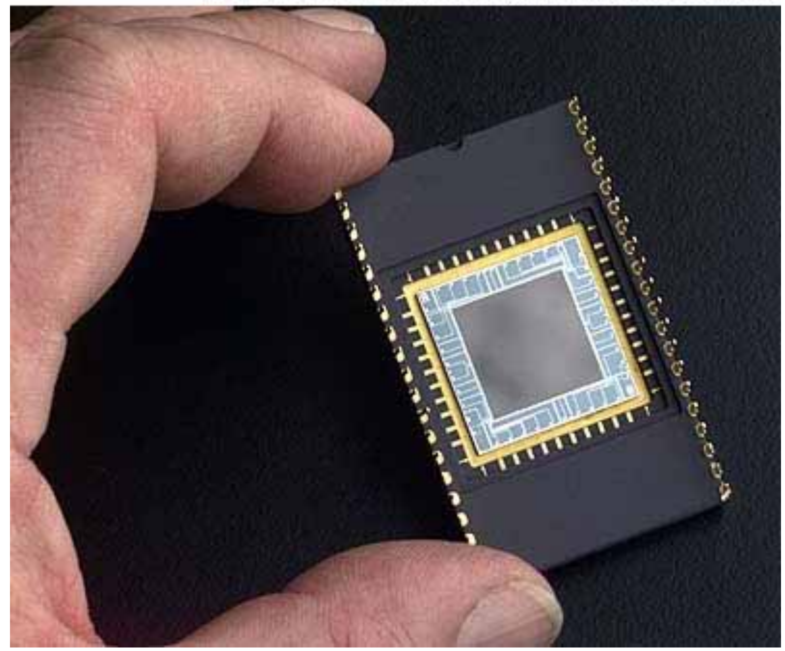
Astronomy 211
Fall 2013

The CCD detector

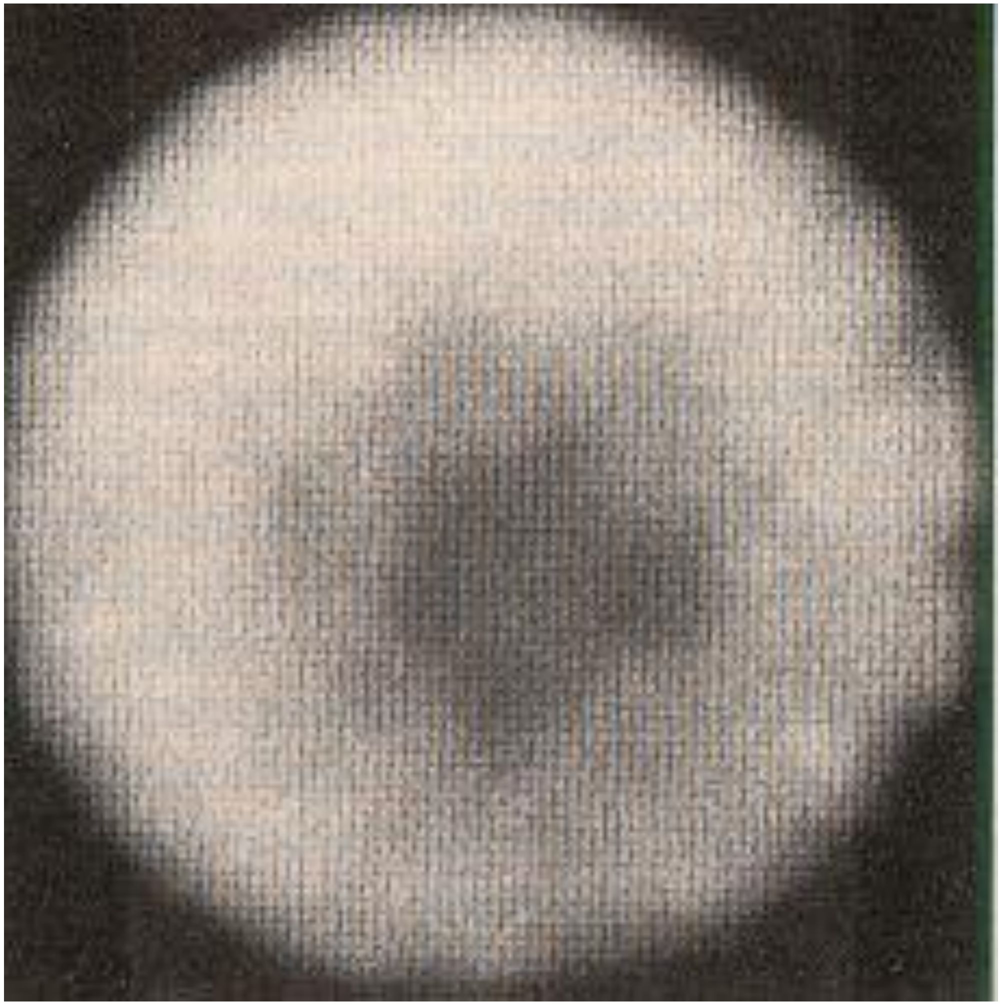
- Introduction
- History of the CCD
- How does a CCD work ?
- Advantages of CCDs

From Computer Desktop Encyclopedia
Reproduced with permission.



Adapted from Dib & Surdej and Henneman, Hippler & Stegmaier, Max-Planck-Institute for Astronomy, Heidelberg

Introduction



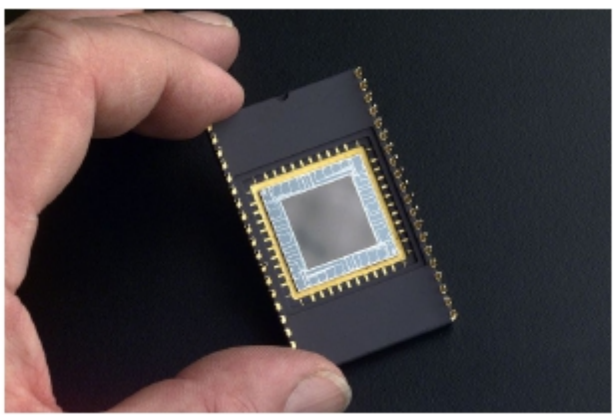
This near-infrared (8900 Å) picture of Uranus was probably the first celestial object to be photographed by a CCD in 1975 by astronomers at the JPL and University of Arizona. This image was obtained by the 61 inch telescope located at Santa Catalina mountains near Tucson. The dark region in the image correspond to an absorption region with some methane bands close to the southern pole of Uranus.

History

In 1969 Willard S. Boyle and George E. Smith, while working at Bell Laboratories, designed the first Charge Coupled Device (CCD); a working version was produced just a year later. The CCD has become the bedrock of the digital imaging revolution including digital photography and video. In January 2006 they were honored with the Charles Stark Draper Prize which is presented by the National Academy of Engineering.

What is a CCD?

- Charge Coupled Device: a pixellated semiconductor detector array.
- Each pixel is essentially a p-n photodiode, with millions of these fabricated on a single wafer, and connected by gate transistors.
- Photoelectric effect -incoming photons liberate electrons, which accumulate in a well.
- The number of electrons in the well increases linearly with increasing exposure. I.e. $N_e \propto N_{photon}$ (this is not true for photographic emulsions)

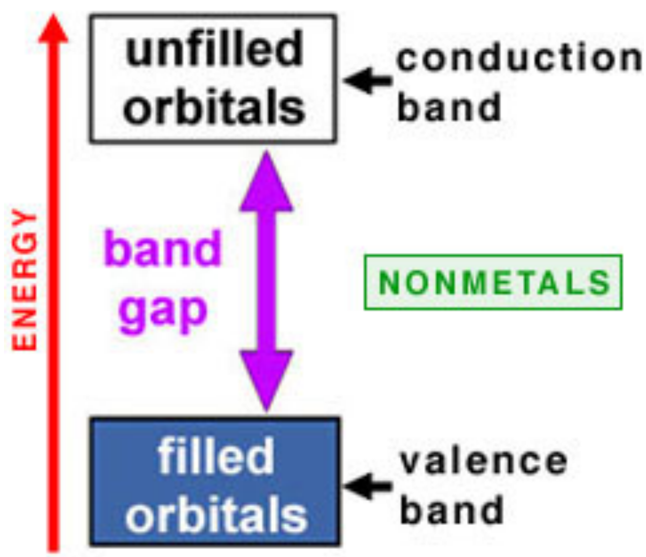


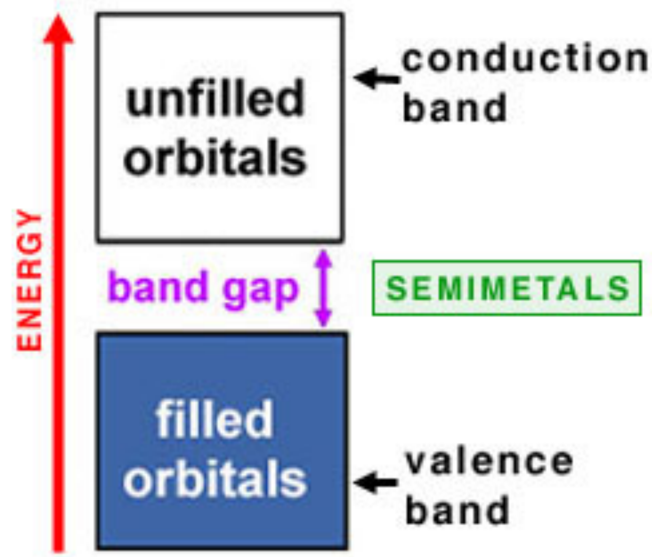
Material	Electromagnetic spectrum wavelength range (nm)
Silicon	190–1100
Germanium	400–1700
Indium gallium arsenide	800–2600
Lead(II) sulfide	<1000–3500

Various dopants are used to tune the bandgap to specific wavelength ranges

adapted from http://faculty.uml.edu/slaycock/95.383/documents/Lecture3_000.pdf

How does a CCD work?



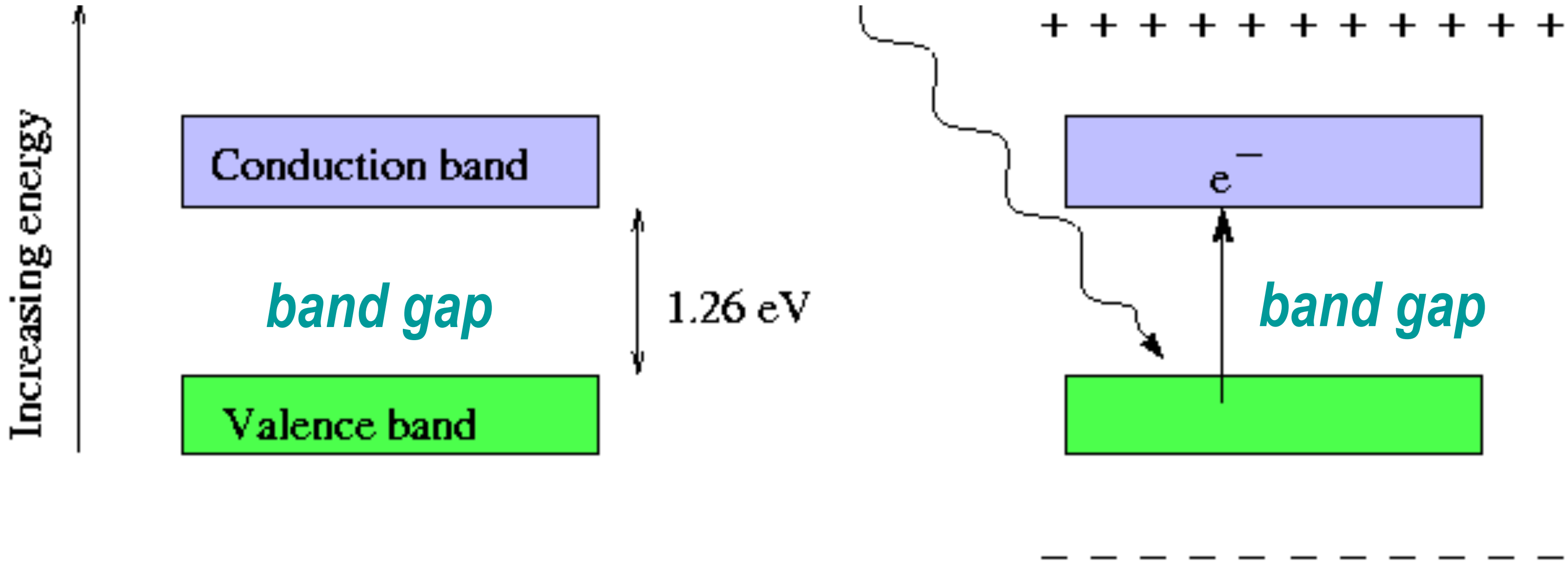


When nonmetal atoms interact to form a solid, their atomic orbitals mix to form two bands of orbitals that are separated by a large band gap that requires a lot of energy to overcome, more than optical photons could provide.

When semimetal atoms interact to form a solid, their atomic orbitals mix to form two bands of orbitals that are separated by a band gap small enough for optical photons to excite electrons into the conduction band.

adapted from http://www.chemistry.wustl.edu/~edudev/LabTutorials/PeriodicProperties/MetalBonding/images/nonmetal.jpg

How does a CCD work?
the photoelectric effect



- Si atoms in crystal lattice → discrete **energy bands:**

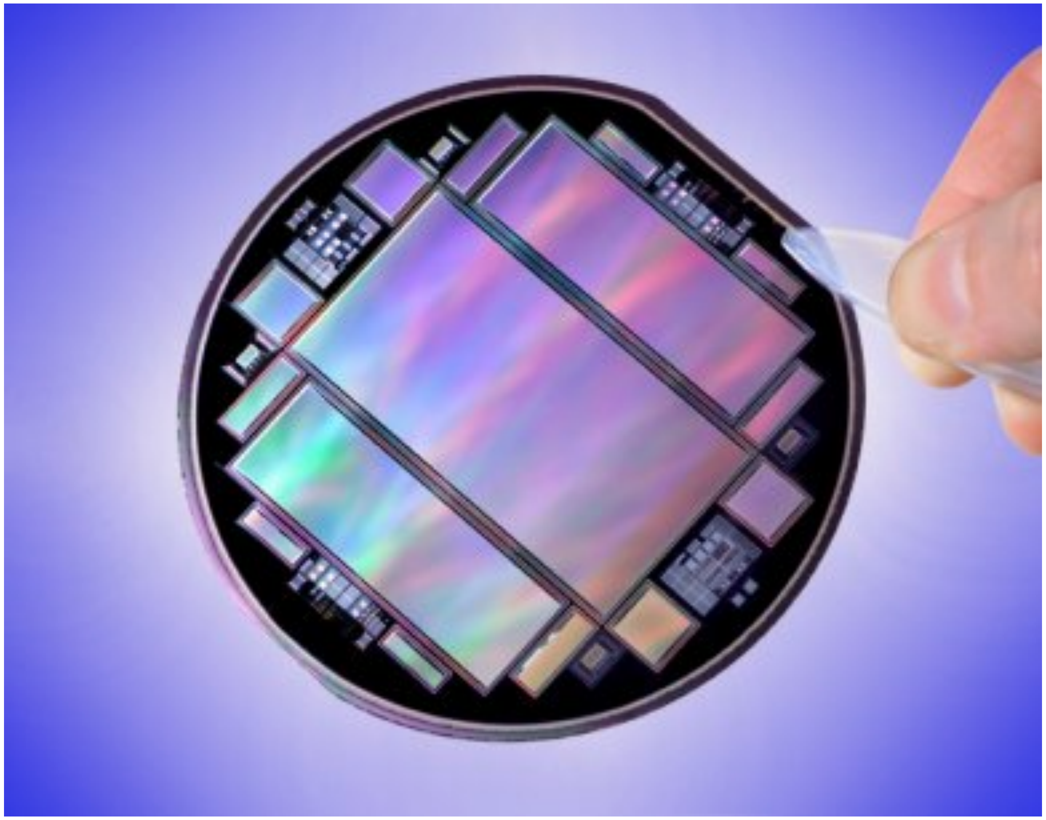
  valence band -- 1.26 eV band gap -- conduction band
- Electrons in valence band can be excited by heating or photon absorption.
- In conduction band, electrons can freely move around lattice.
- Electron leaves behind a positive ***hole*** in valence band.
- Electric field in CCD prevents "recombination"so charges can accumulate and be counted.

http://spiff.rit.edu/classes/phys445/lectures/ccd1/ccd1.html

Structure of a CCD

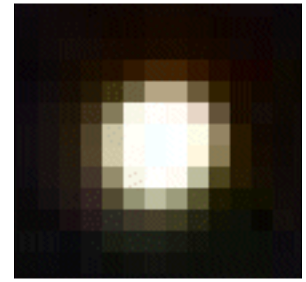
CCDs are are manufactured on silicon wafers using the same photo-lithographic techniques used to manufacture computer chips. Scientific CCDs are very big, only a few can be fitted onto a wafer. This is one reason that they are so costly.

