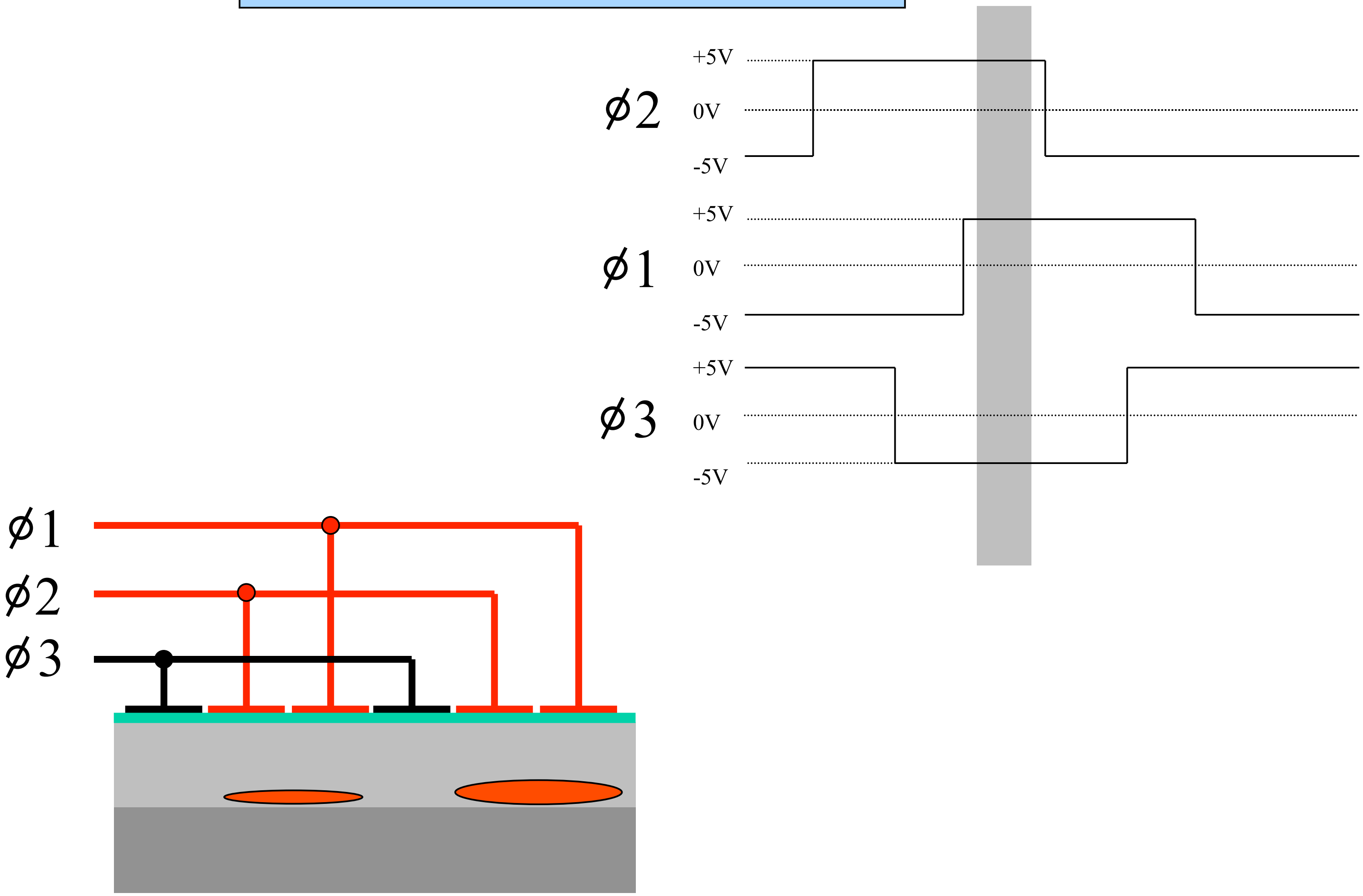


Charge Transfer in a CCD 4.

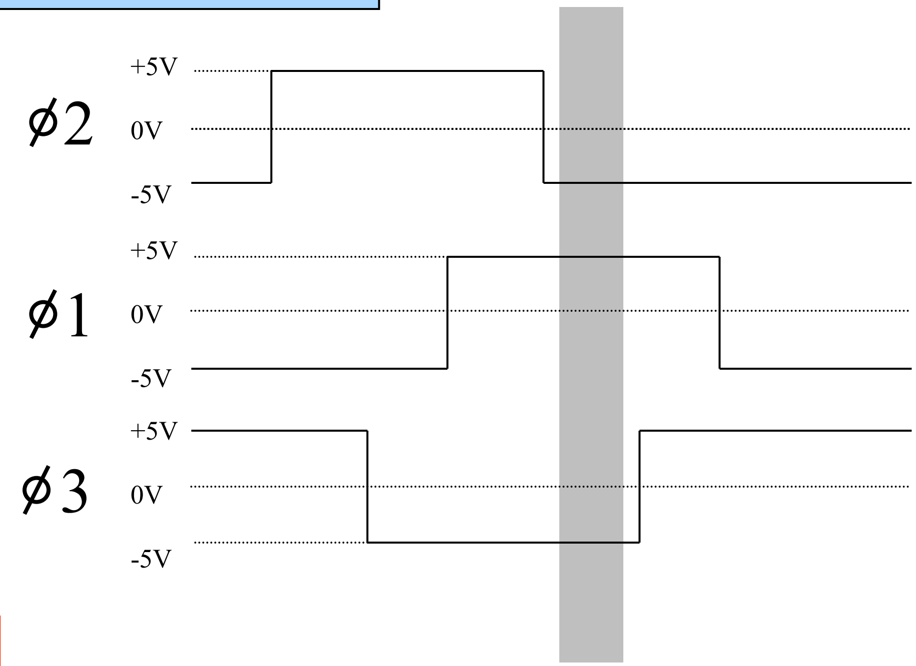


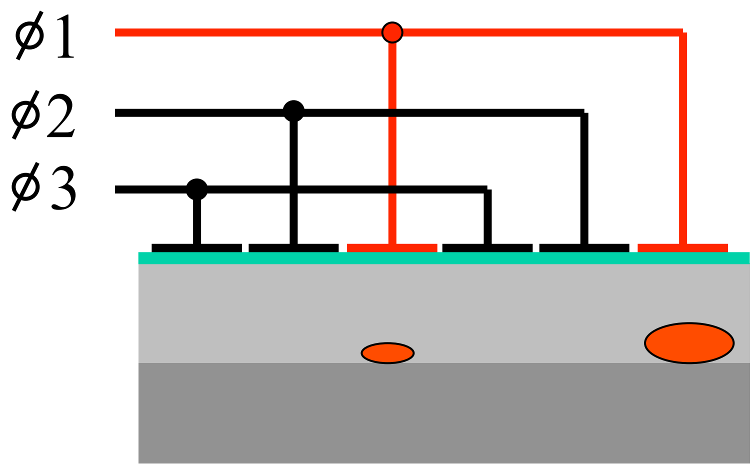


Charge Transfer in a CCD 5.

