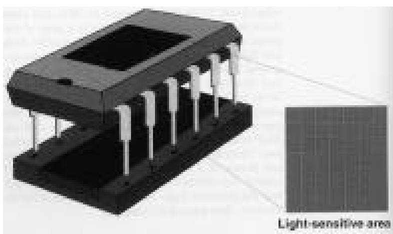
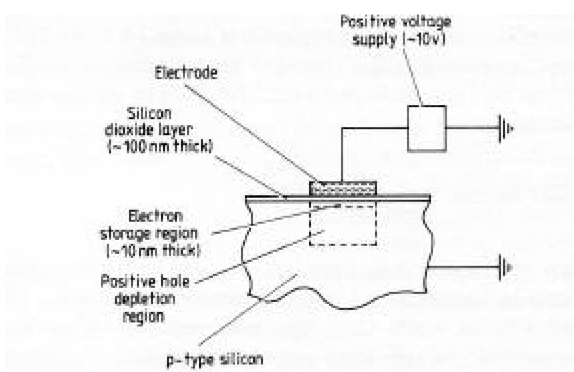
Charge-Coupled Device (CCD) Detectors

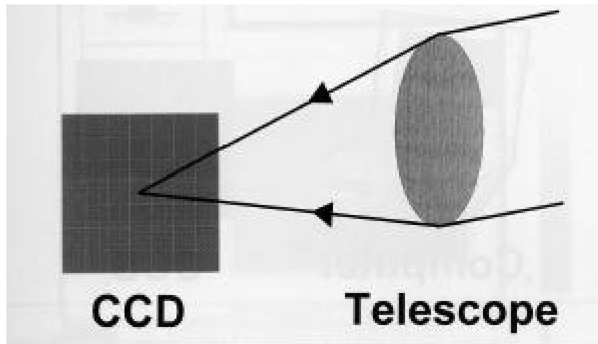
- As revolutionary in astronomy as the invention of the telescope and photography
- semiconductor detectors → a collection of miniature photodiodes, each called a picture element, or **pixel**



Light-sensitive **silicon chip**
+ **electronics** (recording and digitization)
+ **cryogenics** (cooling system: thermoelectric, liquid N_2/He, refrigerator, etc)



hν → semiconductor → electron-hole pair
Electrons trapped in potential wells (electrodes), and accumulated until read out by charge coupling the detecting electrodes to a single read-out electrode



Each pixel receives light from the object at which the telescope is pointing.

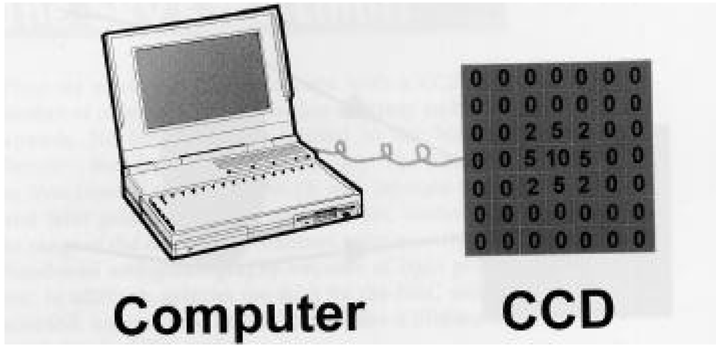
Plate Scale and Field of View

- Recall that the focal ratio of a telescope
  f/ = [focal length]/ [diameter] (of primary)
- Plate scale

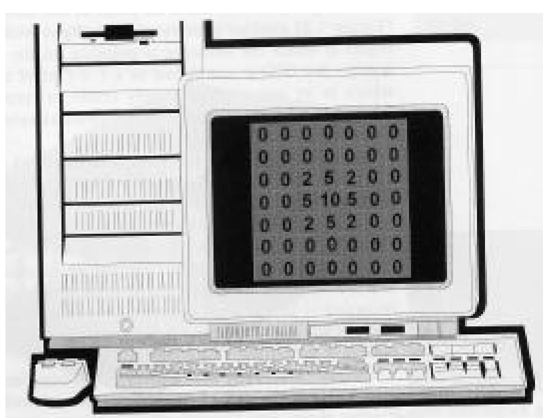
  $$P = 206{,}265\ m\ /\ f \quad \textbf{[arcsec/pixel]}$$

  where m : pixel size [in microns]
  f : focal length of the primary [in mm]

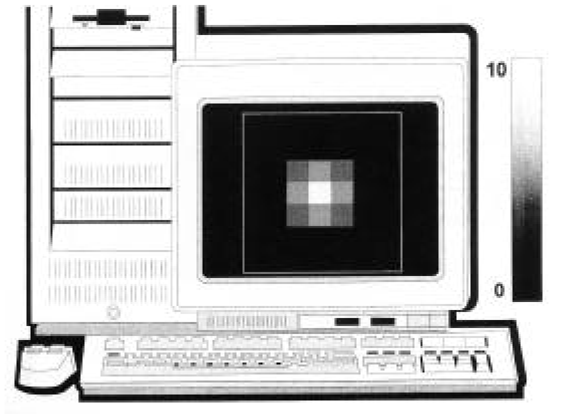
  e.g., Lulin 1 m, f = 8000 mm
  AP-8 CCD camera m = 24 μm,
  ∴ P = 0.62”/pixel
  FOV = P x 1024 ~ 10.6’