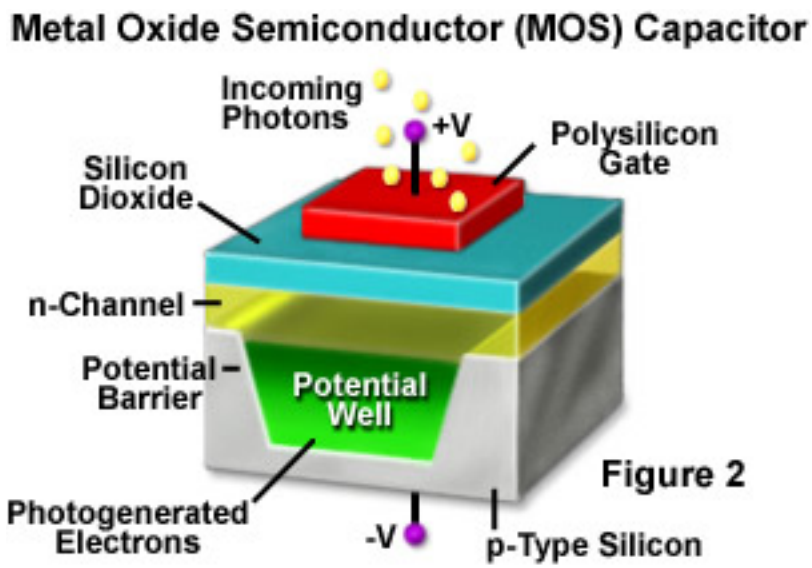
The photo below shows a silicon wafer with three large CCDs and assorted smaller devices. A CCD has been produced by Philips that fills an entire 6 inch wafer! It is the world's largest integrated circuit.



Don Groom LBNL

Structure of a CCD - MOS

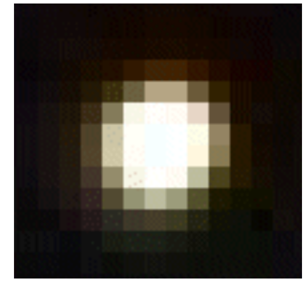


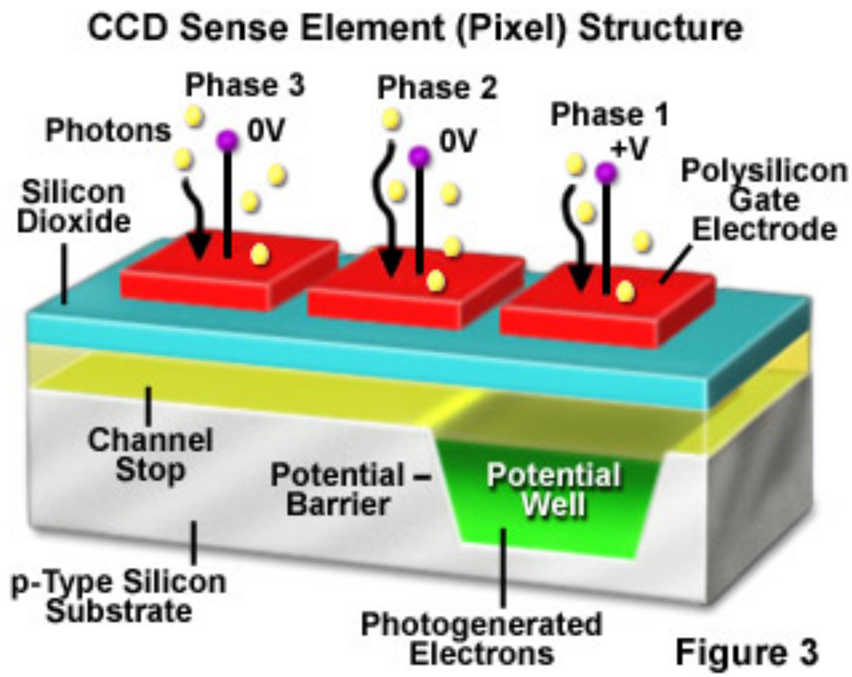


Photoelectrons generated and stored

http://www.microscopyu.com/articles/digitalimaging/images/ccdintro/ccdintrofigure2.jpg

Structure of a CCD - Pixel





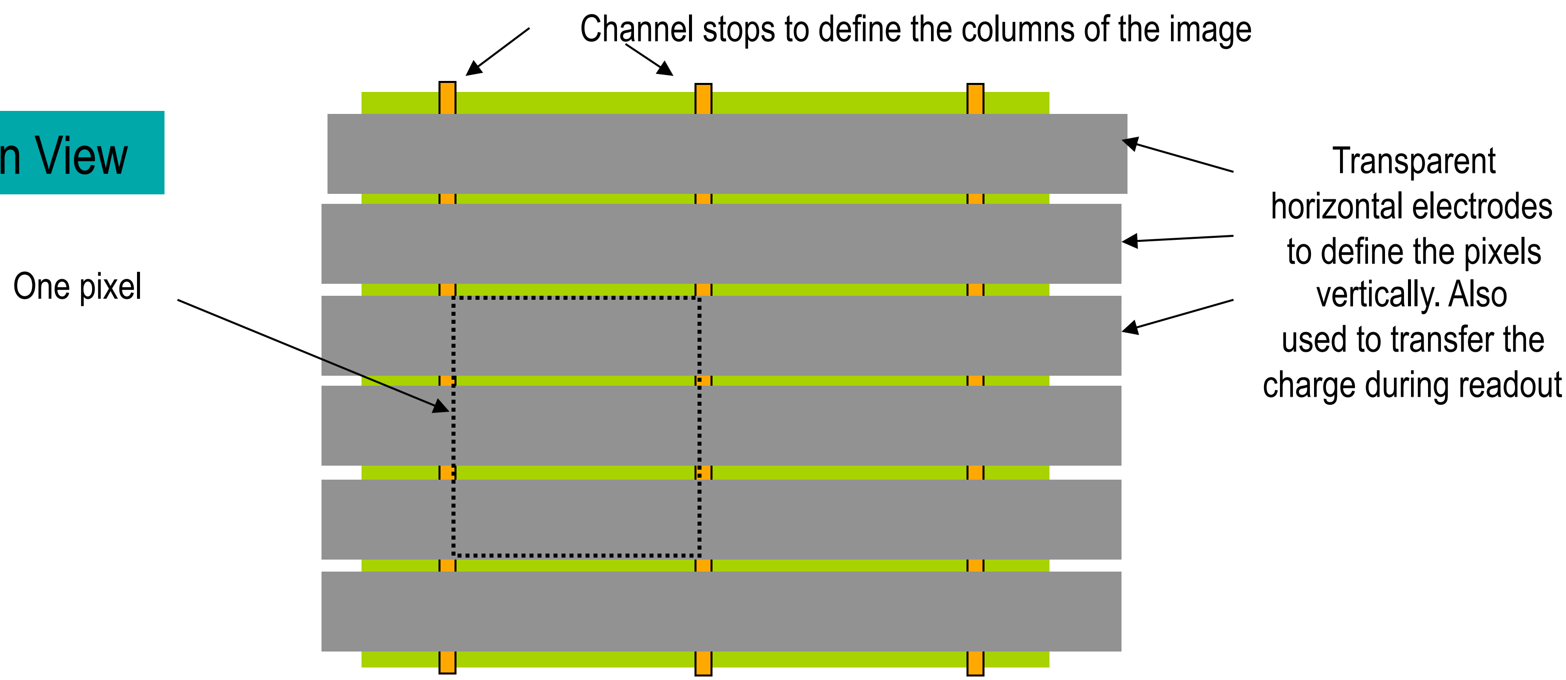
Manipulation of voltage moves charge packets along.

http://www.microscopyu.com/articles/digitalimaging/images/ccdintro/ccdintrofigure2.jpg

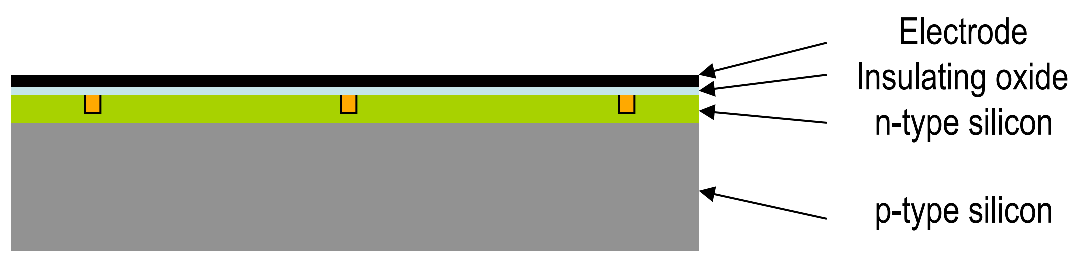
Structure of a CCD

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

Plan View



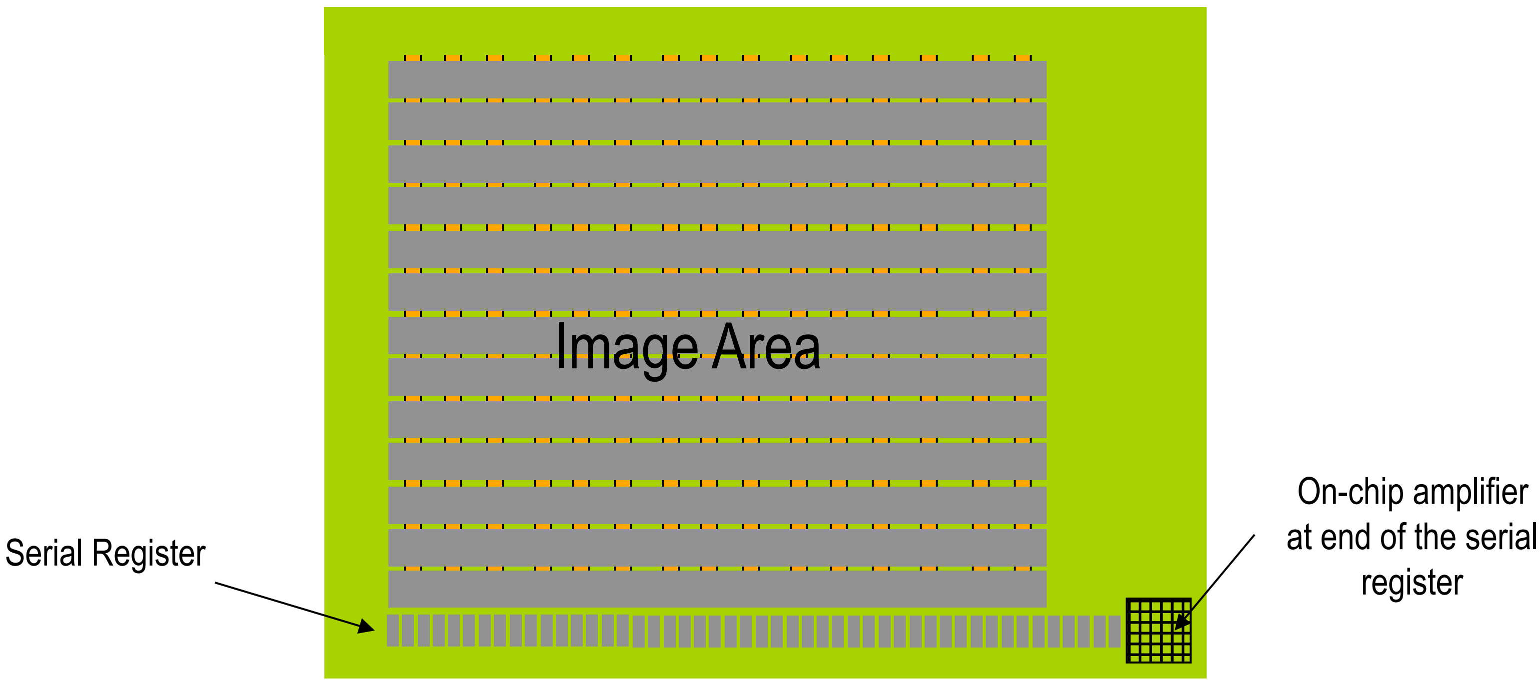
Cross section



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.

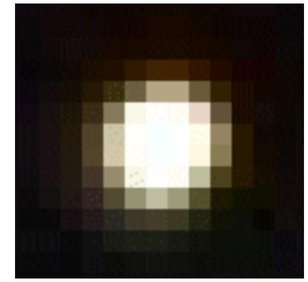
Structure of a CCD

Below the image area (the area containing the horizontal electrodes) is the 'Serial register' . This also consists of a group of small surface electrodes.



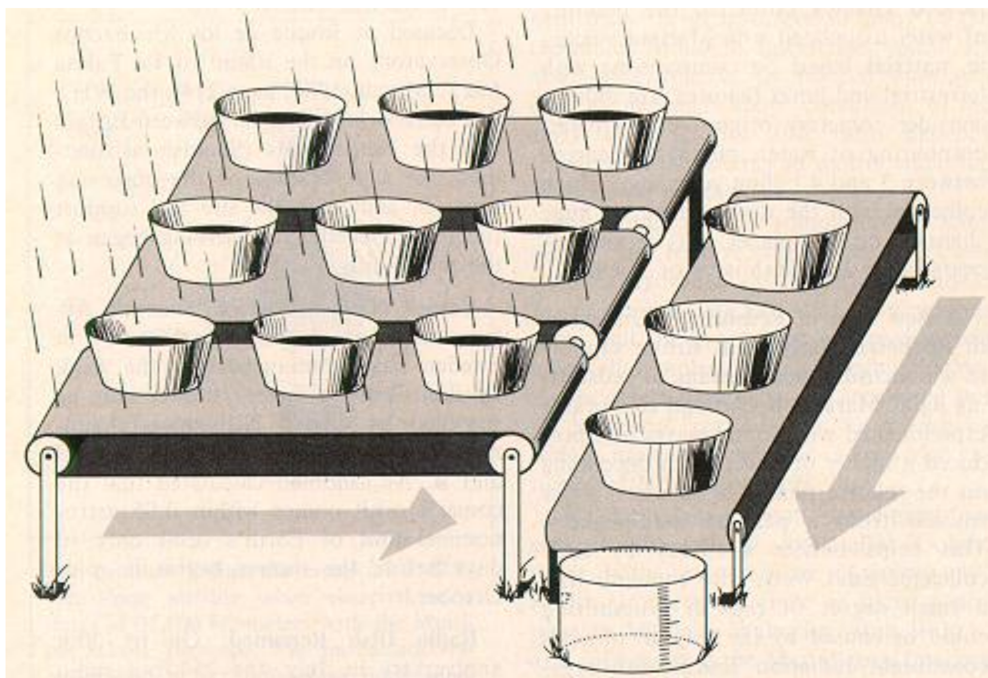
Cross section of serial register

How does a CCD work?



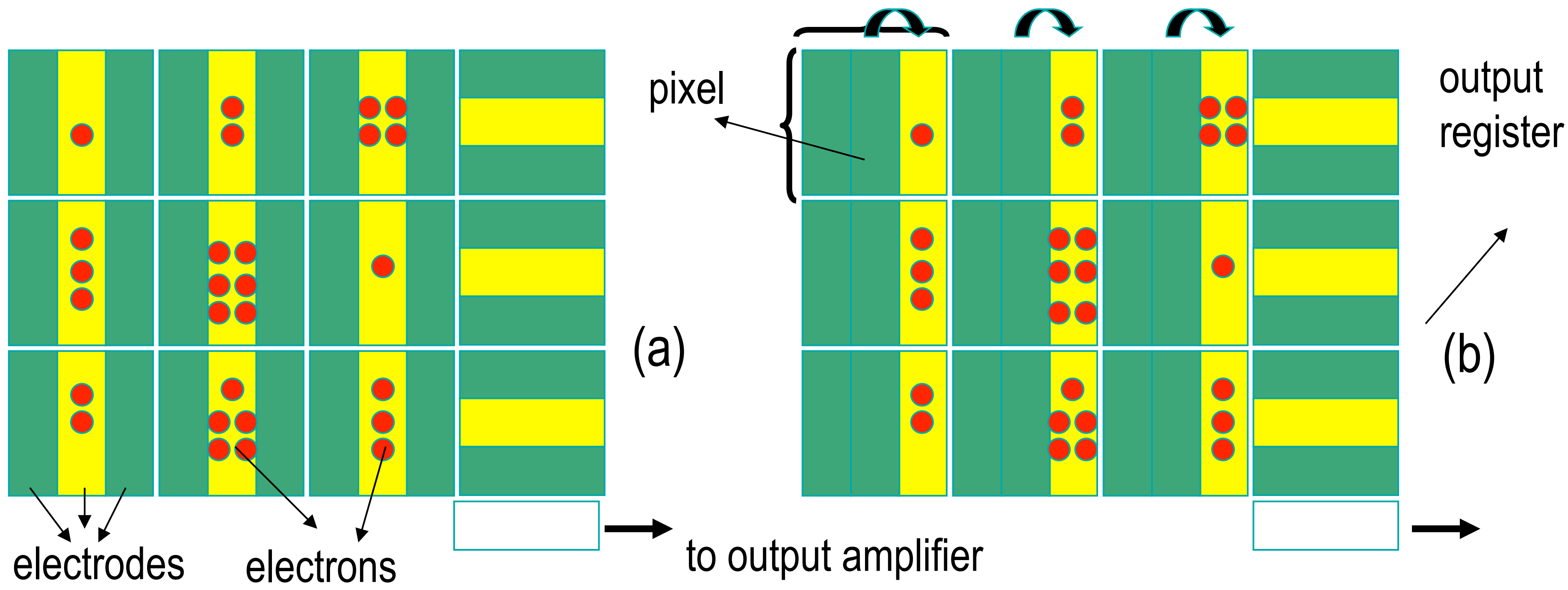
It requires four steps to create a CCD image:

1) generate photoelectrons (i.e., rain drops)
2) collect electrons (i.e., the buckets)
3) transfer the collected charges (i.e., the conveyor belts)
4) read the charges (i.e., weighting device)



How does a CCD work?