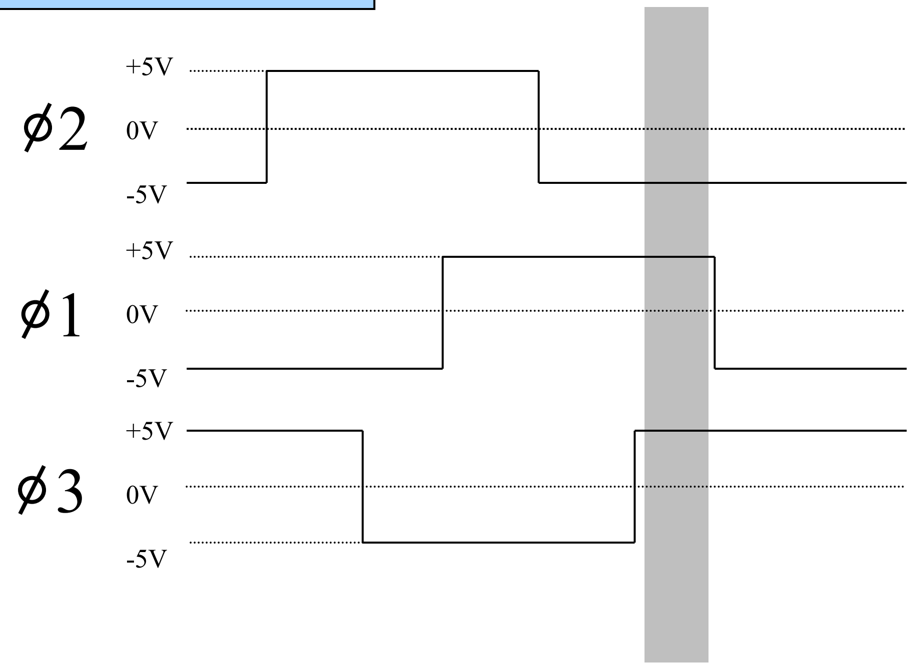


Charge Transfer in a CCD 6.

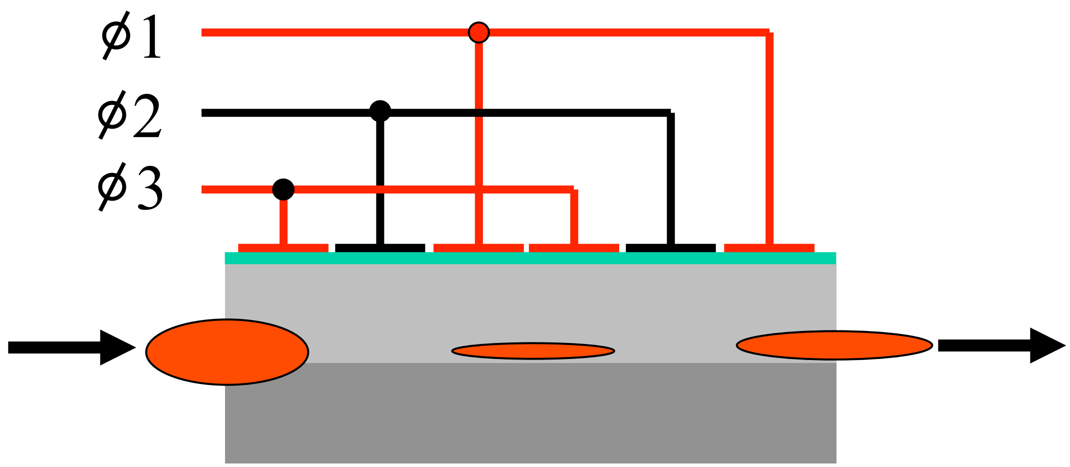




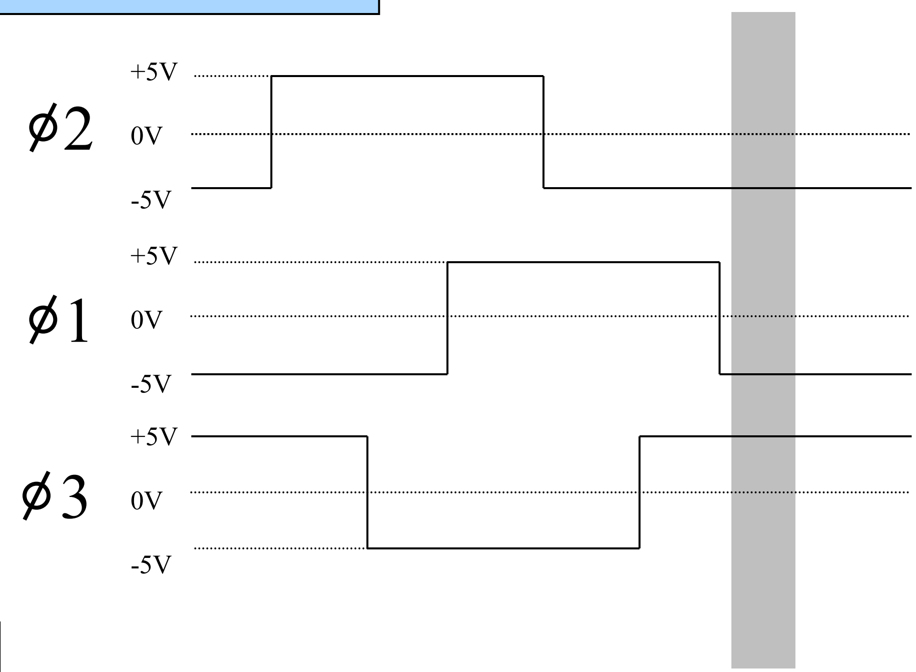
Charge Transfer in a CCD 7.

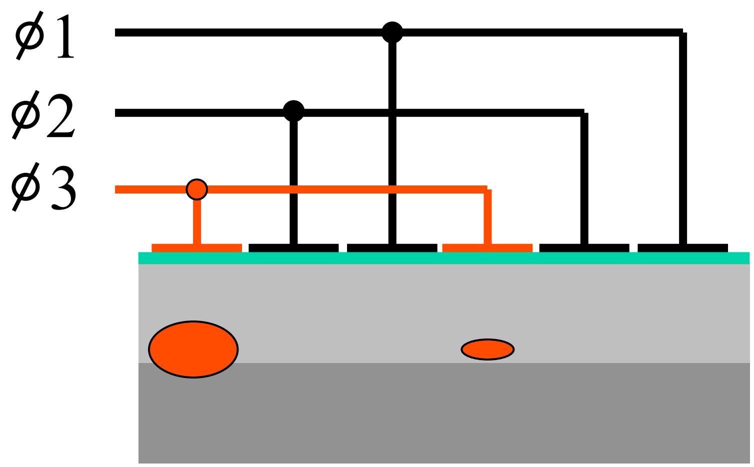


Charge packet from subsequent pixel enters from left as first pixel exits to the right.



Charge Transfer in a CCD 8.

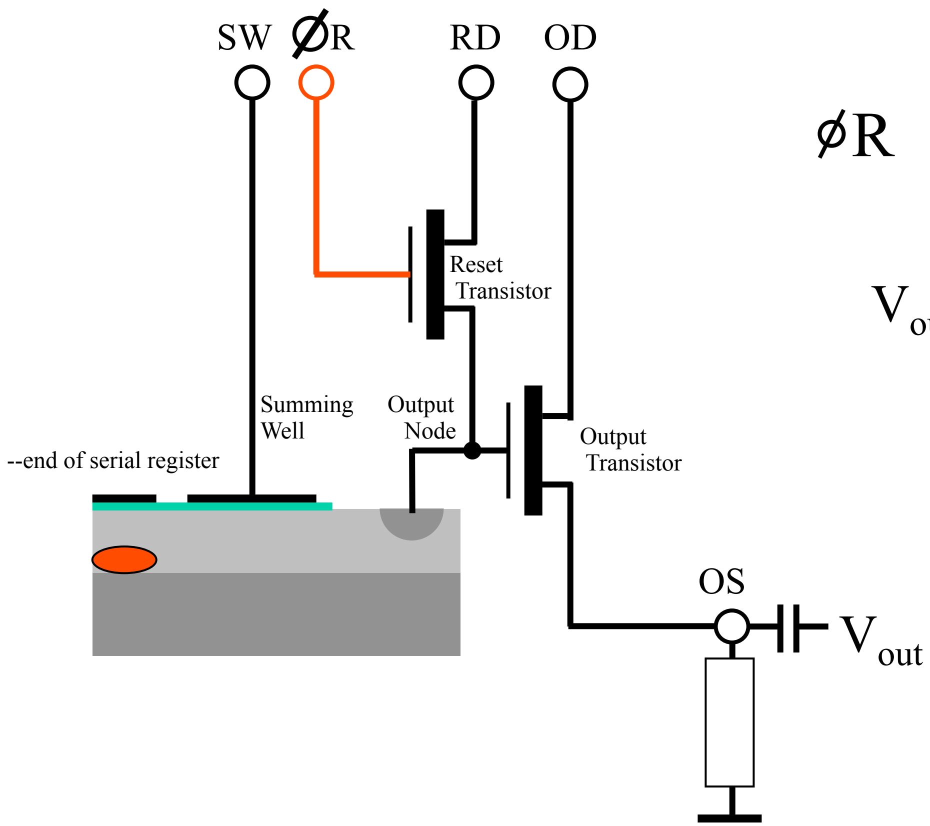


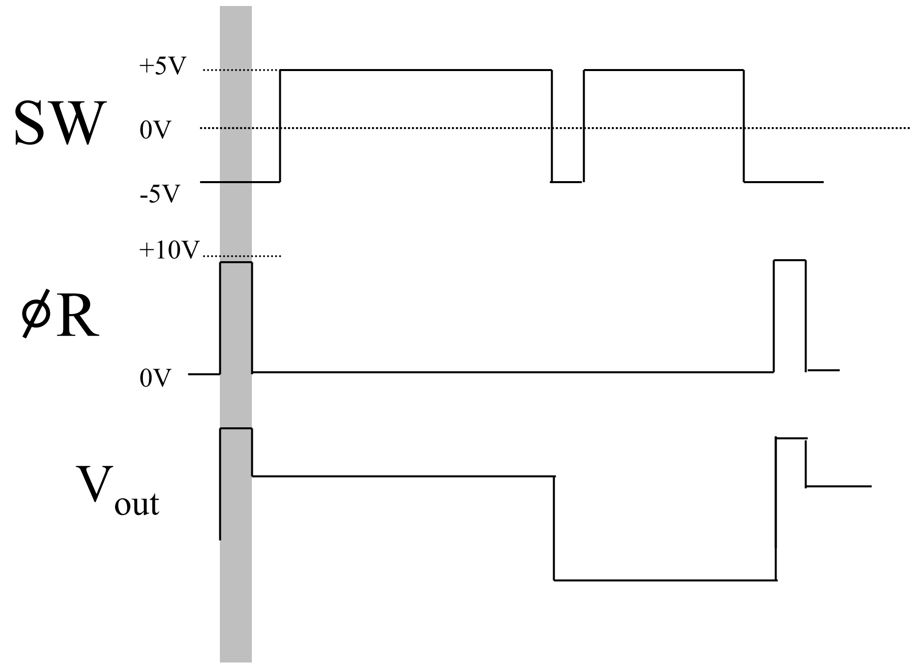


On-Chip Amplifier 1.

The on-chip amplifier measures each charge packet as it pops out the end of the serial register.

RD and OD are held at constant voltages



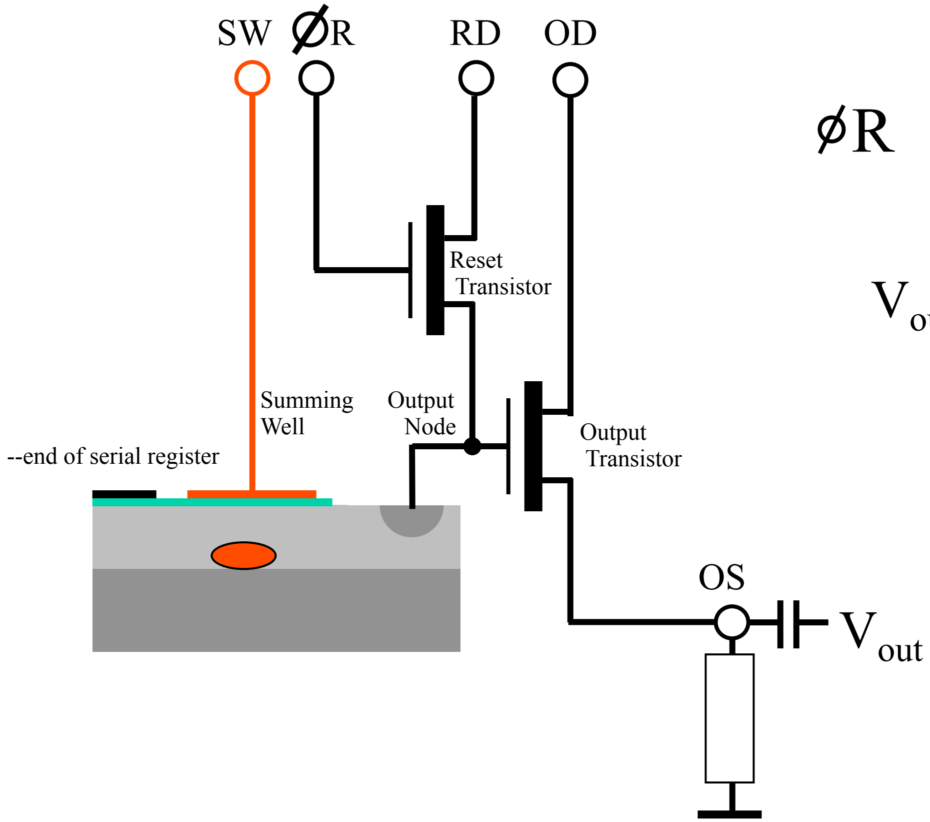


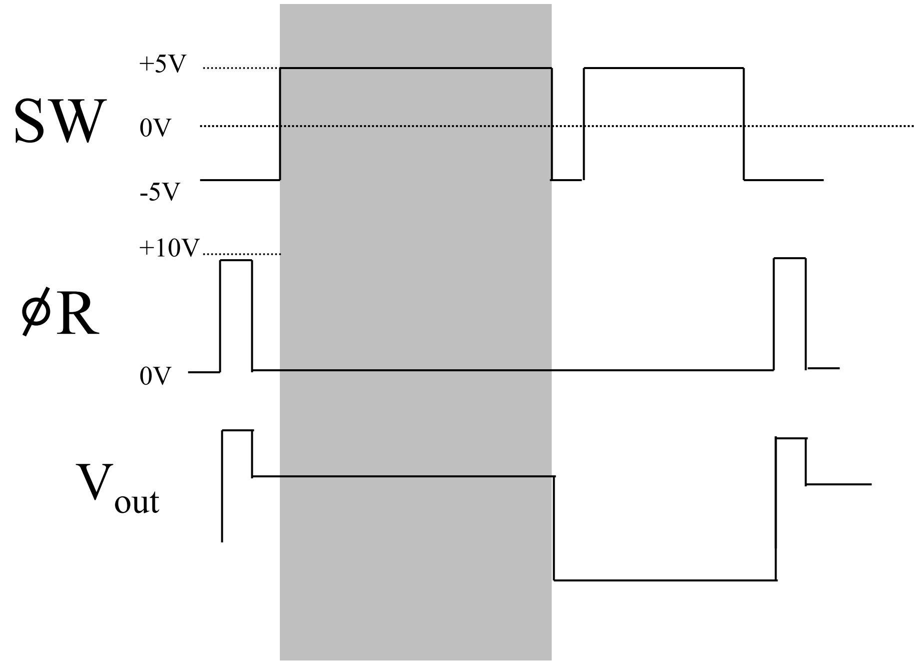
(The graphs above show the signal waveforms)

The measurement process begins with a reset of the 'reset node'. This removes the charge remaining from the previous pixel. The reset node is in fact a tiny capacitance (< 0.1pF)

On-Chip Amplifier 2.