A simplified 9-pixel CCD plus output register and amplifier:

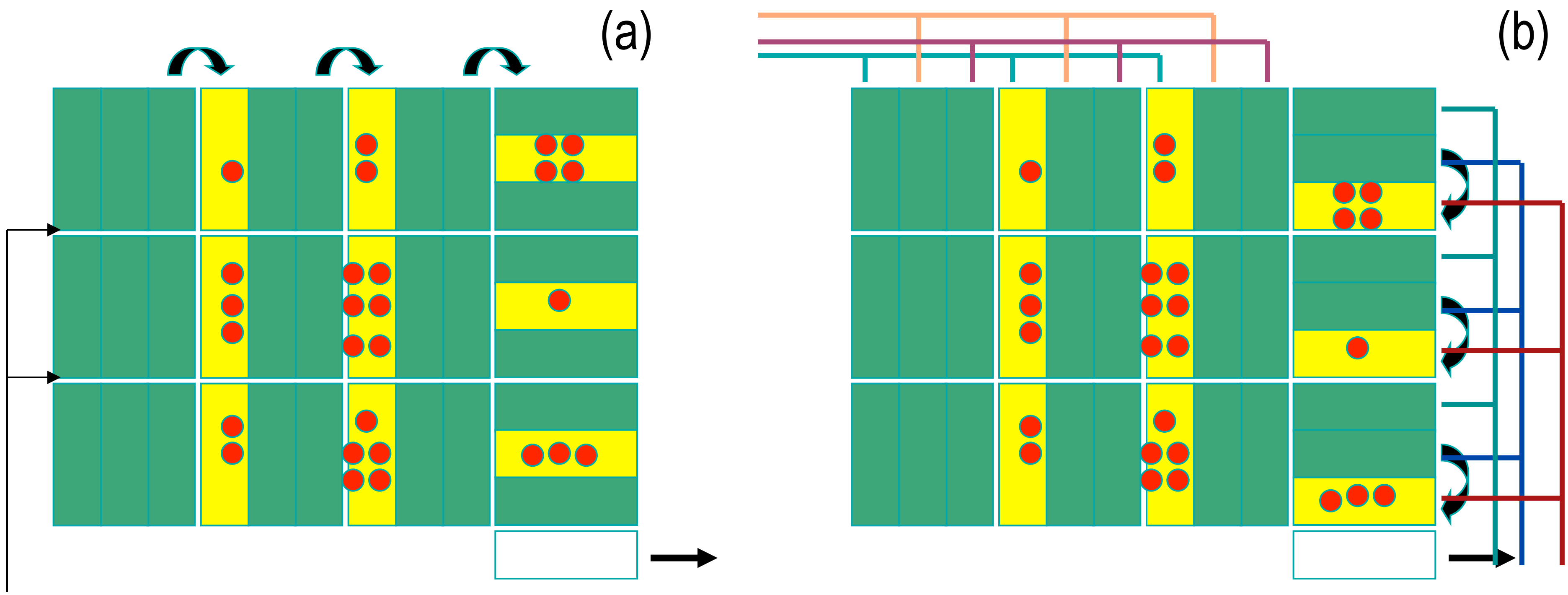


Each pixel is divided into **3 regions** (electrodes that create a potential well).

(a) For charge collection during exposure, the central electrode of each pixel is maintained at a higher potential (yellow) than the others (green).

(b) At the end of the exposure, the electrodes' potentials are changed and the charges transferred from one electrode to the other.

How does a CCD work?

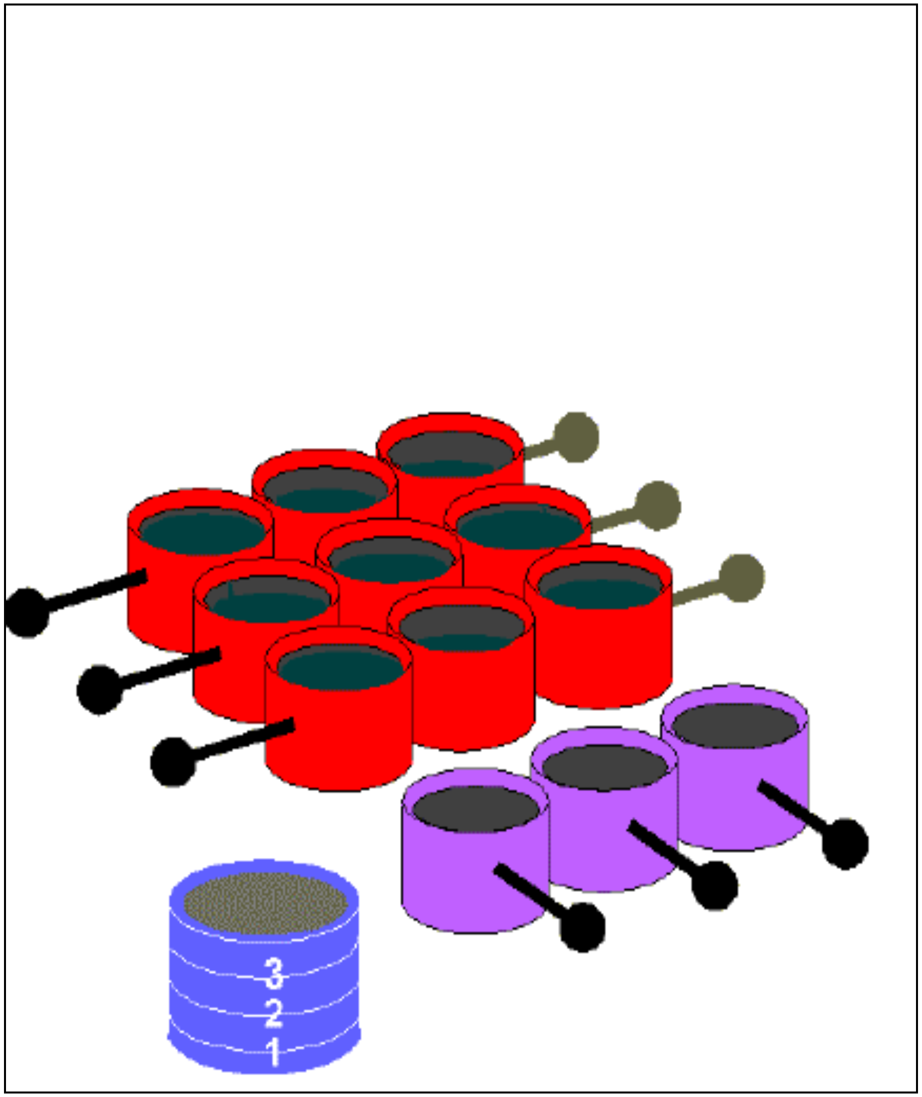


(a) By changing the potential of the electrodes in a synchronized way, electrons are transferred from pixel to pixel. Charges on the right are guided to the output register

(b) The horizontal transfer of charges is then stopped and each charge package at the output register is transferred vertically to an output amplifier and then read one by one. The cycle starts again until all the charges have been read. The reading time amounts to about one minute for a large CCD.

How does a CCD work?

- Buckets (pixels) are distributed across a field (telescope focal plane) in a square array, on top of a series of parallel conveyor belts to collect rainfall.
- Conveyor belts are stationary until rain stops. (shutter open).
- When rain stops (shutter closes) the conveyor belts transfer the buckets of rain, one by one, to a measuring cylinder (on-chip amplifier) at the corner of the field (at the corner of the CCD).



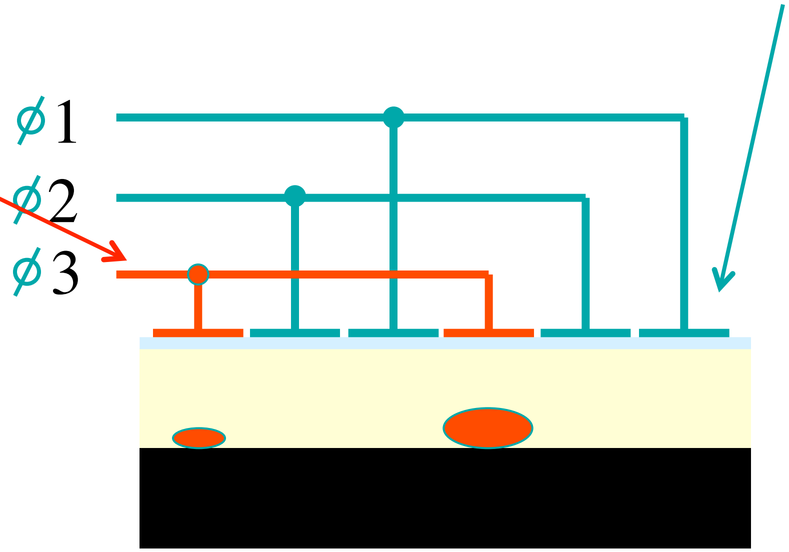
based on smt@ing.iac.es

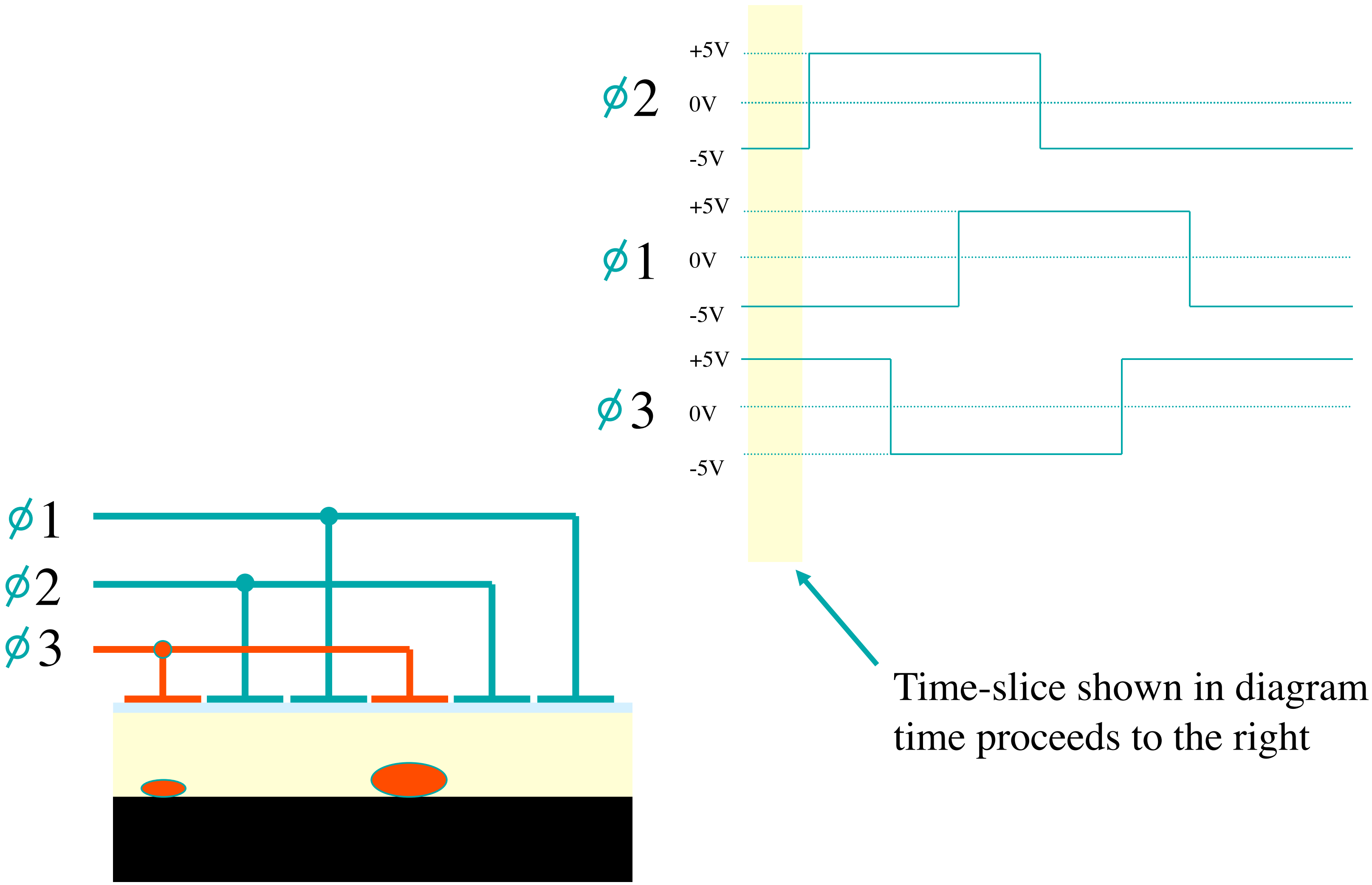
How does a CCD work?

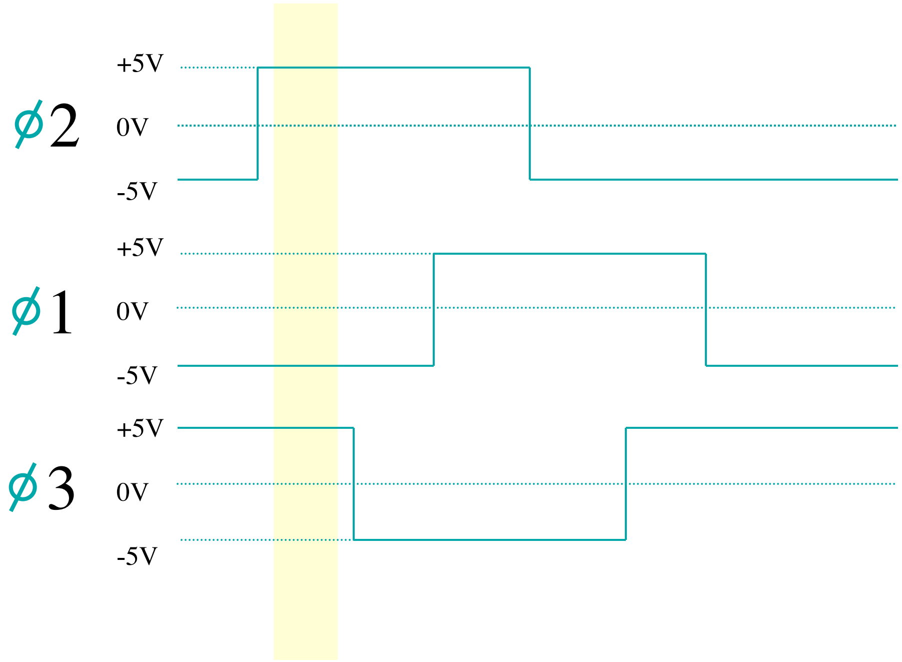
How do the “conveyor belts” actually work?

Charge is moved by modulating the voltages on the electrodes positioned on the surface of the CCD.