The charge is then transferred onto the Summing Well. V_{out} is now at the 'Reference level'

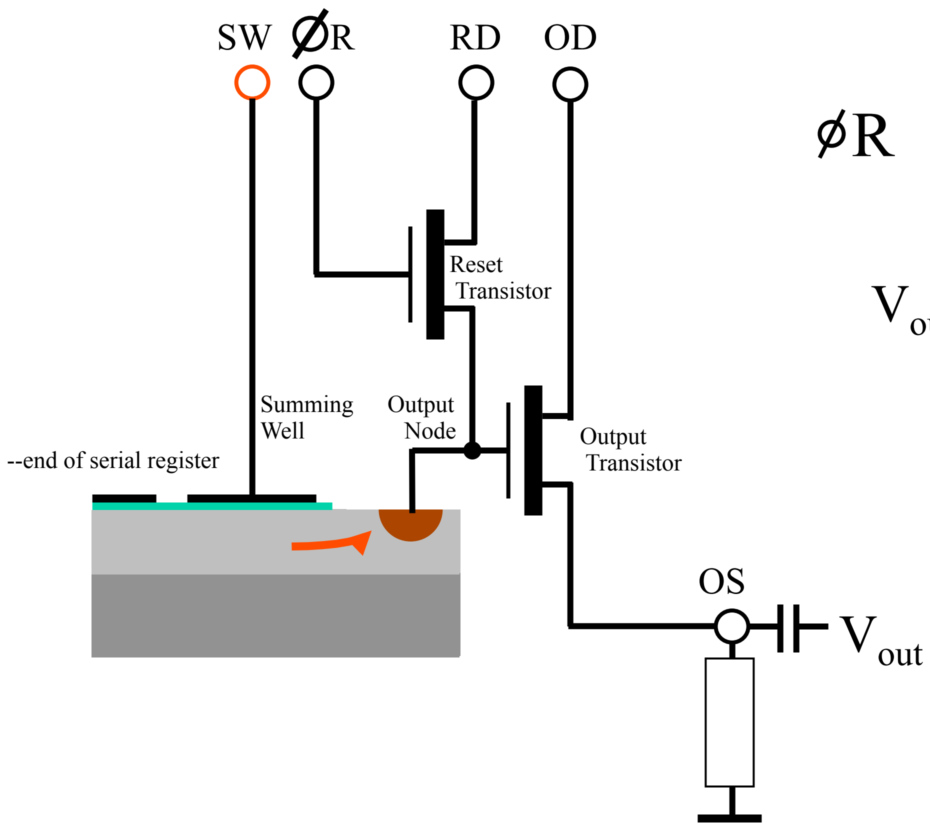


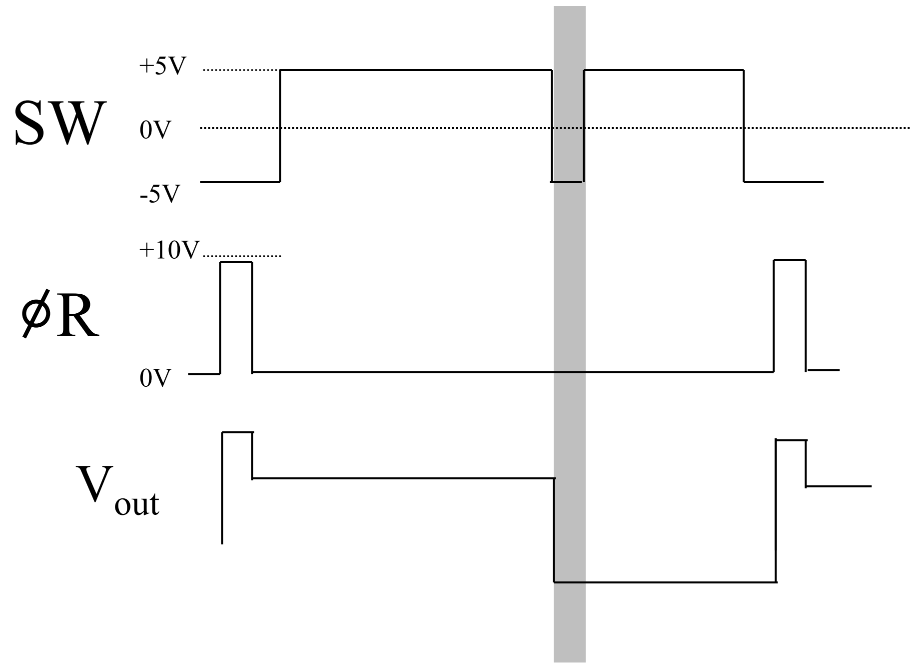


There is now a wait of up to a few tens of microseconds while external circuitry measures this 'reference' level.

On-Chip Amplifier 3.

The charge is then transferred onto the output node. V_{out} now steps down to the 'Signal level'

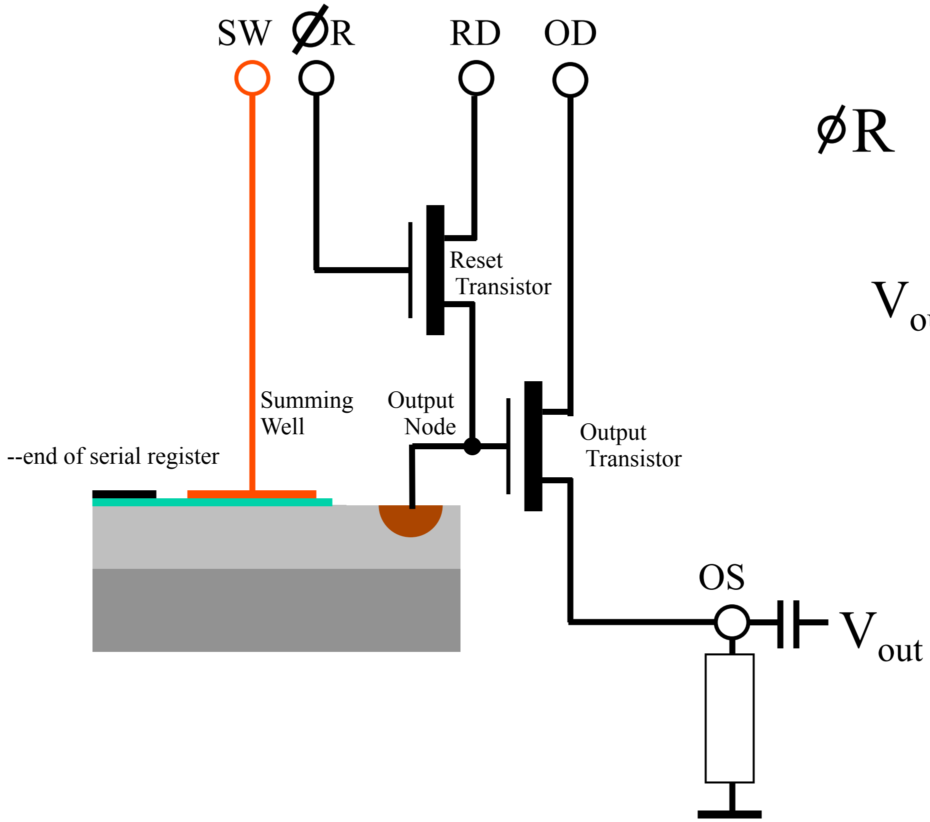


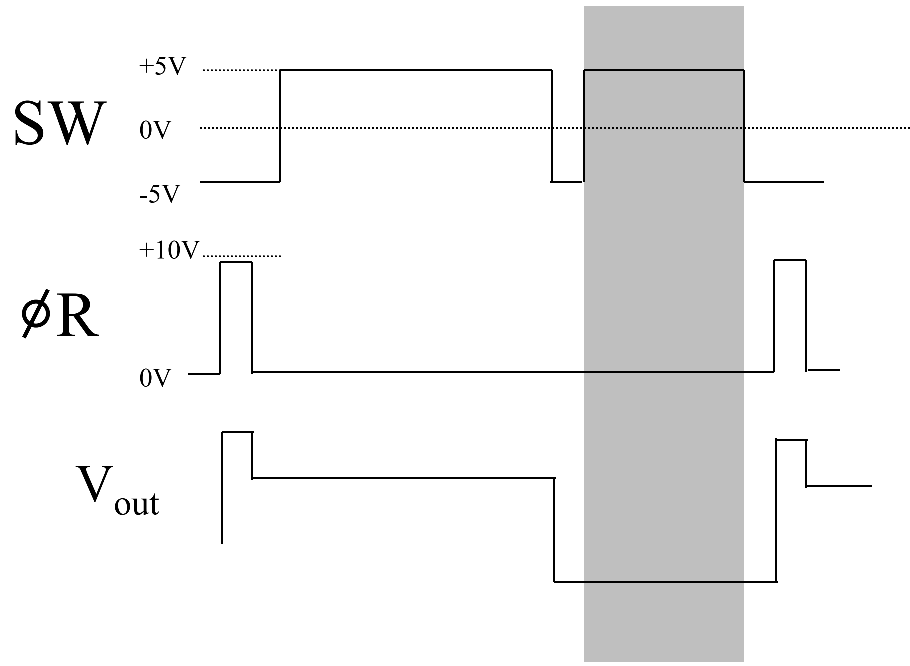


This action is known as the 'charge dump'
The voltage step in V_{out} is as much as several μV for each electron contained in the charge packet.