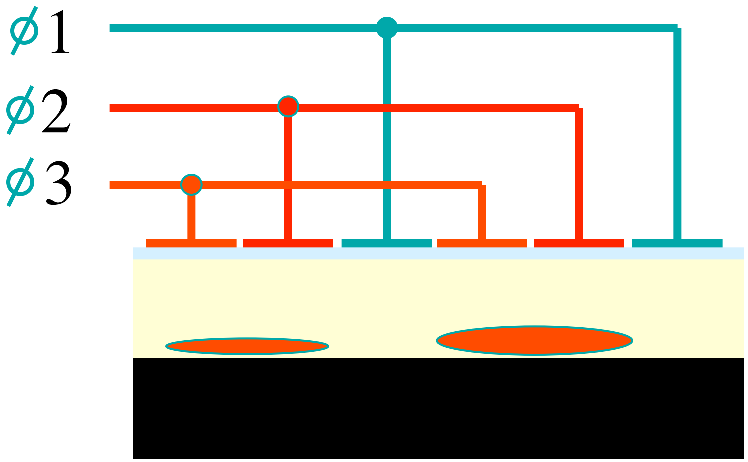
Red = positive potential (+V)   Green= negative potential(-V)



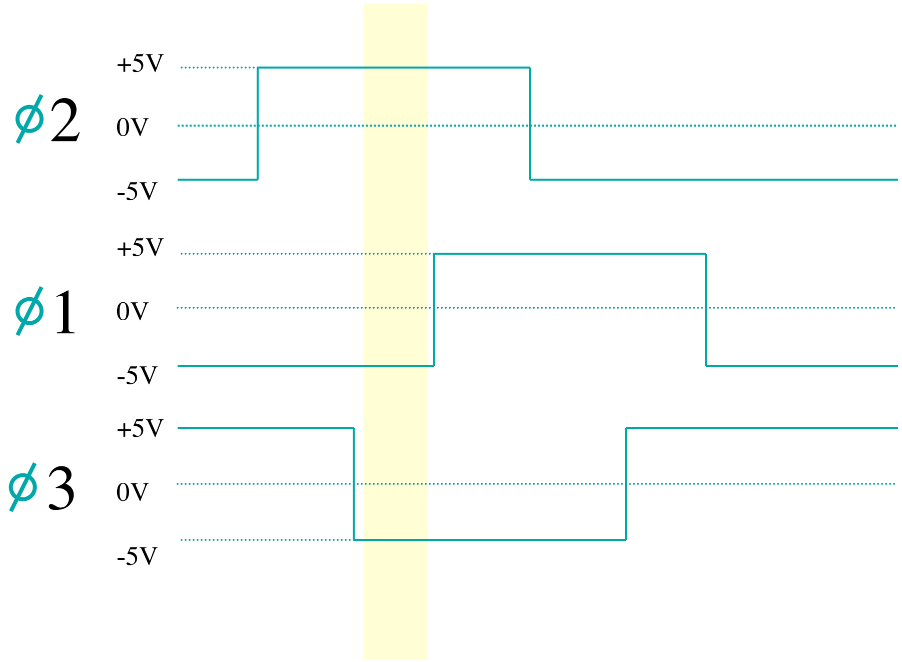

ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V
ϕ1
ϕ2
ϕ3
Time-slice shown in diagram
time proceeds to the right



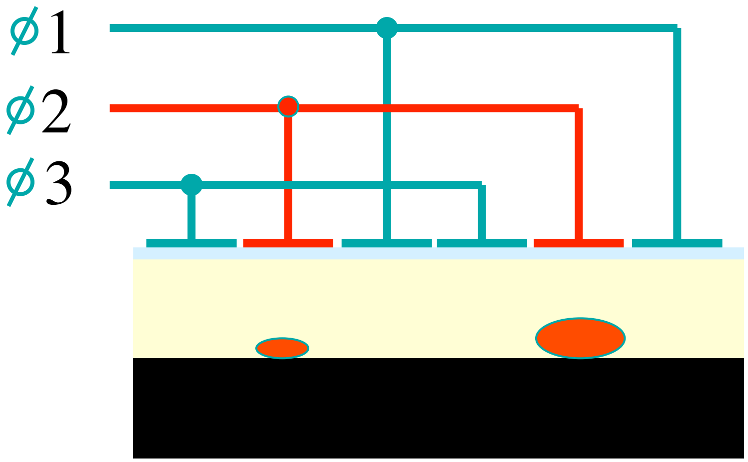
ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V



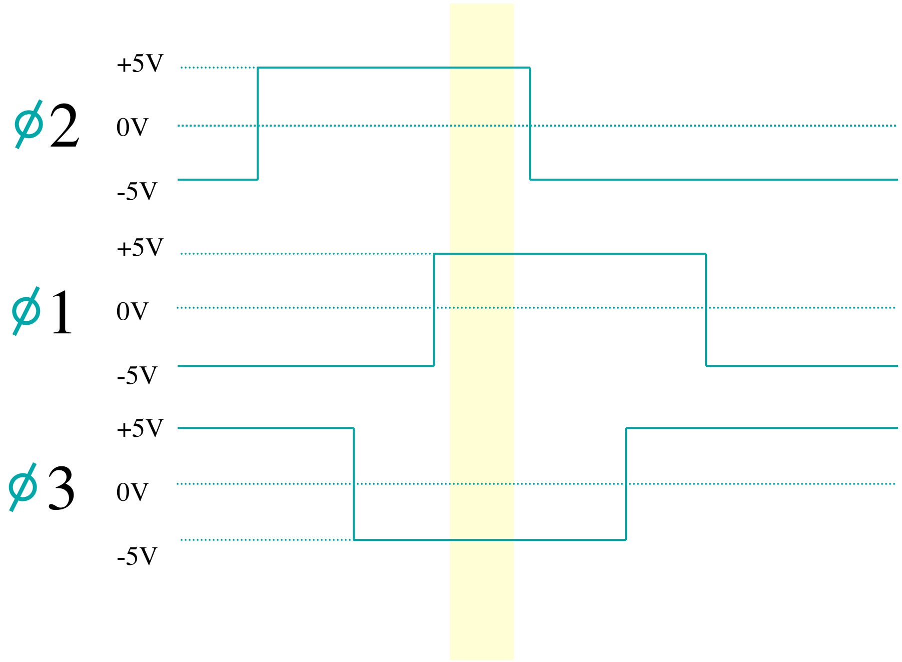
ϕ1
ϕ2
ϕ3



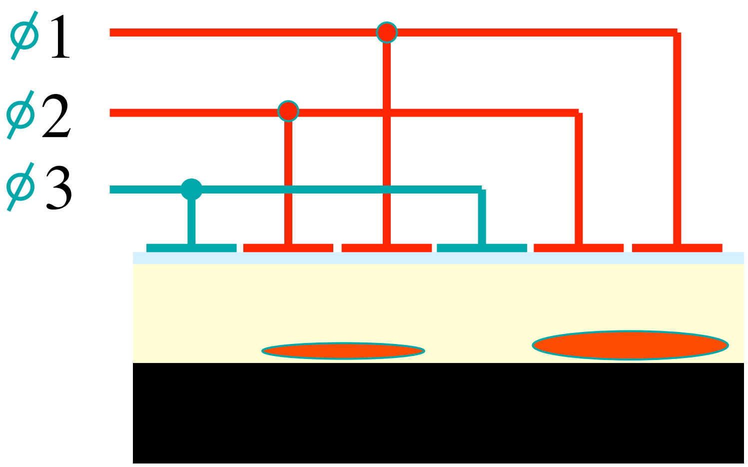
ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V



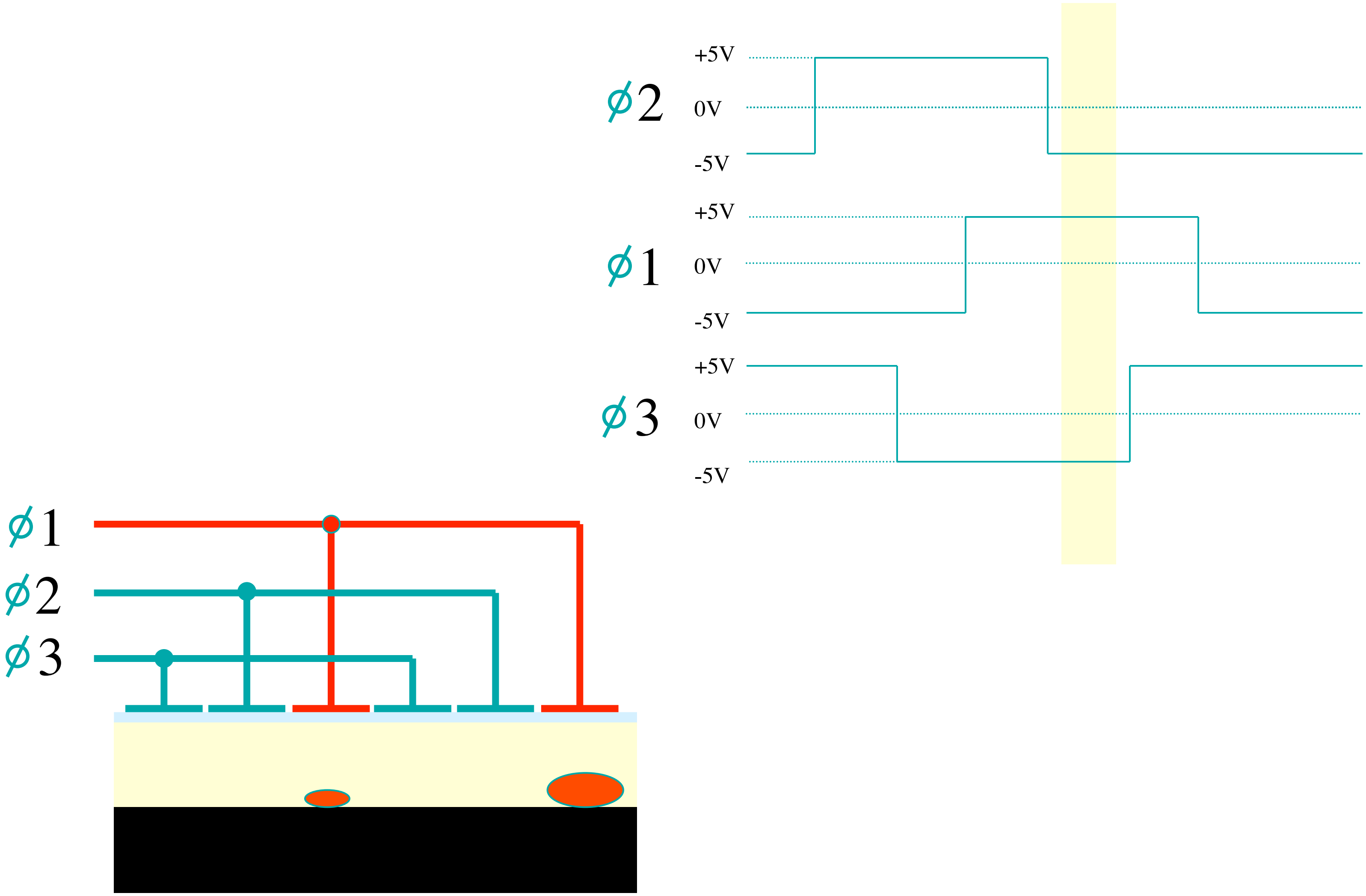
ϕ1
ϕ2
ϕ3



φ2
+5V
0V
-5V
φ1
+5V
0V
-5V
φ3
+5V
0V
-5V

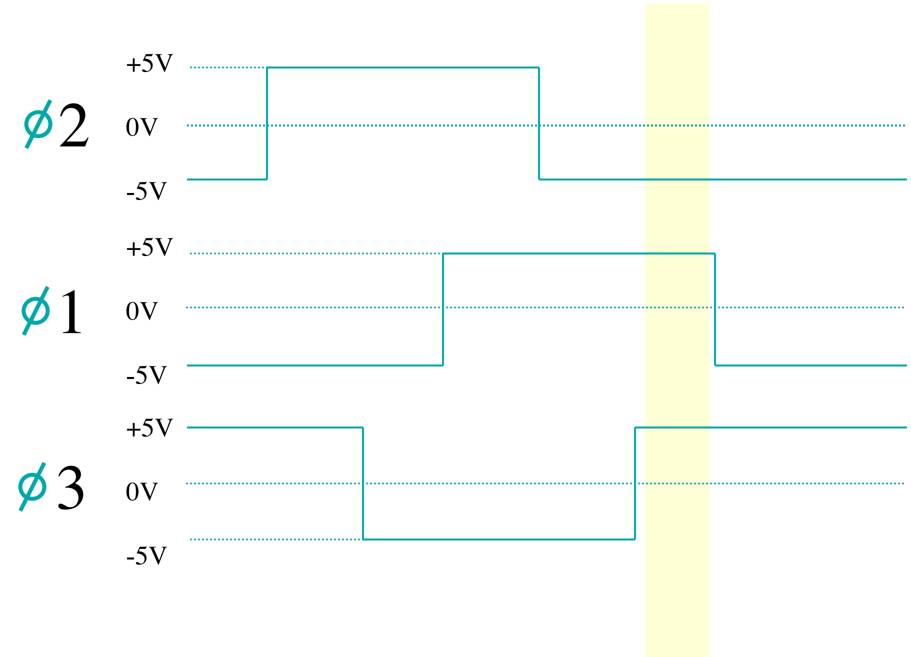


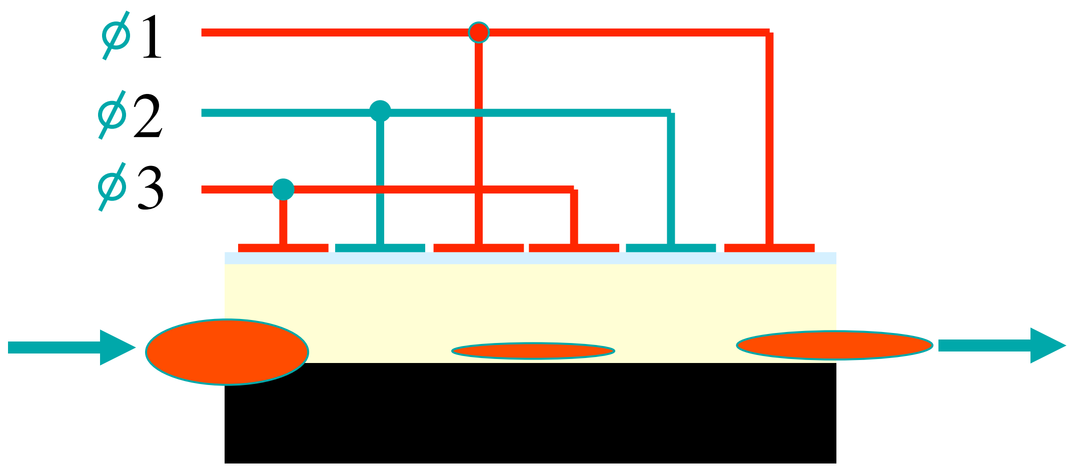
φ1
φ2
φ3



φ2
+5V
0V
-5V
φ1
+5V
0V
-5V
φ3
+5V
0V
-5V
φ1
φ2
φ3

Charge packets from subsequent pixels enter from left as previous pixels exit to the right.





How does a CCD work?

CHARGE TRANSFER EFFICIENCY

Kerry

How does a CCD work?

CHARGE TRANSFER EFFICIENCY

CTE = fraction of charge transferred from one pixel to another

$TTE_{CCD} = (CTE)^n$ n= # of transfers=rows+columns

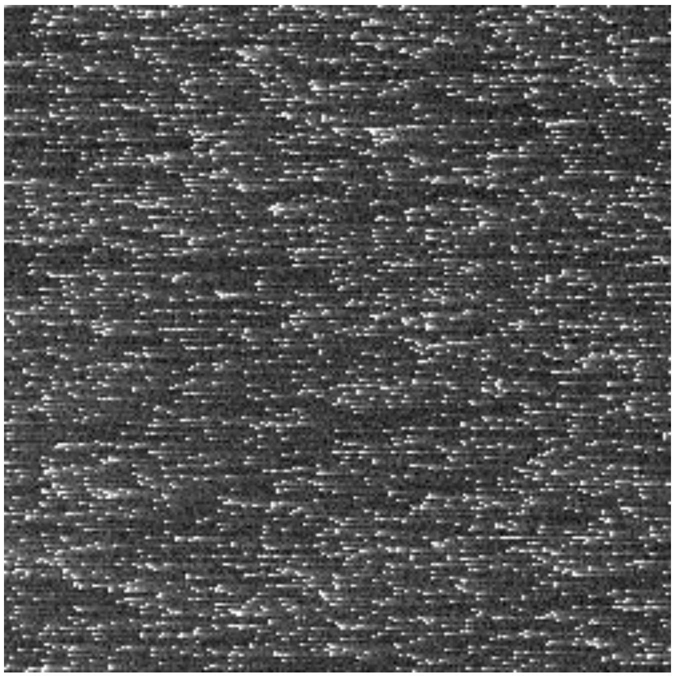
Example: CTE=0.999 n=2048x2=4096→ TTE = only **17%!**

CTE=0.99999 (5 nines) → TTE = 96%

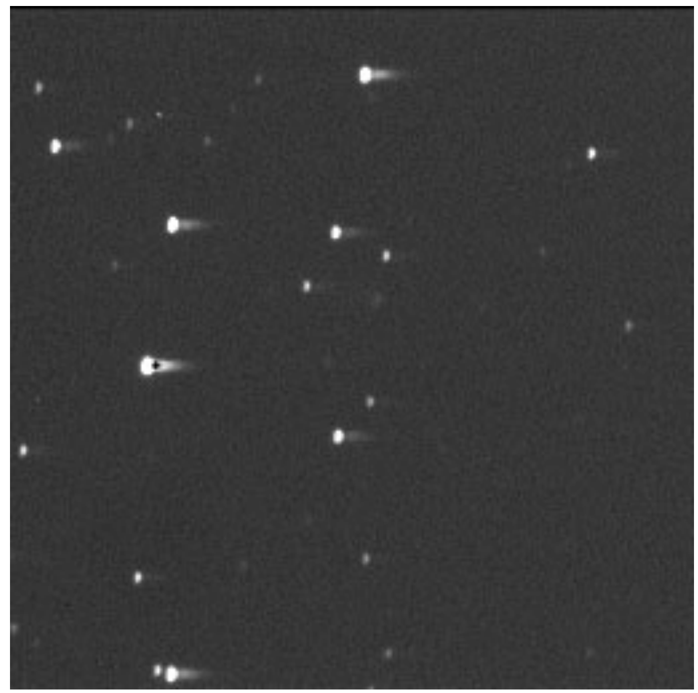
CTE=0.999999 (6 nines) → TTE = 99.6%

How does a CCD work?

CHARGE TRANSFER EFFICIENCY



5-min dark frame – hot pixels smeared

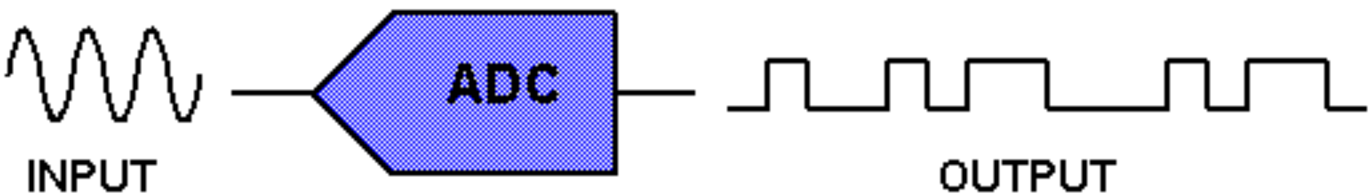


sky exposure; high-level CTE issue

http://darkerview.com/CCDProblems/serialcte.php

How does a CCD work?

The A to D converter (ADC)



analog (voltage)

digital (data number)
DN, ADU

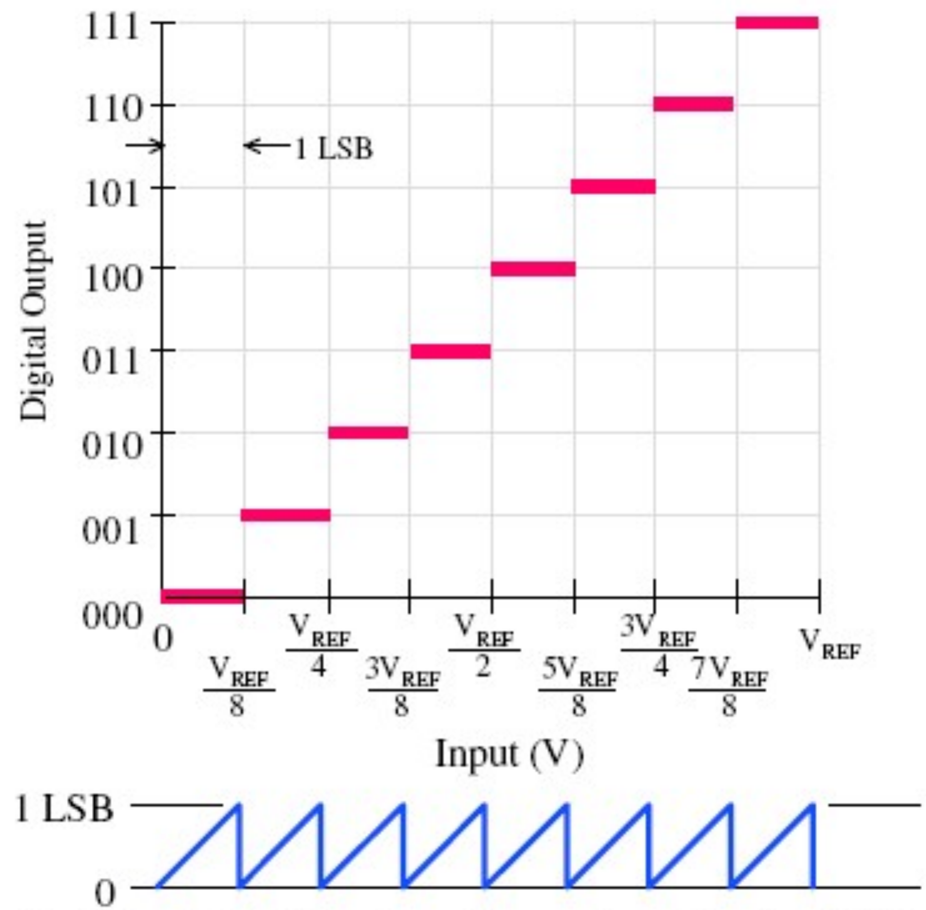
National Semiconductor

Digitization “noise” from ADU

LSB= least significant bit

Here, 3-bit depth→ 8 values

For V range ≤ 1 LSB, output stays constant.



The Magnitude of the Error Ranges from Zero to 1 LSB

http://www.national.com/AU/design/courses/175/print.htm

How does a CCD work?

Some Properties of a CCD System

Full well depth: # of electrons that can be accommodated in a single pixel, e.g., 100,000 electrons

ADU limit: range of values the ADU is capable of reporting, e.g. 16 bits means 2^{16} = 65536 values

Readnoise: unavoidable signal introduced into each readout by system electronics (typically 5-10 electrons/pix)

Gain: conversion factor from electrons to counts (DN, or ADU)

Linearity limit: maximum number of electrons that can be detected before the response becomes non-linear (i.e., useless)

How does a CCD work?

CCD Gain

What's the relationship between electrons and pixel values?

$$\text{gain} = \frac{\text{number of electrons in a pixel}}{\text{number of counts in a pixel}}$$

counts=ADU=DN

How to choose: one way to go is to have a value that takes advantage of the full-well depth and ADU characteristics, so, say, design for g~FWD/max ADU value

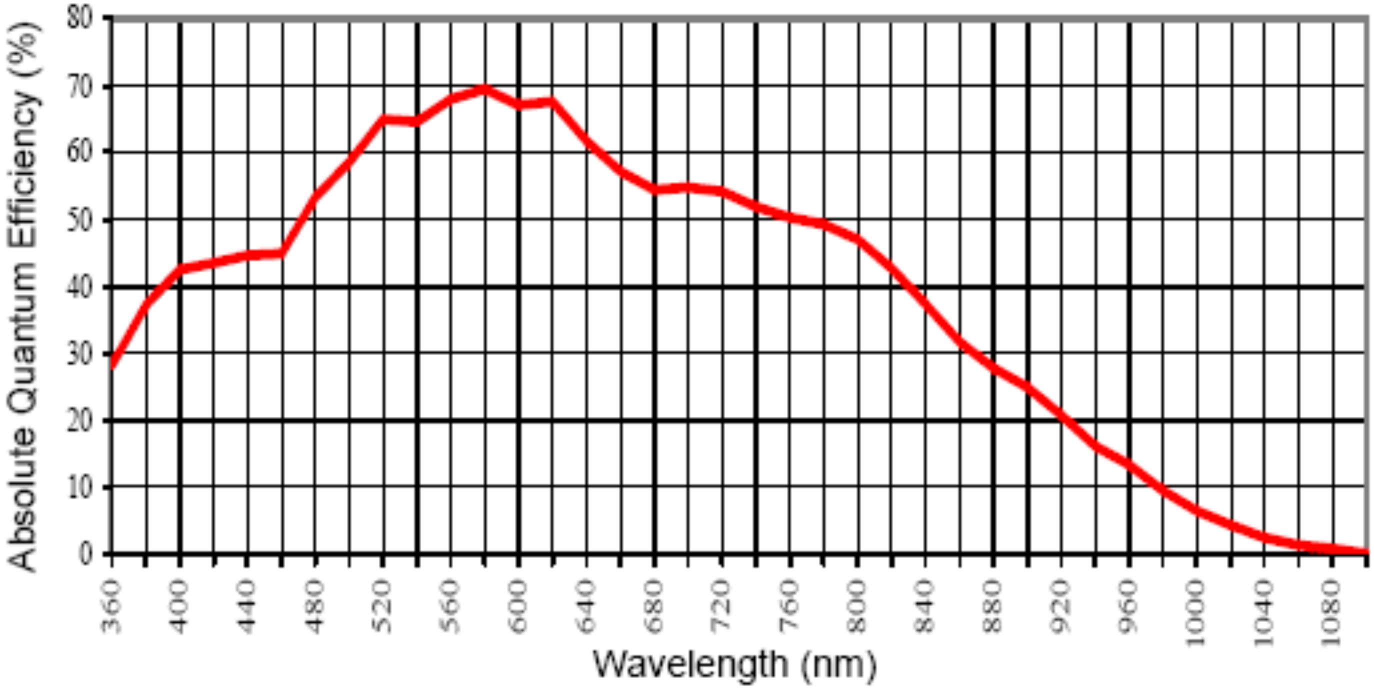
e.g., for FWD=100,000 electrons, and max ADU value =65536→g~1.5

Not only consideration, though: if max ADU value is only 8 bits (256)→ g=390! Think of the information lost in the graininess of the digitization!

Our CCD: Apogee U9000

12µ pixels
3056 x 3056 (37mm square)
16 bits (=65536 gray levels)
Full well depth=110,000 e^-
Linearity limit ~15,000 ADU
Peak QE @5500A = 64%

Readnoise (e^-/pix)
Gain (e^-/ADU)
Dark Current (e^-/pix/s)
above TBD by you

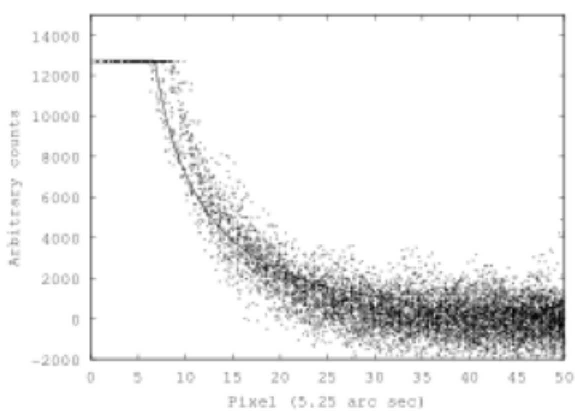


Apogee

How does a CCD work?

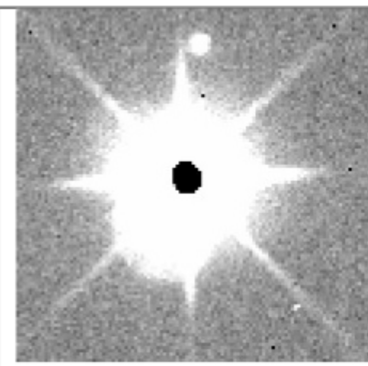
Three Possible Kinds of Saturation

1. *Exceeding the ADU maximum:* #photons/gain >65536, due to overexposure or, poor choice of gain value
2. *Exceeding the pixel full-well depth:* overfilling pixels due to integration time being too long – **even if ADU not saturated**
   e.g., FW=100,000e^-, g=2.5 e^-/ADU→saturation @ 40,000 ADU, even with 16-bits



Profile of the image of a saturated star

http://arxiv.org/pdf/astro-ph/0502411



What a saturated star may look like on the CCD. The center part is dark because the counts have gone to negative numbers.

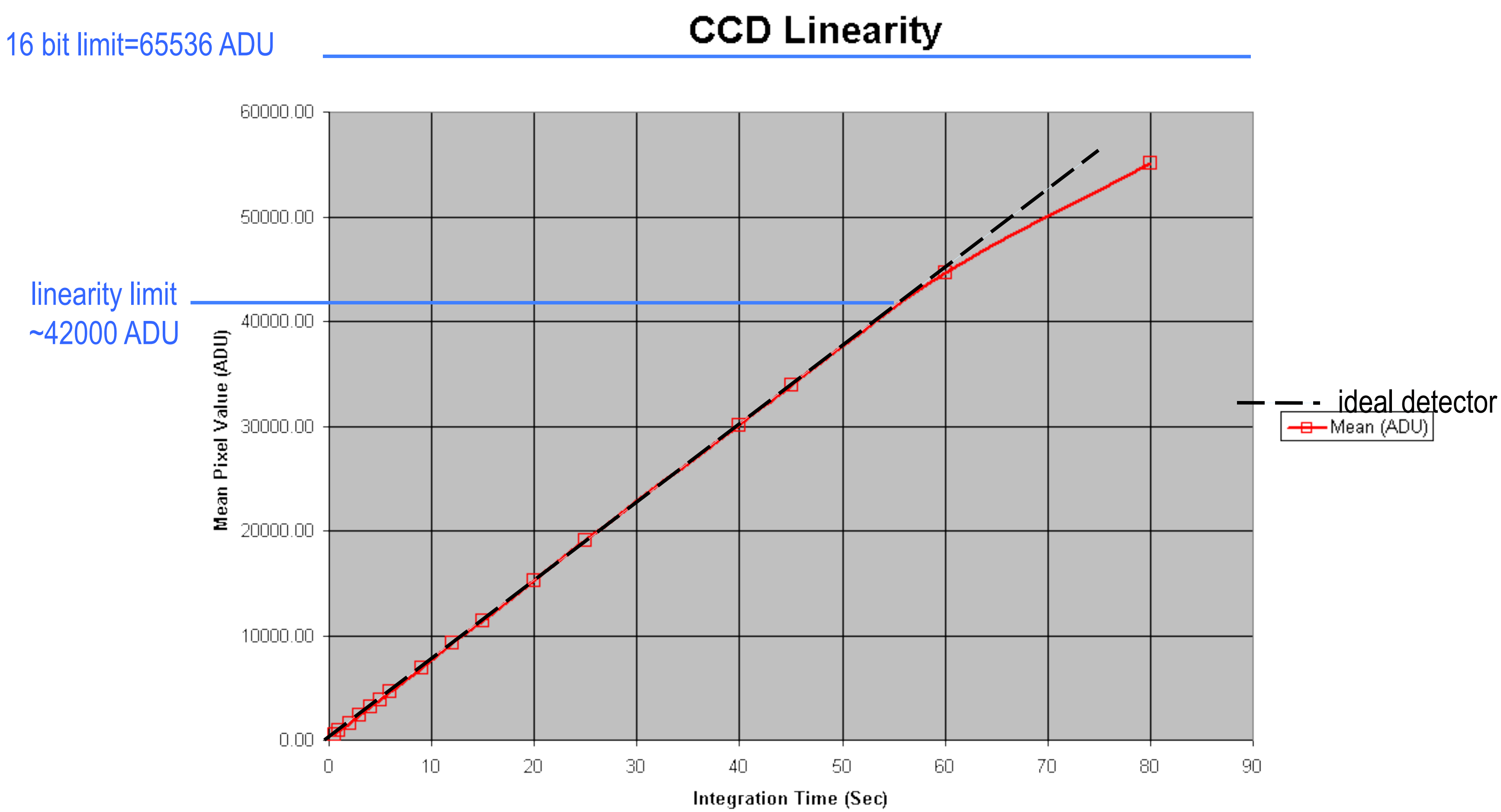
http://casu.ast.cam.ac.uk/

http://www.astro.washington.edu/courses/astro480/CCD/characterize_CCD_a480.pdf

How does a CCD work?

Three Possible Kinds of Saturation

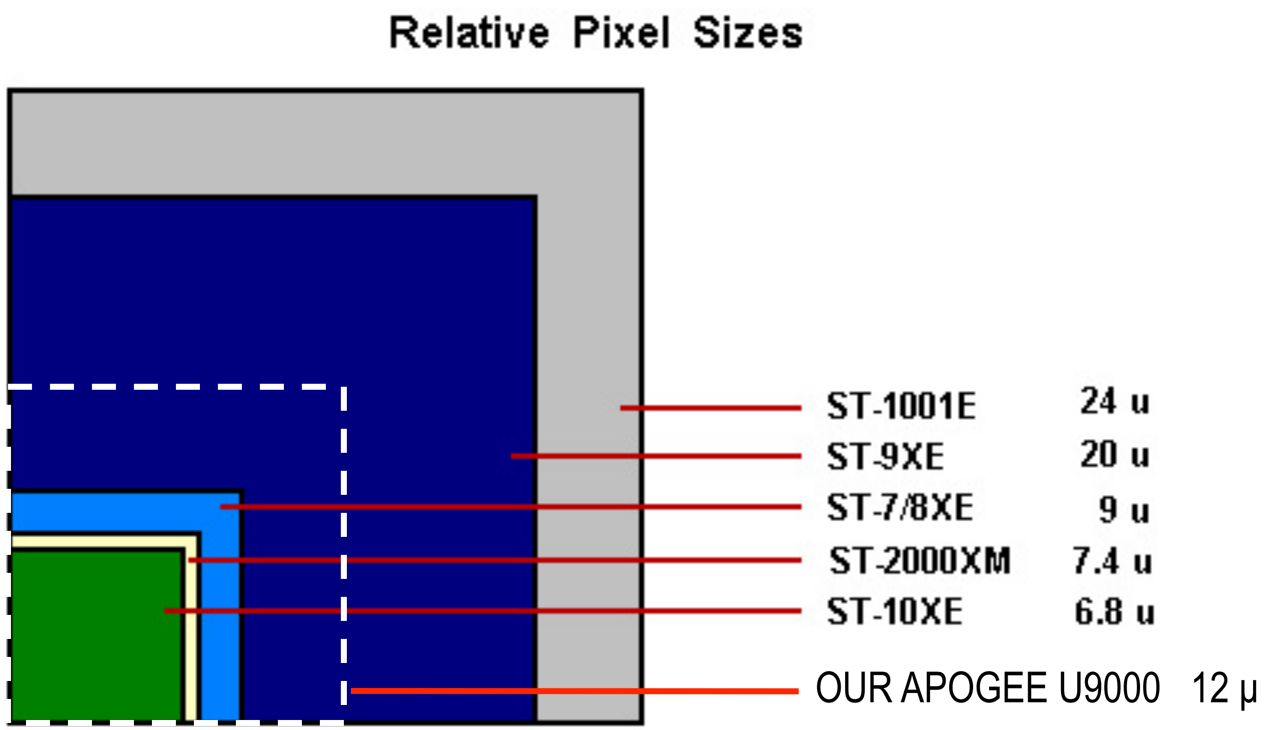
3. *Exceeding the linearity limit:* more insidious – things look OK.



http://astroham.com/astrophotography_ccdtesting.html

Pixel Sizes

typically ~6-24 μm



Nyquist's Theorem

Q: How many/what size pixels do we want?