On-Chip Amplifier 4.

V_{out} is now sampled by external circuitry for up to a few tens of microseconds.





The sample level - reference level will be proportional to the size of the input charge packet.

Pixel Size and Binning

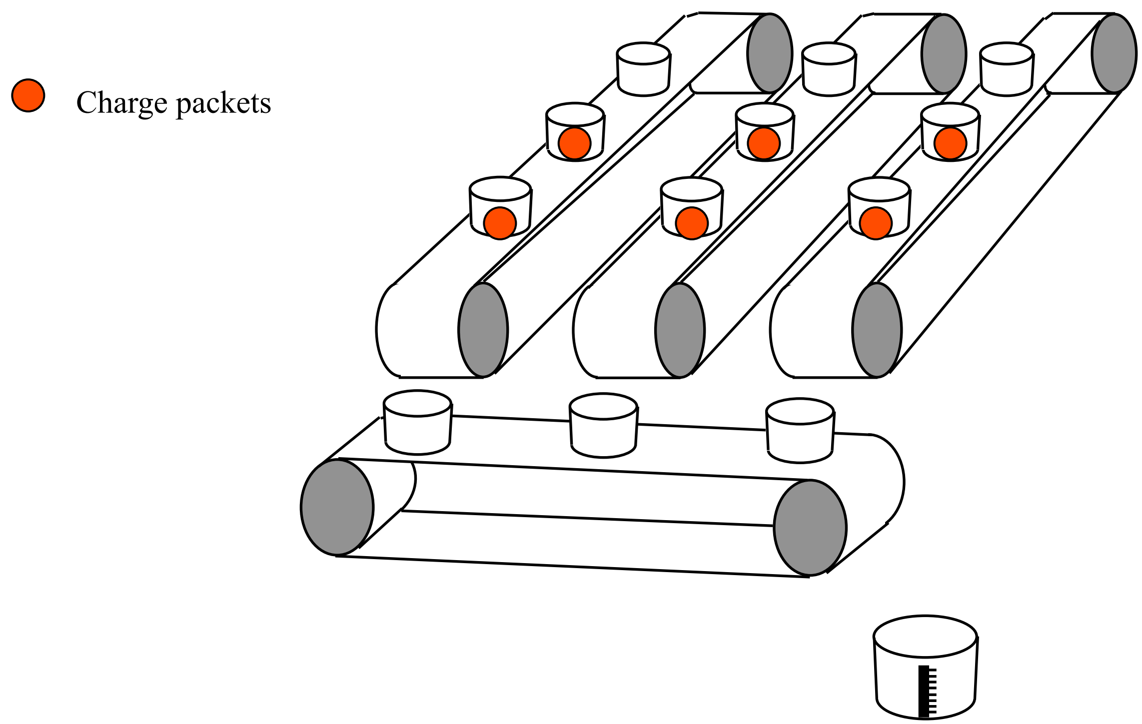
There is a way to read out a CCD so as to increase the effective pixel size, this is known as 'Binning'. With binning we can increase pixel size arbitrarily. In the limit we could even read out the CCD as a single large pixel. Astronomers will more commonly use 2 x 2 binning which means that the charge in each 2 x 2 square of adjacent pixels is summed on the chip prior to delivery to the output amplifier. One important advantage of 'on-chip binning' is that it is a noise free process.

Binning is done in two distinct stages : vertical binning and horizontal binning. Each may be done without the other to yield rectangular pixels.

Pixel Size and Binning

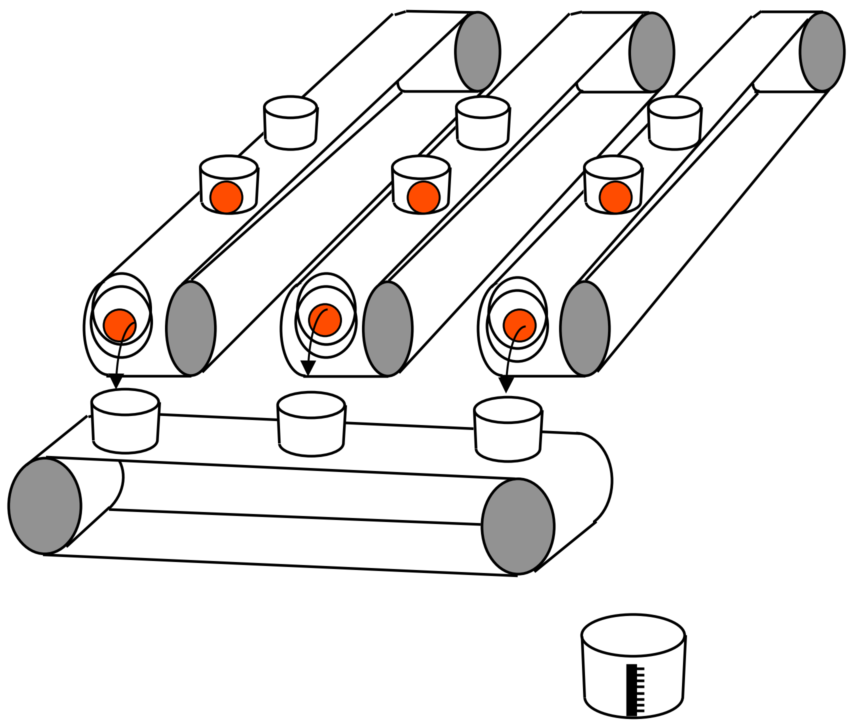
Stage 1 :Vertical Binning

This is done by summing the charge in consecutive rows .The summing is done in the serial register. In the case of 2 x 2 binning, two image rows will be clocked consecutively into the serial register prior to the serial register being read out. We now go back to the conveyor belt analogy of a CCD. In the following animation we see the bottom two image rows being binned.