- Big blocky pixels are bad → position and shape information are lost.
- Contrast is reduced if neighboring stars are blurred together.
- Poisson noise is increased due to additional sky background in a large pixel.
- On the other hand, the more pixels over which a given star's image is spread, the more read noise will be introduced.

A: Nyquist's theorem* states that all the information in an image is captured when there are ***3 samples per resolution element***.

- So no point in packing pixels more densely than 1/3 the FWHM of the seeing disk (conventionally defined as the FWHM of a stellar image).
- Example: In 1" seeing, you need ~0.3" pixels for optimal sampling.
- Imagers are usually designed with pixels small enough for the best seeing conditions that might occur; but that can be ***binned*** to give effectively larger pixels for more ordinary-to-poor seeing conditions.

*applies to all frequency analysis problems.

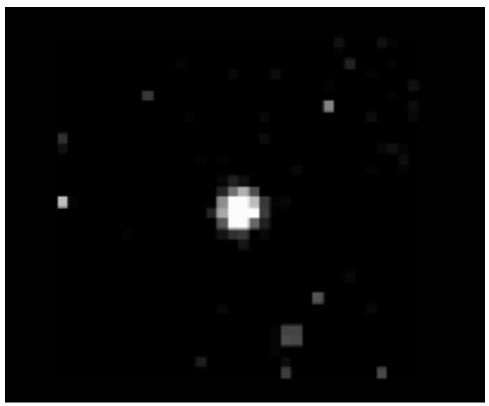
www.thrushobservatory.org/sig/CCD%20Astronomy.ppt

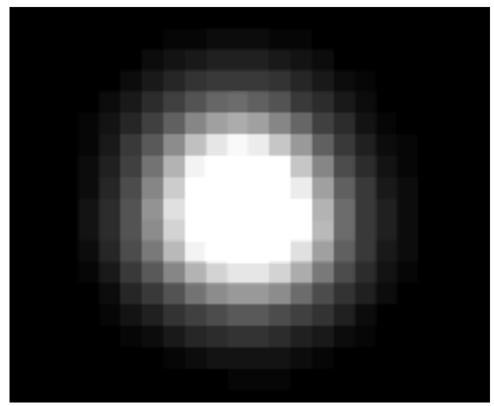
Pixel Size

Nyquist Sampling, Nyquist Criterion (3 pix/resel)

- Large pixels that do not meet NC → image is *under-sampled* and **information is lost**.
- Exceeding NQ → *over-sampling,* which wastes chip area; with improved matching of detector and optics, a larger area of sky could be imaged.

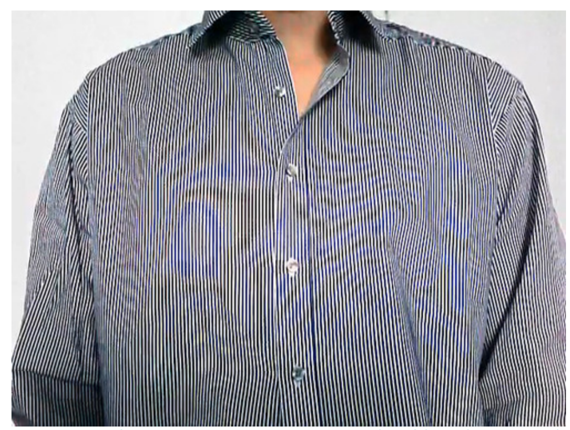
undersampled





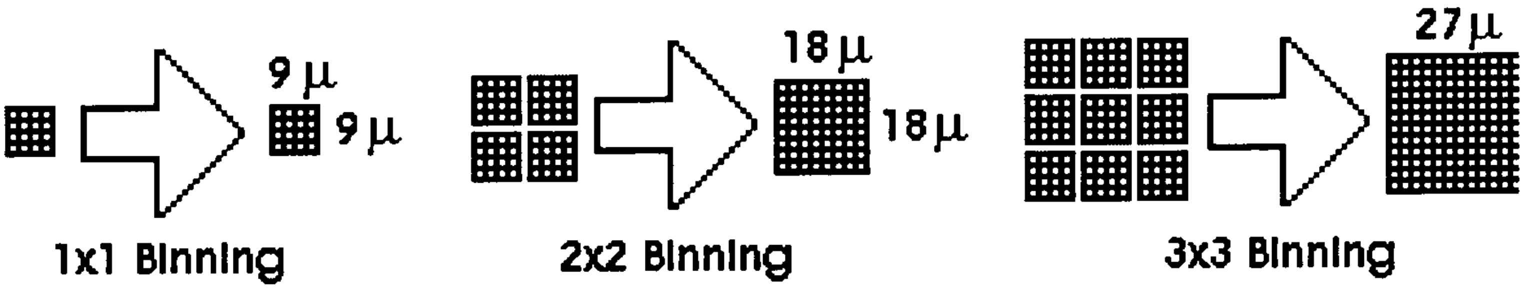
oversampled

Fun fact: Under-sampling an image can produce some interesting effects. One of these is 'aliasing,' which is the apparent detection of a pattern at a smaller spatial frequency than it really has. This is sometimes seen on TV when, for example, a finely-striped shirt pattern breaks up into wavy bands and ripples. The TV camera pixels are too big to record the fine detail present in the shirt pattern.



http://25.media.tumblr.com/tumblr_l6lko23Tsx1qz7ymyo1_500.jpg

Binning



One important advantage of ‘on-chip binning’ is that it is a **noise free process: reading out the resulting larger pseudopixel still “costs” only a single pixel’s worth of read noise.**

www.thrushobservatory.org/sig/CCD%20Astronomy.ppt

Pixel Size and Binning

Binning

Example 1 showed that with 13.5 micron pixels the system exceeded the Nyquist criterion even with exceptionally good sub-arcsecond seeing. If the seeing were 2”, the size of a stellar image becomes 120 microns on the detector. The image will now be *grossly over-sampled.*
(One way to think of this is that the image is less sharp and therefore requires fewer pixels to record it).
It would be more efficient now to switch to a detector with larger pixels since the resulting image files would be smaller, quicker to read out and would occupy less disk space.

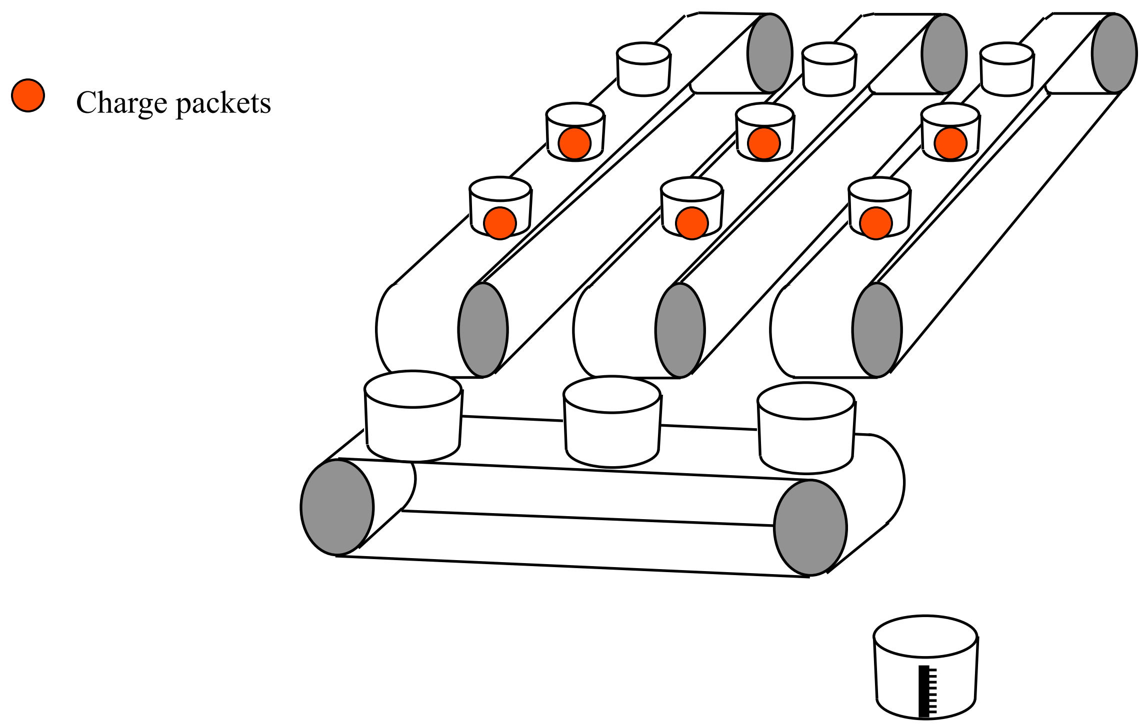
There **is** a way to read out a CCD so as to increase the effective pixel size: *binning*. Binning allows us to increase pixel size arbitrarily. In the limit we could even read out the CCD as a single large pixel! Astronomers commonly use 2 x 2 binning, which means that the charge in each 2 x 2 square 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: reading out the resulting larger pseudopixel still “costs” only a single pixel’s worth of read noise.**

Vertical and horizontal binning can each/both be done – they are independent.

Pixel Size and Binning

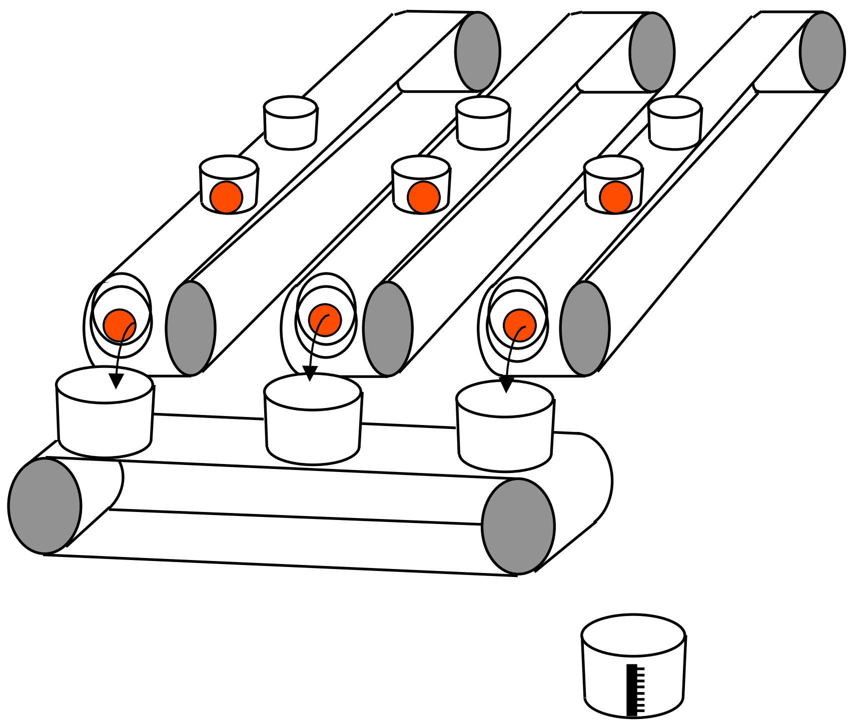
Example: Vertical Binning

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.



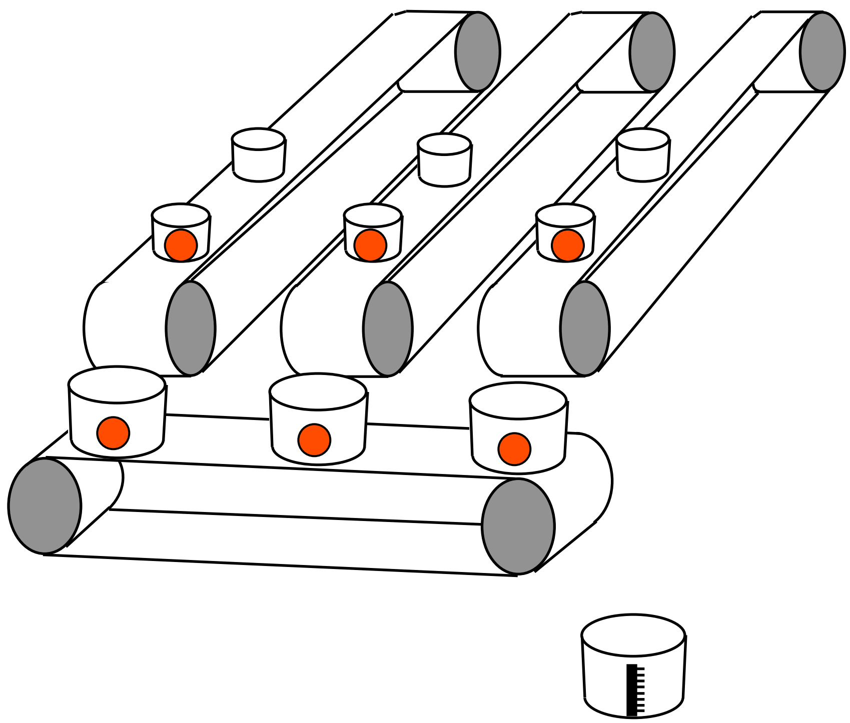
Pixel Size and Binning

The first row is transferred into the serial register



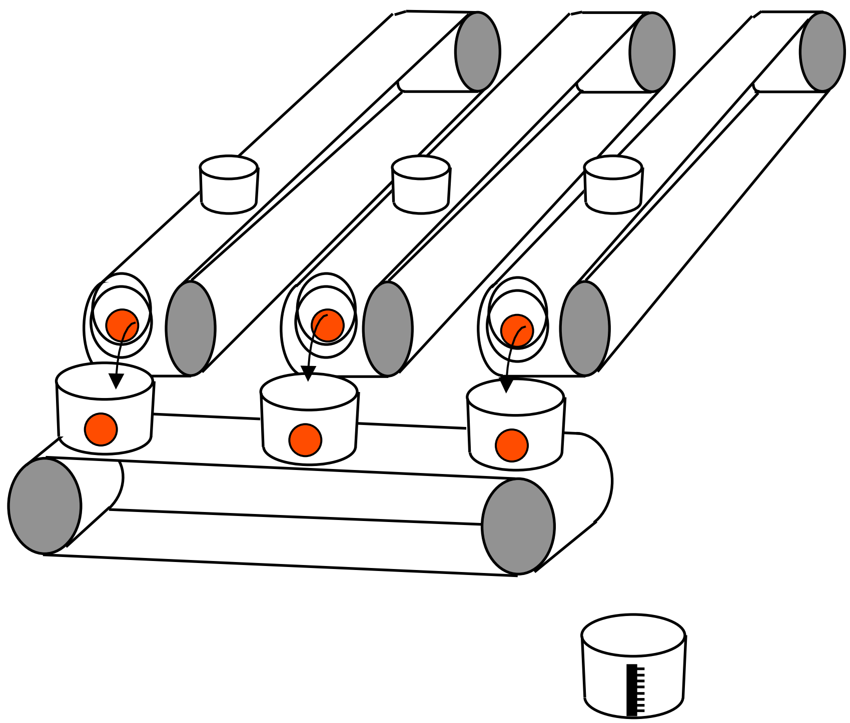
Pixel Size and Binning

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



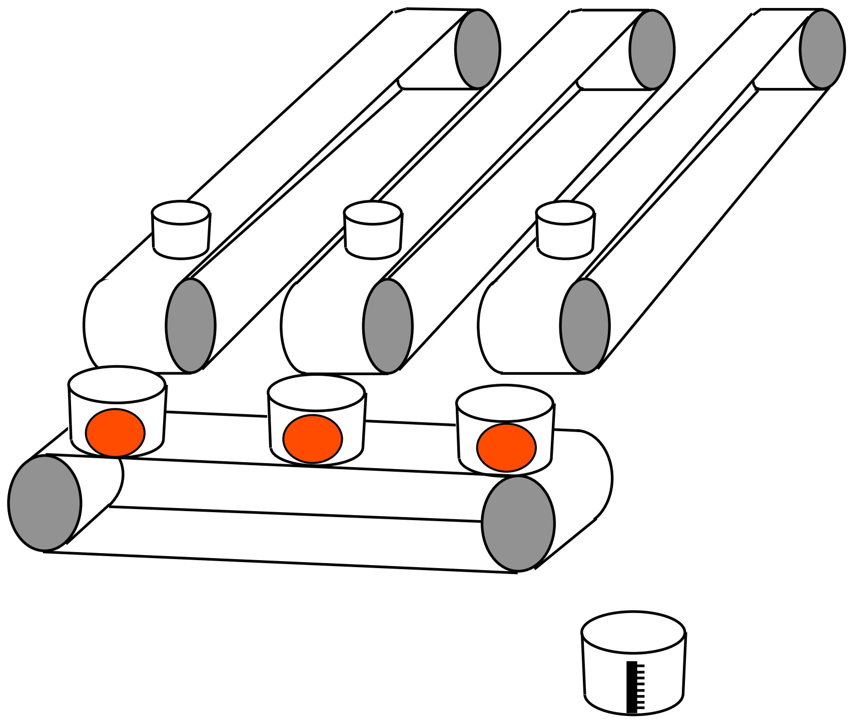
Pixel Size and Binning

The second row is now transferred into the serial register.



Pixel Size and Binning

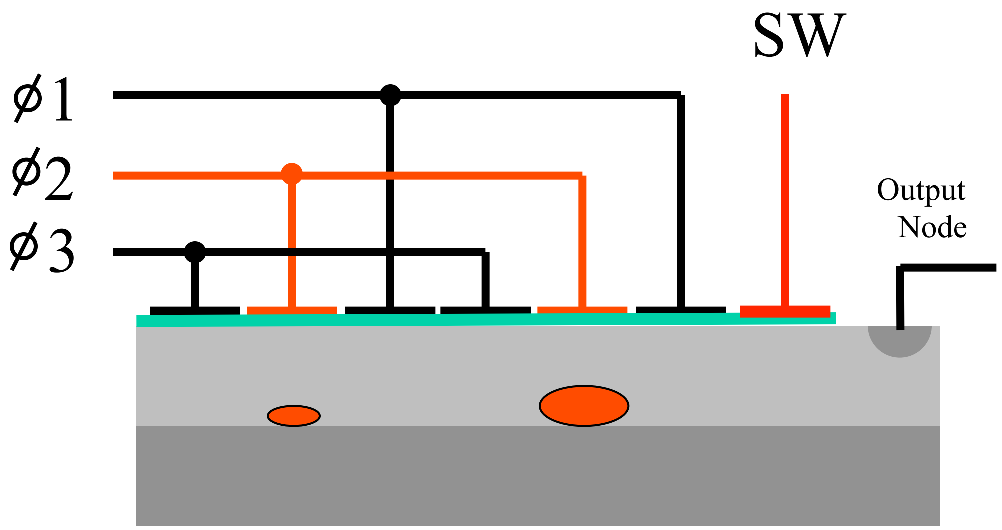
Each pixel in the serial register now contains the charge from two pixels in the image area. It is thus important that the serial register pixels have a higher charge capacity. This is achieved by giving them a larger physical size.



Pixel Size and Binning

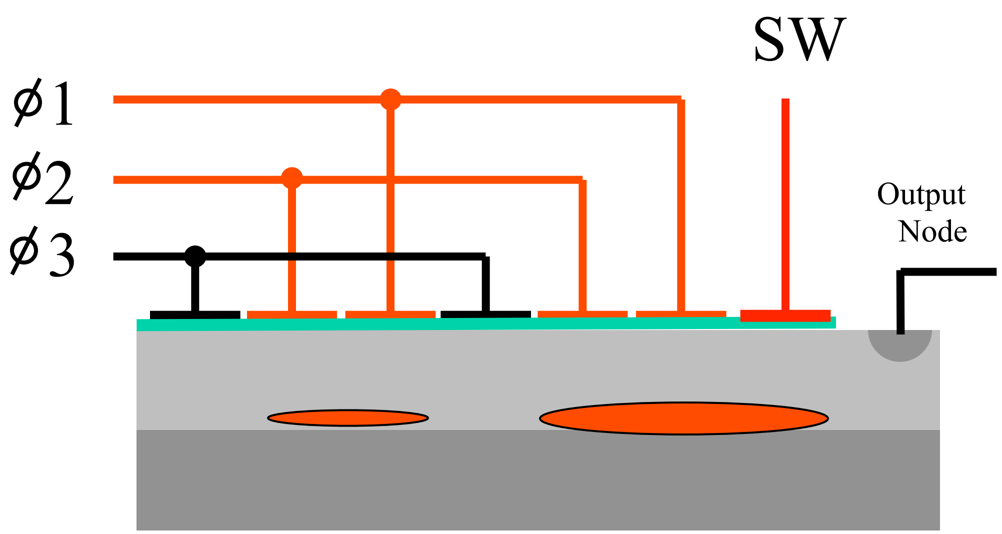
Stage 2 :Horizontal Binning

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 :

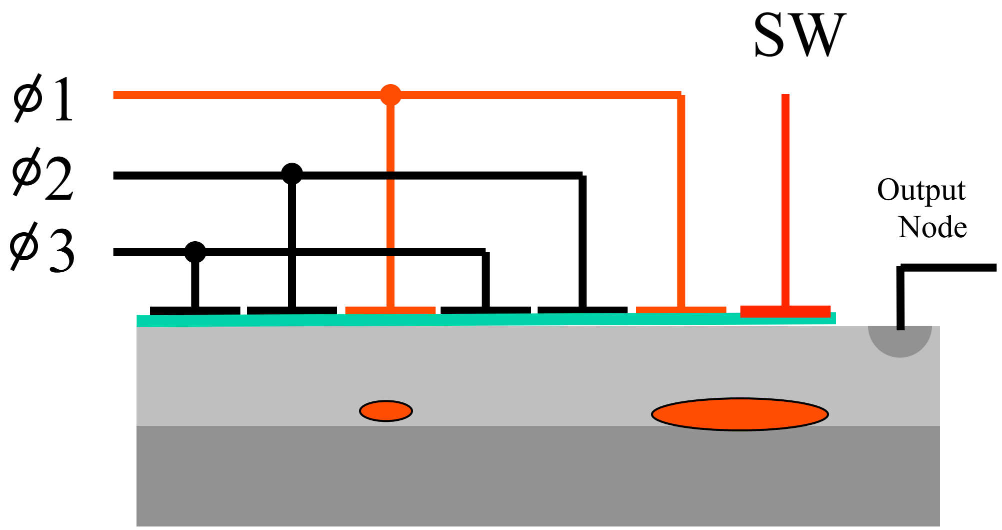


Pixel Size and Binning

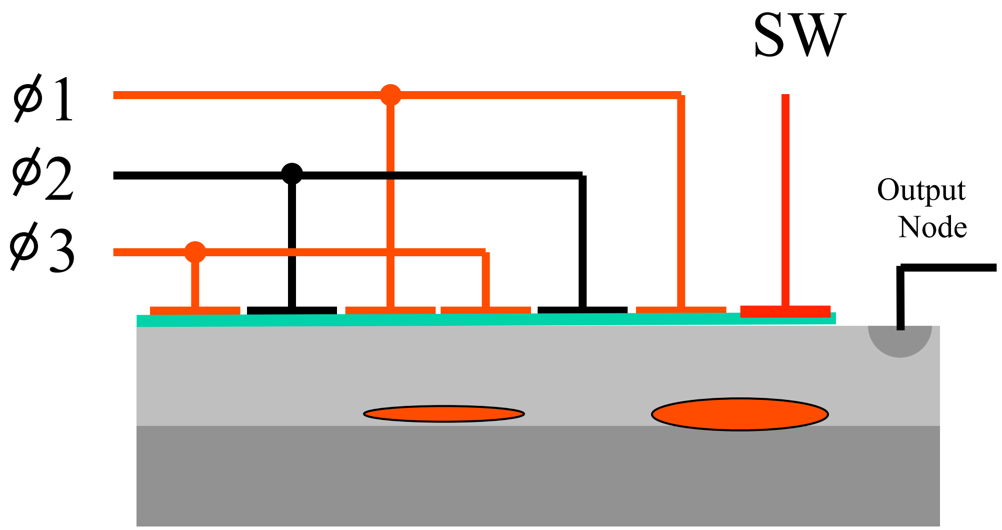
Charge is clocked horizontally with the SW held at a positive potential.



Pixel Size and Binning

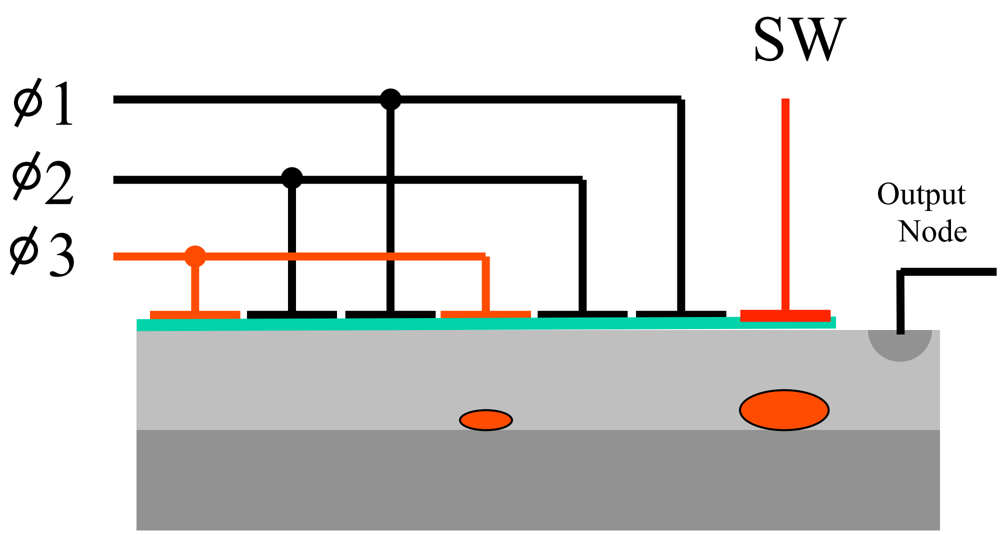


Pixel Size and Binning



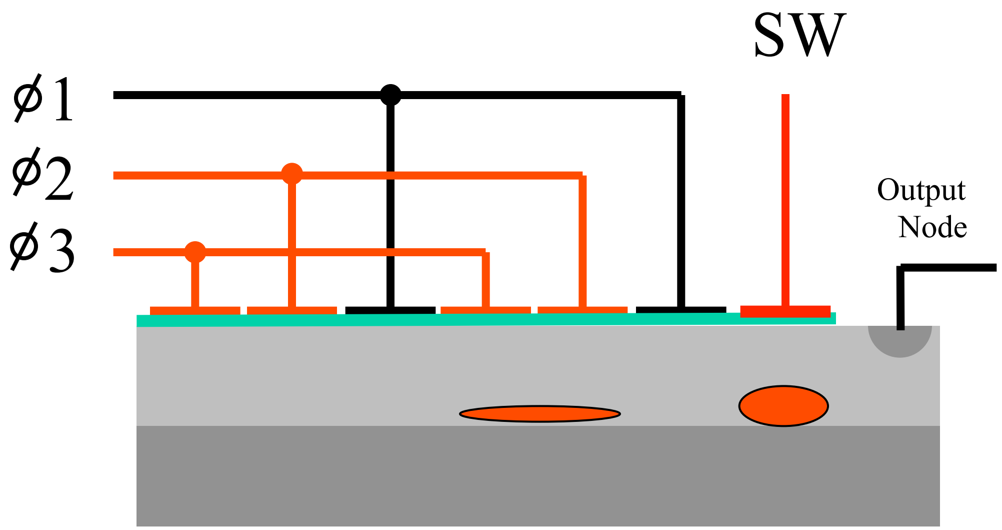
Pixel Size and Binning

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

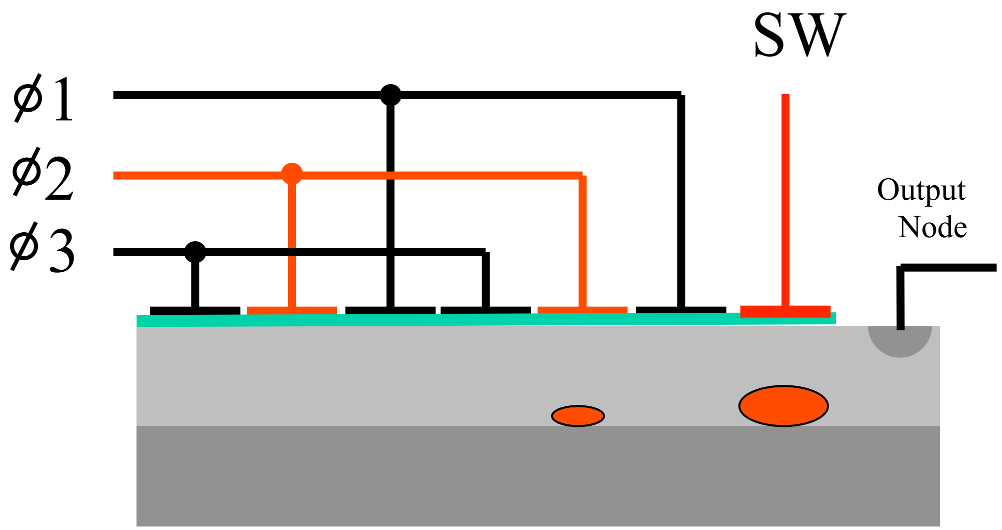


Pixel Size and Binning

The serial register continues clocking.