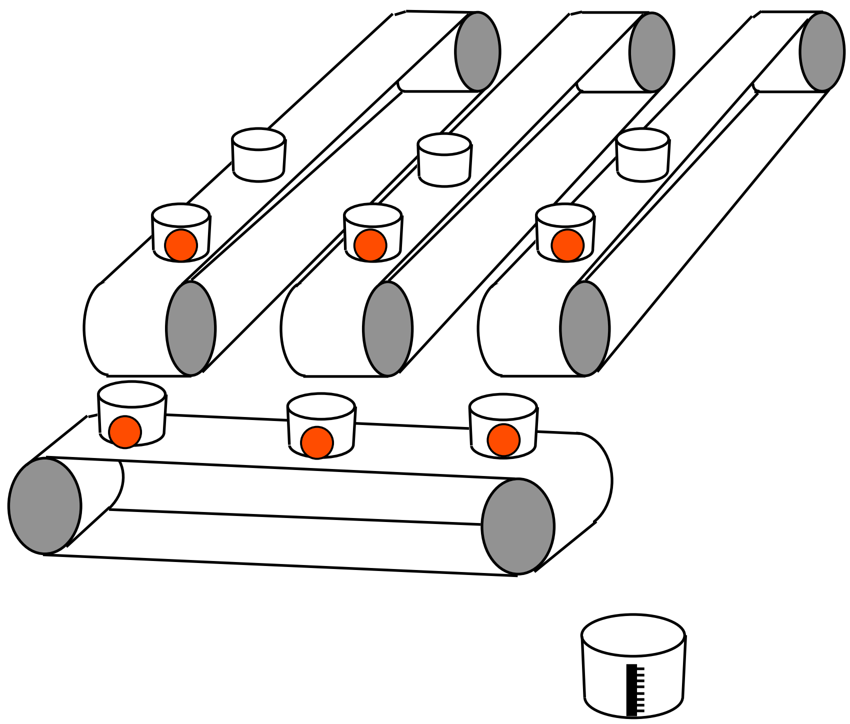
Pixel Size and Binning

The first row is transferred into the serial register



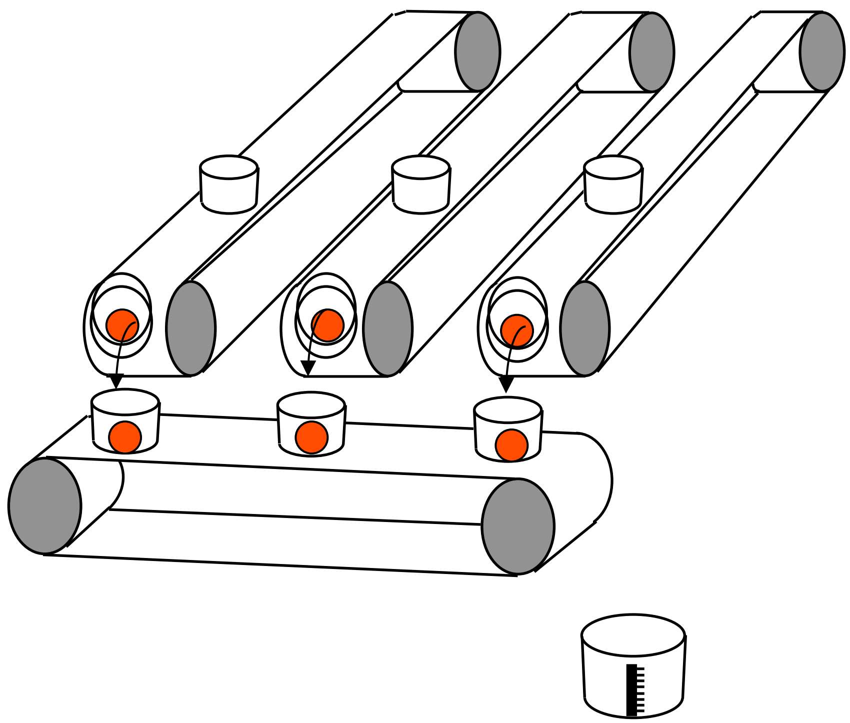
Pixel Size and Binning 7.

The serial register is kept stationary ready for the next row to be transferred.



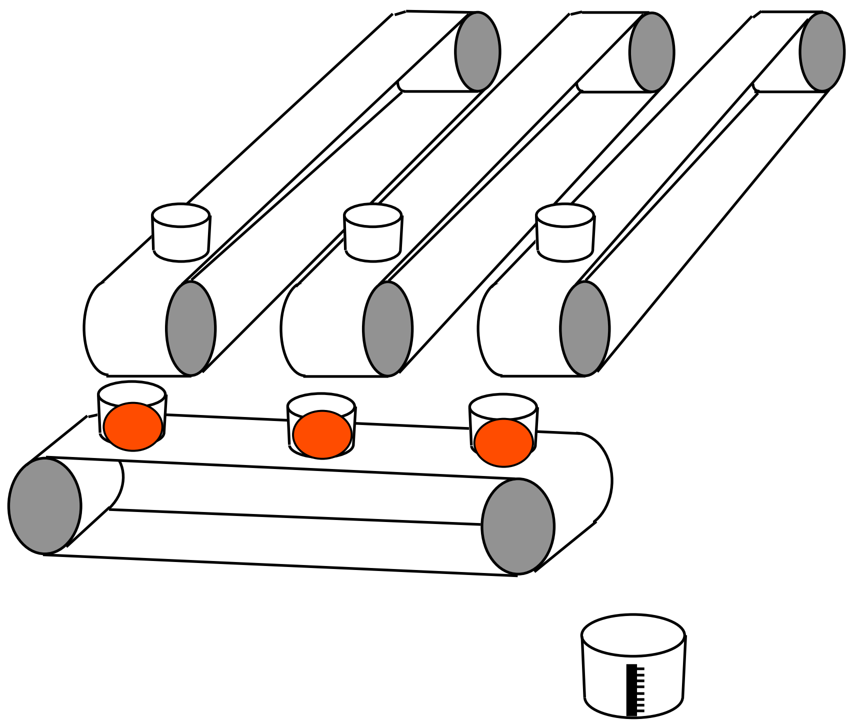
Pixel Size and Binning 8.

The second row is now transferred into the serial register.



Pixel Size and Binning

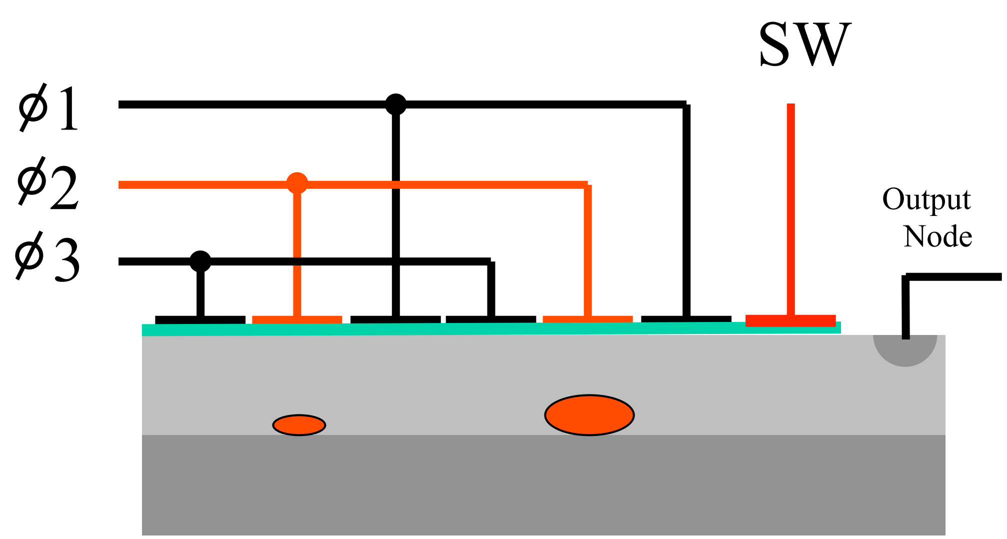
Each pixel in the serial register now contains the charge from two pixels in the image area. It is thus important that the serial register pixels have a higher charge capacity. This is achieved by giving them a larger physical size.