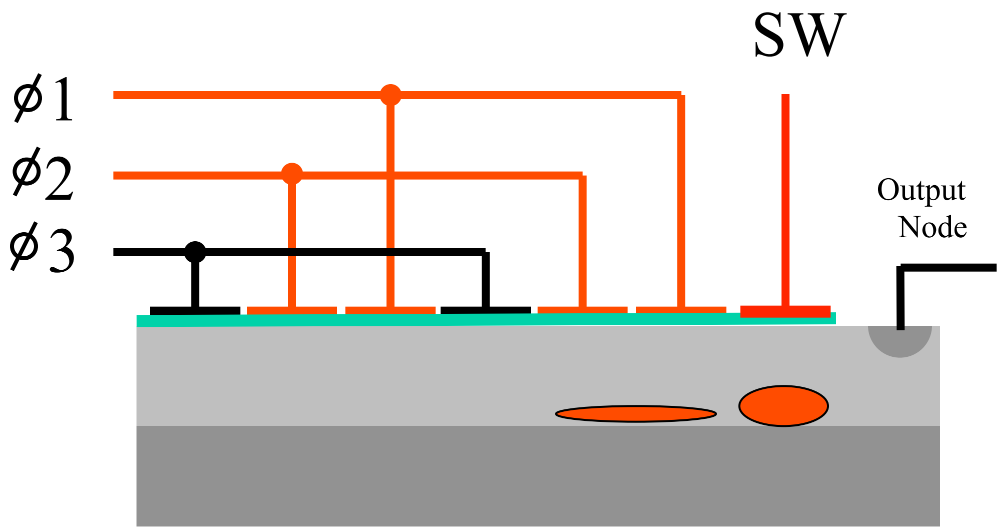


Pixel Size and Binning

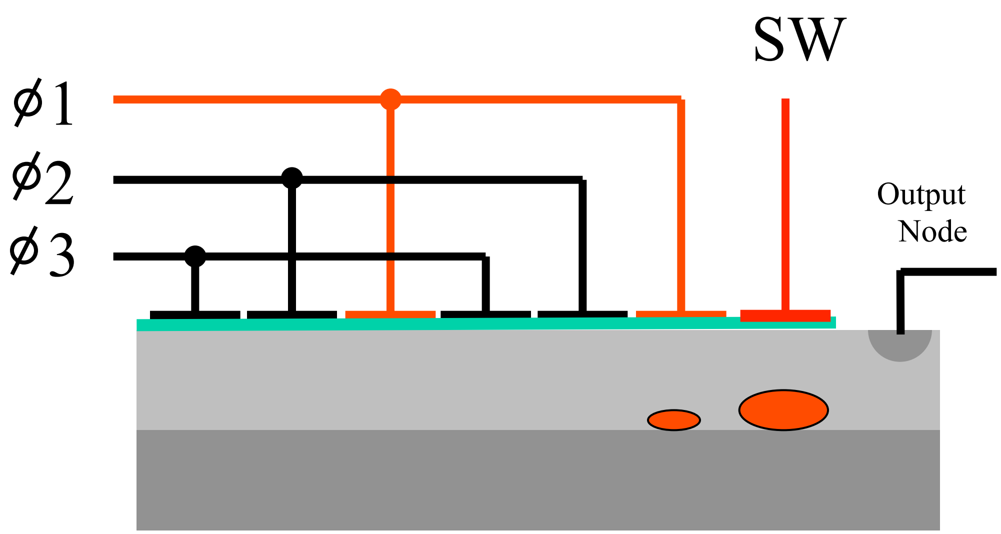


Pixel Size and Binning

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



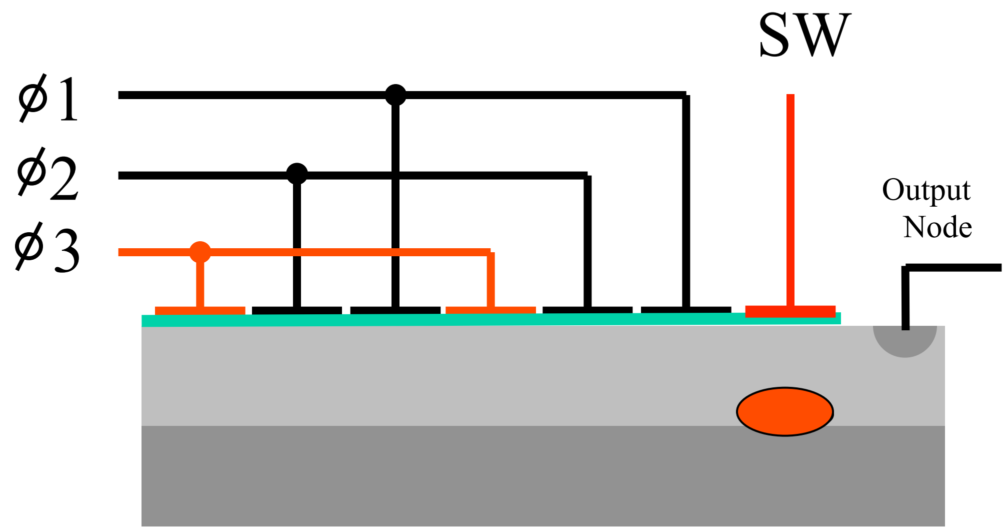
Pixel Size and Binning



Pixel Size and Binning

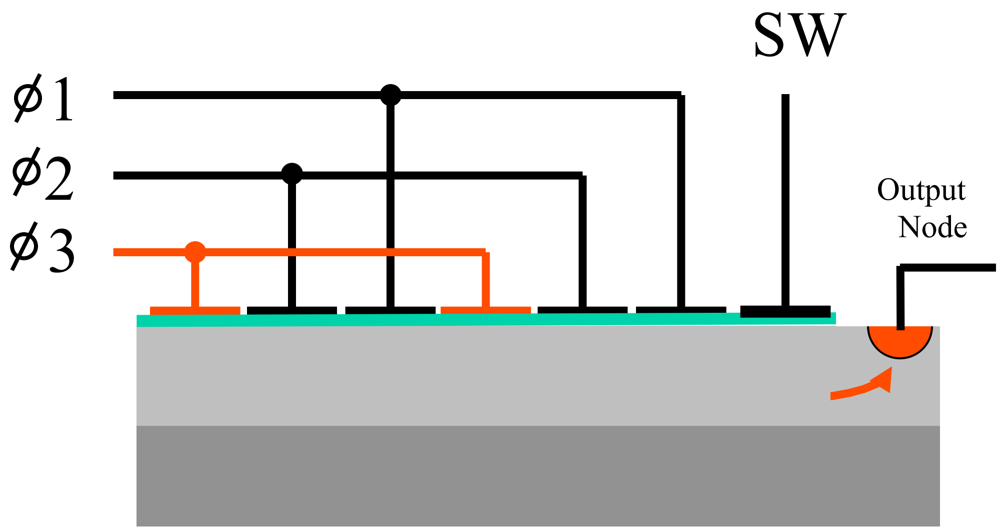
The charge from the second pixel is now transferred onto the SW. The binning is now complete and the combined charge packet can now be dumped onto the output node (by pulsing the voltage on SW low for a microsecond) for measurement.

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



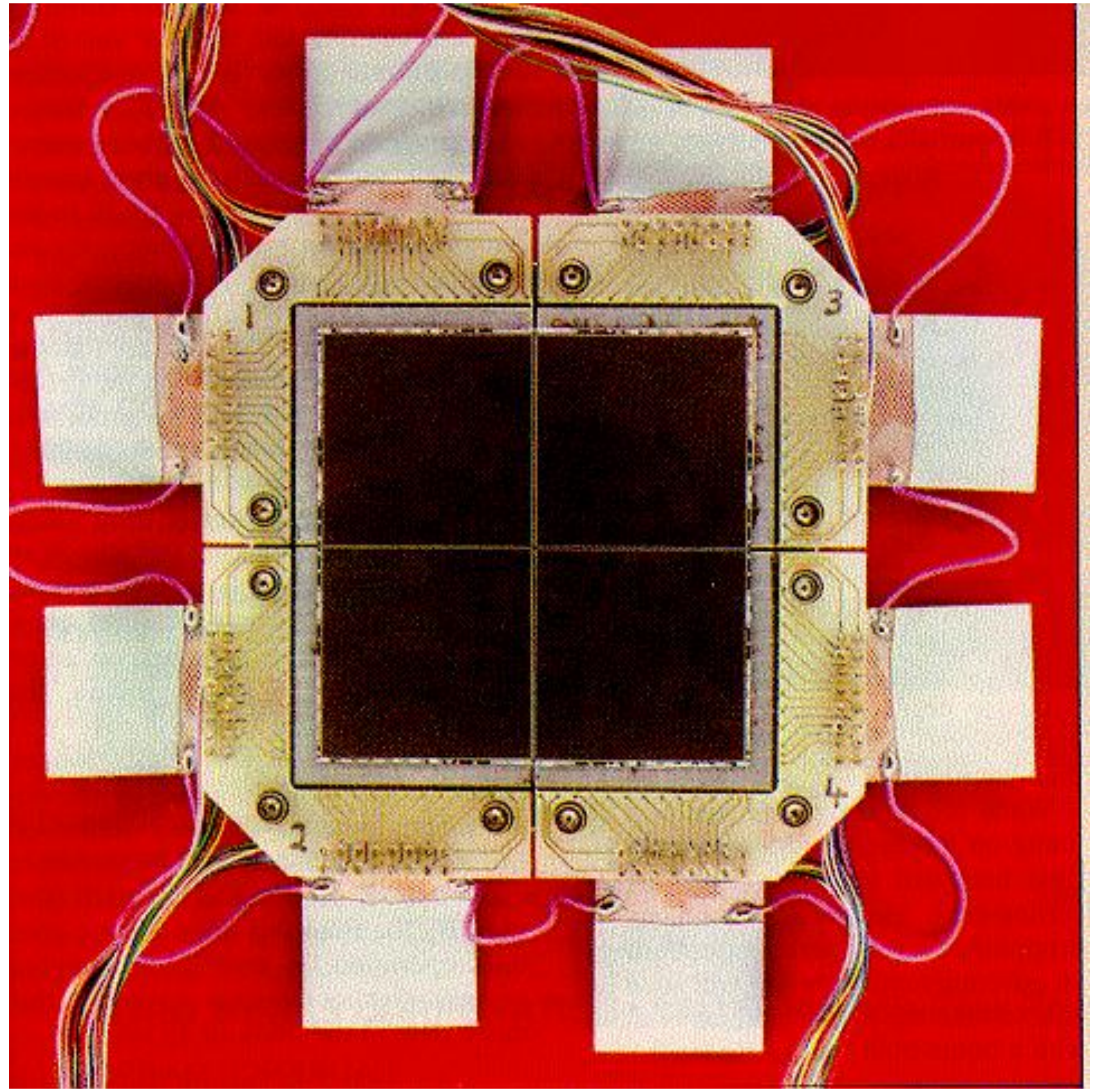
Advantages of CCDs

1) Good spatial resolution
2) Very high quantum efficiency
3) Large spectral window
4) Very low noise
5) Large variations in the signal strength allowed (high dynamic range)
6) High photometric precision
7) Very good linearity
8) A reliable rigidity

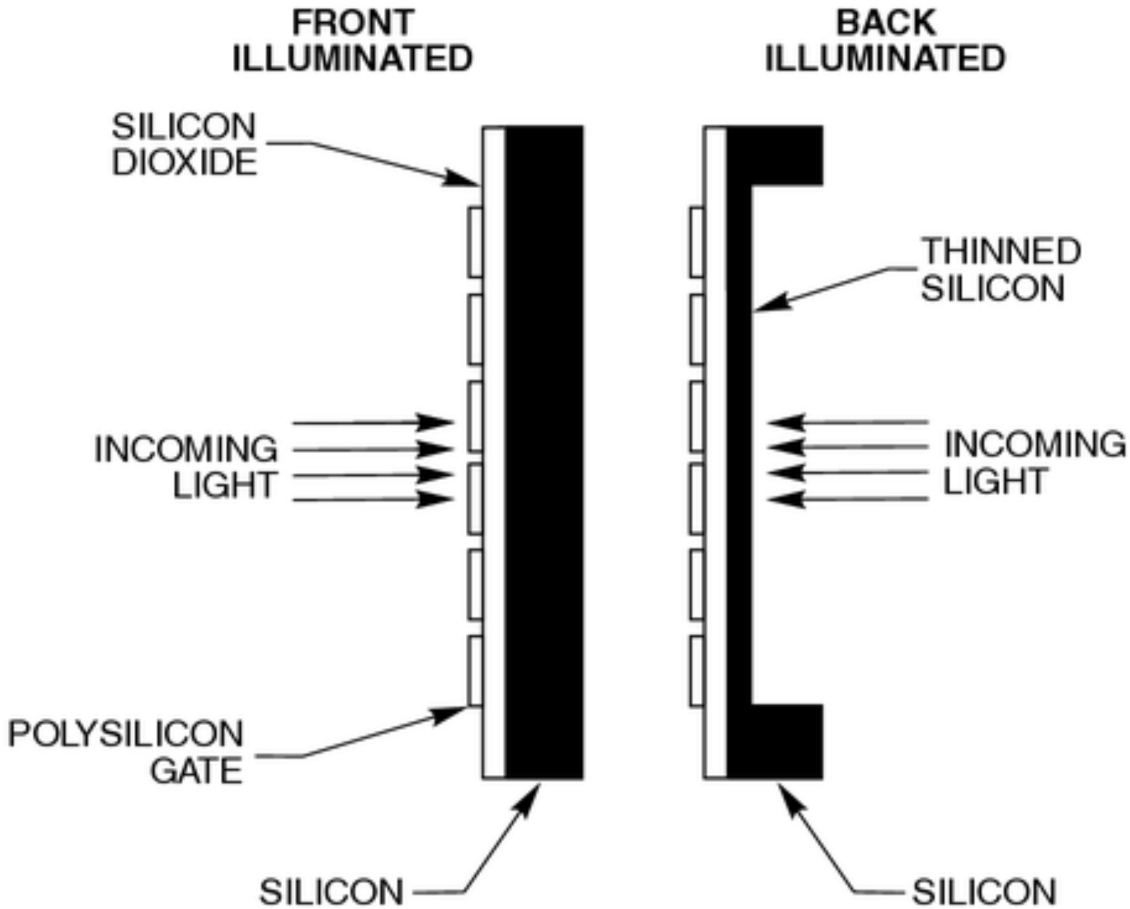
Advantages of CCDs

Spatial Resolution

Mosaic of 4 CCDs containing four times 2040 x 2048 pixels. This composite detector is about 6 cm large and contains a total of 16 million pixels (Kitt Peak National Observatory, Arizona).

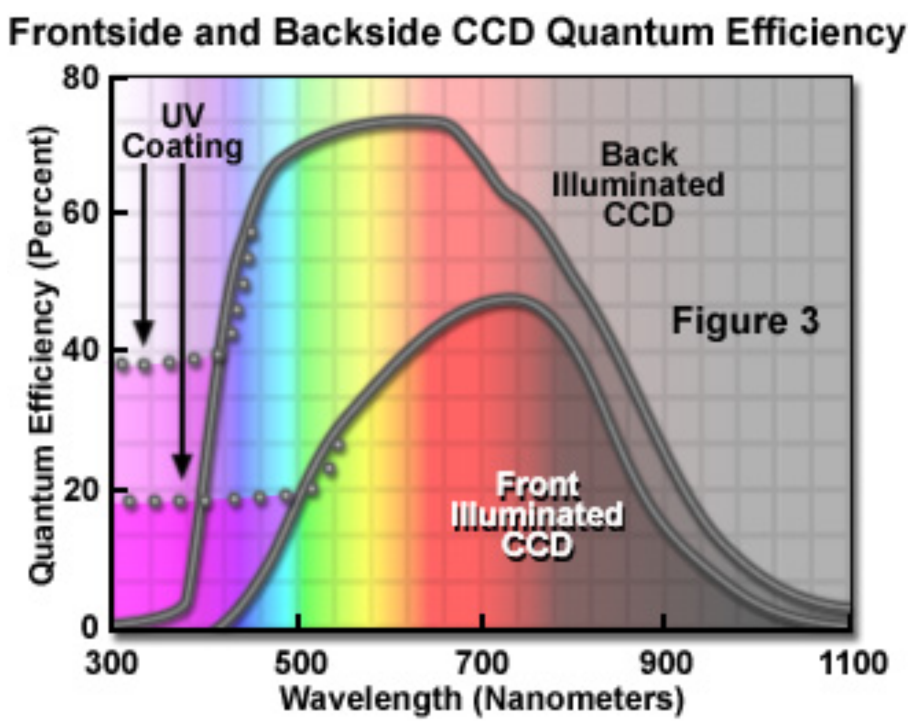


Advantages of CCDs



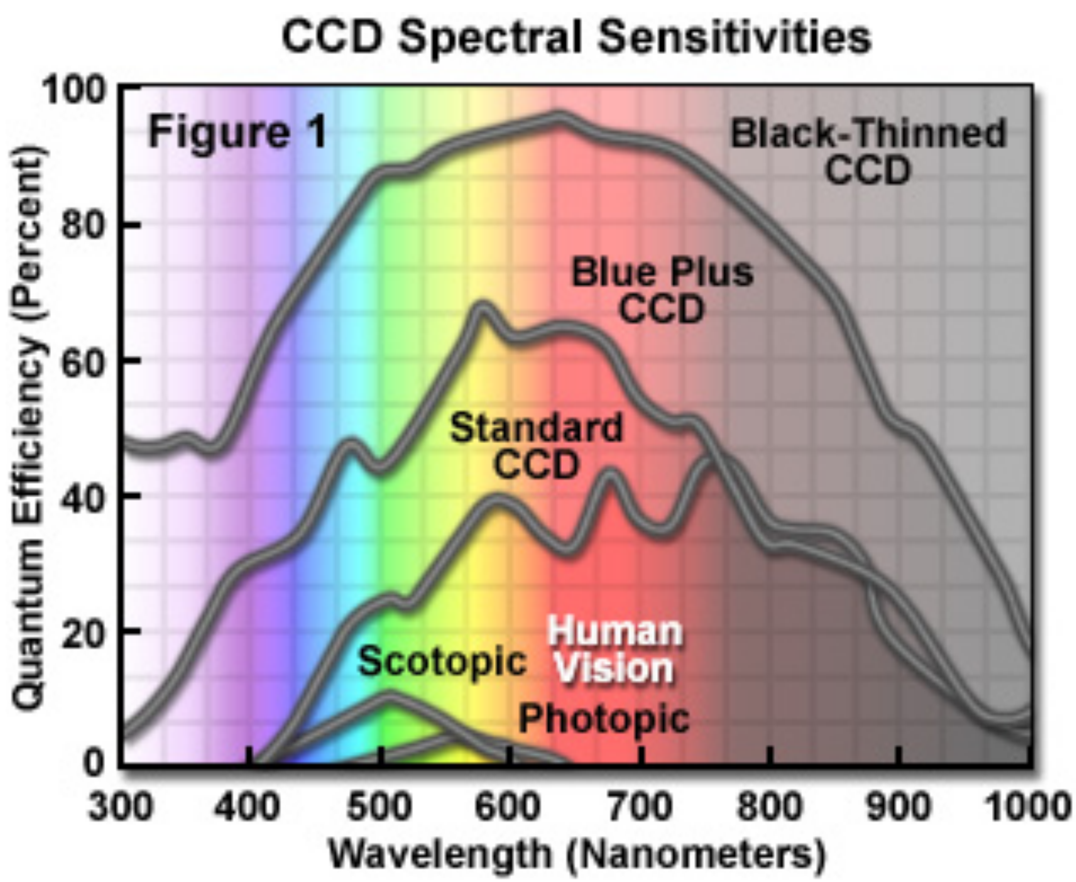
Advantages of CCDs

Quantum Efficiency



Advantages of CCDs

Spectral Range



Advantages of CCDs

Film vs Electronic

- Back in the day (1880-1990) astronomers used photographic plates.
- Excellent wide-field coverage
- Good resolution
- Large dynamic range
- Low sensitivity (~1%)
- Non-linear response to light
- Terrible to work with (messy, hazardous, laborious and difficult to analyze)

- Today we use semiconductor devices
- Incredibly high sensitivity (90%)
- Linear response
- Data in digital form
- Operate at liquid nitrogen temps
- Small size of devices, makes wide field instruments expensive

adapted from http://faculty.uml.edu/slaycock/95.383/documents/Lecture3_000.pdf

CCD Limitations

- There is a *maximum well capacity*, after which the electrons leak into neighboring pixels, and the net charge inhibits further electron capture.
- This process is called *saturation*, linearity breaks down at ~90% of saturation. sGenerally operate at much lower levels.
- *Dynamic range* is limited primarily by well depth, but is obviously affected by noise (and hence gain) also.
- *Full well depth* is 100,000-200,000 electrons
- Consequently, very deep observations require multiple exposures.
- *Dark current* (electrons liberated by thermal fluctuations) can limit exposure time, and increase noise. Simple solution - Liquid Nitrogen
- *Read Noise*: In the process of shuffling the charge clusters across the array, and sensing them at the amp, some noise is added. Can range from a few to tens of electrons per pixel.
- Read noise means that co-adding lots of exposures costs some noise compared with one long exposure.