Pixel Size and Binning

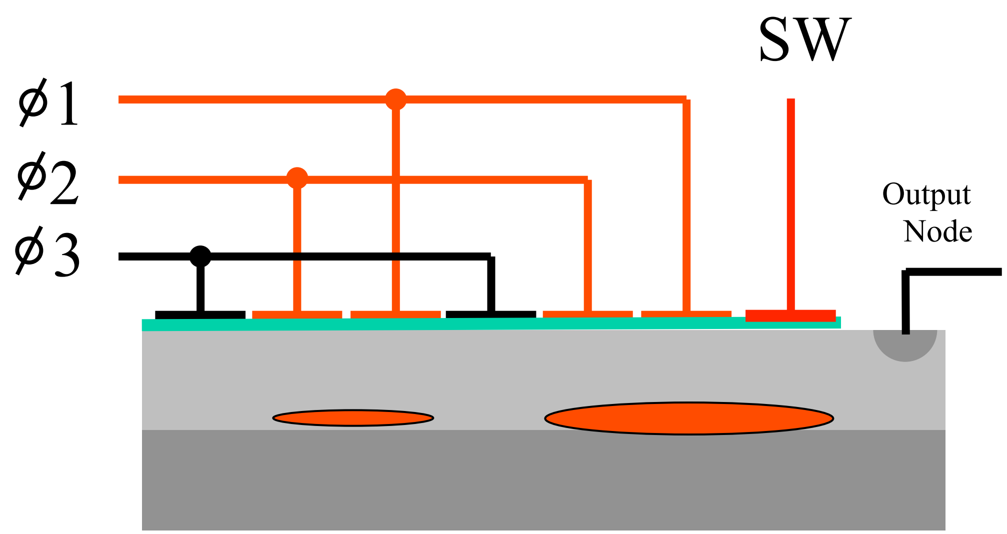
Stage 2 :Horizontal Binning

This is done by combining charge from consecutive pixels in the serial register on a special electrode positioned between serial register and the readout amplifier called the Summing Well (SW).
The animation below shows the last two pixels in the serial register being binned :

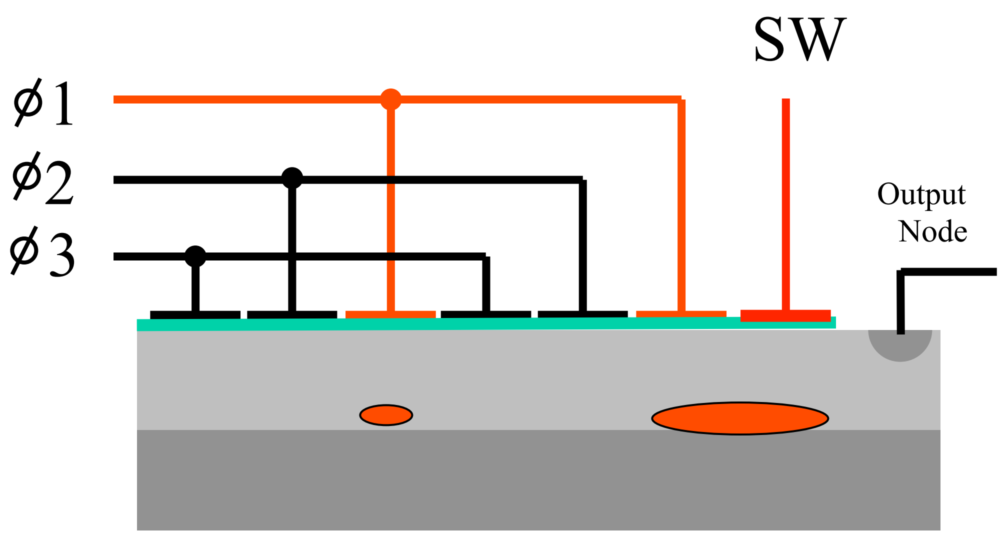


Pixel Size and Binning

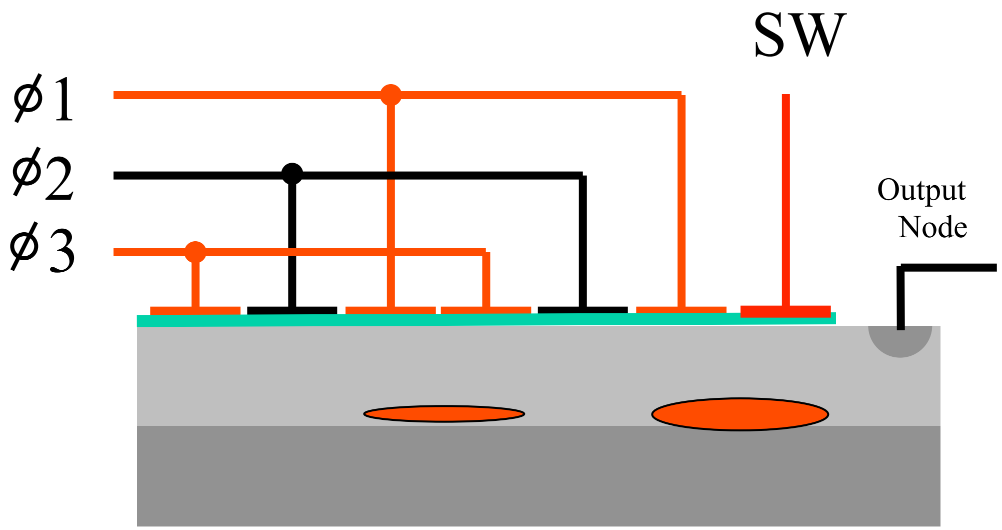
Charge is clocked horizontally with the SW held at a positive potential.



Pixel Size and Binning

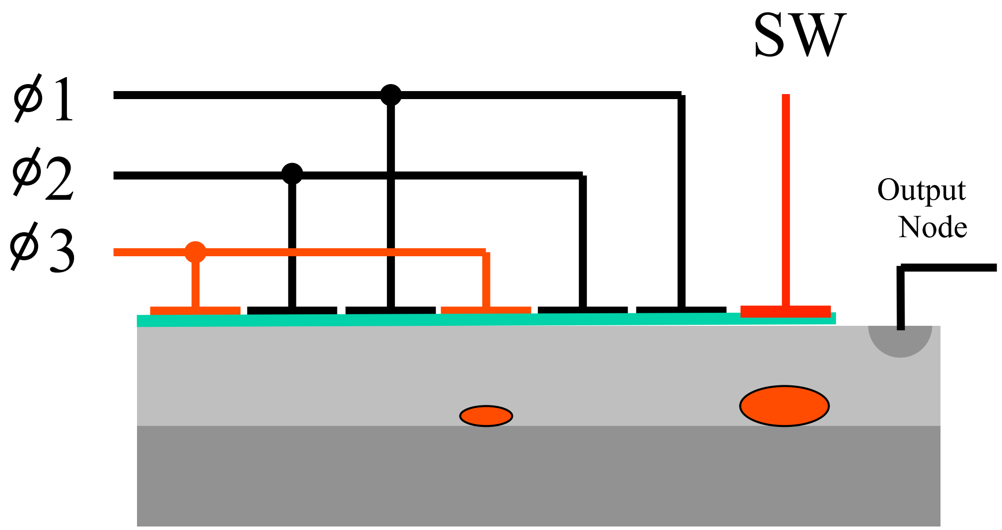


Pixel Size and Binning



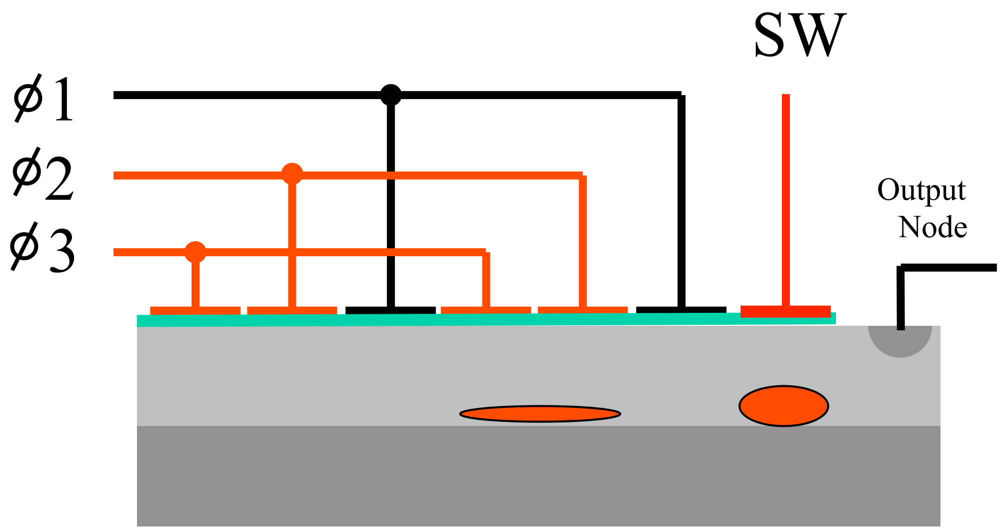
Pixel Size and Binning

The charge from the first pixel is now stored on the summing well.

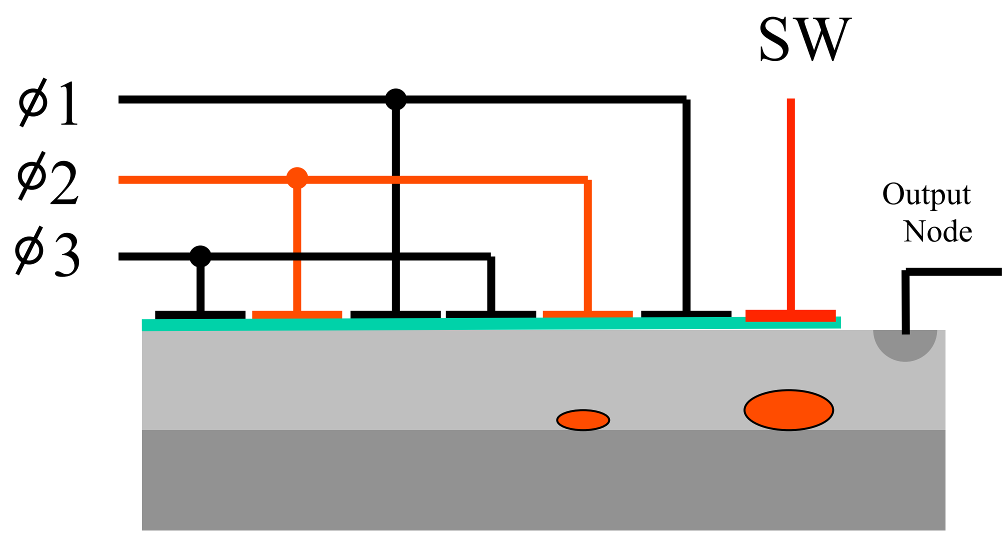


Pixel Size and Binning

The serial register continues clocking.

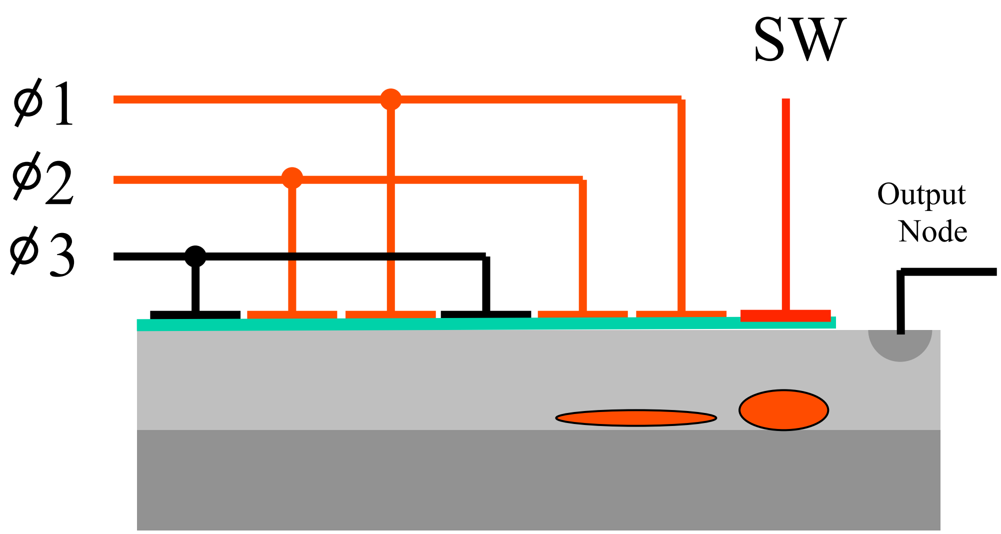


Pixel Size and Binning

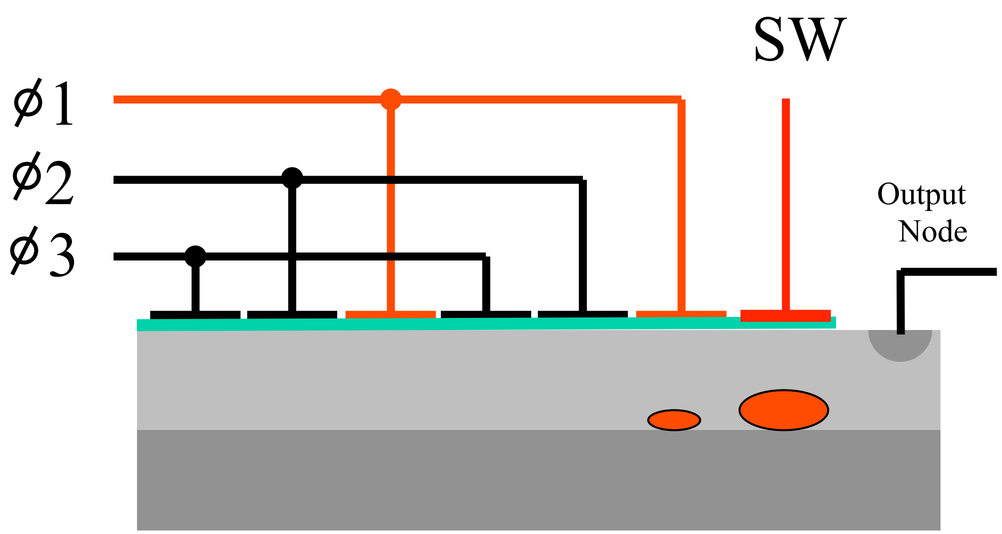


Pixel Size and Binning

The SW potential is set slightly higher than the serial register electrodes.



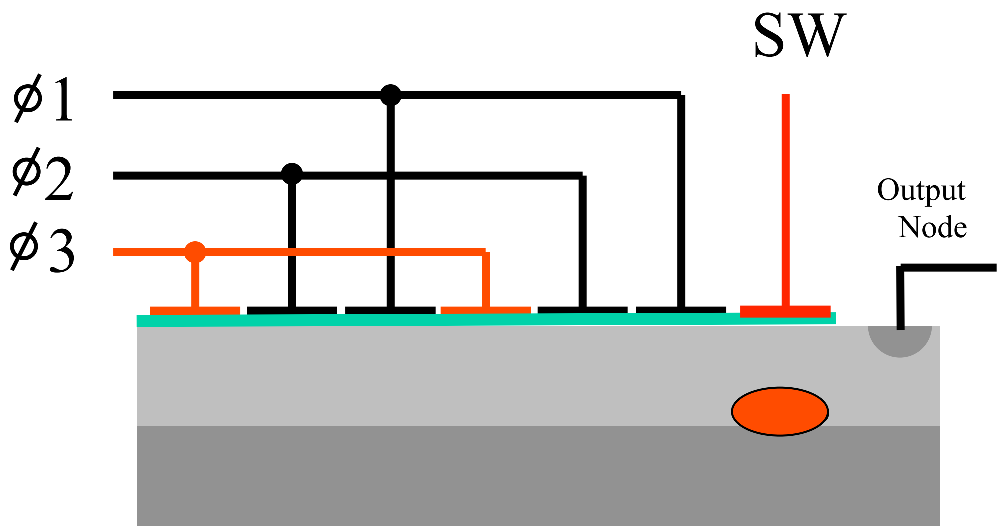
Pixel Size and Binning



Pixel Size and Binning

The charge from the second pixel is now transferred onto the SW. The binning is now complete and the combined charge packet can now be dumped onto the output node (by pulsing the voltage on SW low for a microsecond) for measurement.

Horizontal binning can also be done directly onto the output node if a SW is not present but this can increase the read noise.



Pixel Size and Binning

Finally the charge is dumped onto the output node for measurement