After exposure, transfer all pixel values (49 in this example) to a computer for storage. Count=10 where the star is, and drops to 0 where there is no star (sky) E.g., for a 2048 x 2048 CCD, there are 4 million pixels

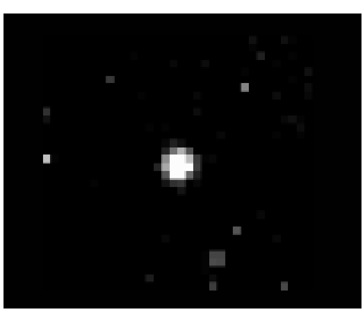


Difficult to make sense out of pure numbers ….

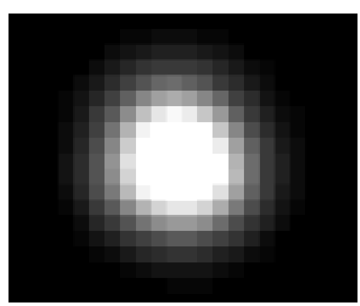


Representing numbers by proportional shades of gray is much easier to visualize.

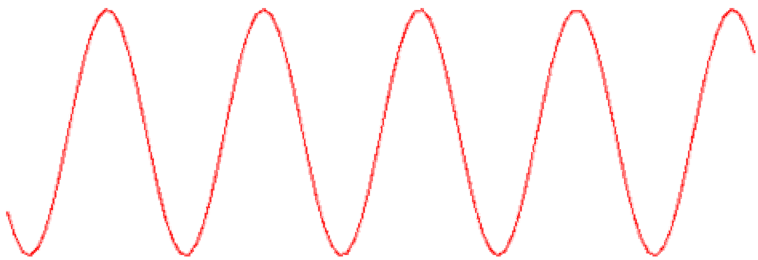
Undersampled



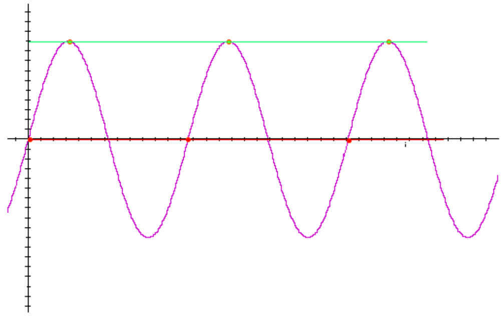
Oversampled



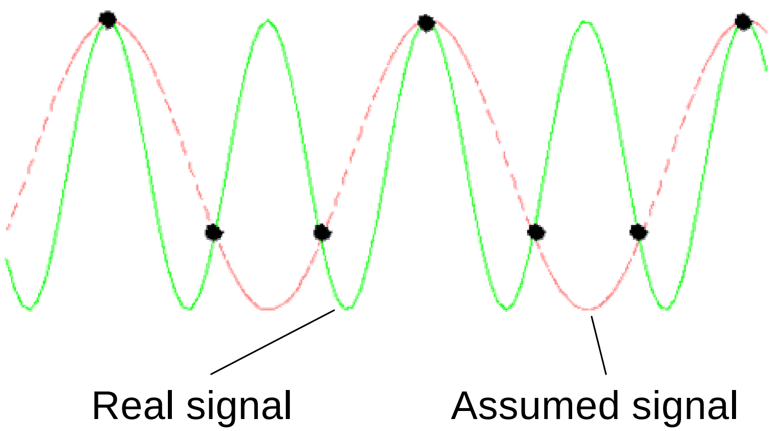
Suppose we are sampling a sine wave, how often do we need to sample it to figure out its frequency?



If we sample at 1 time per cycle, we may be led to think it is a constant



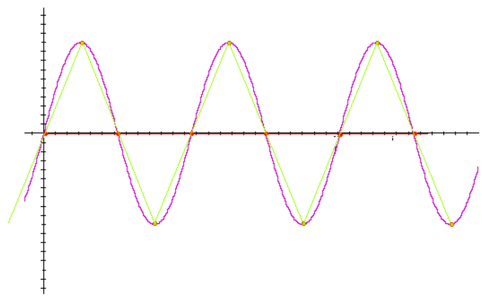
If we sample at 1.5 times per cycle, we might think it's a lower frequency sine wave



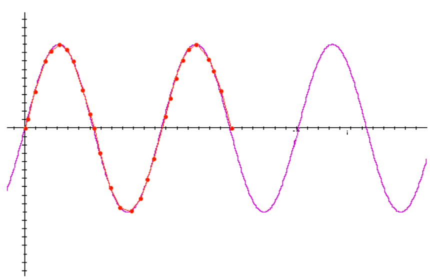
Nyquist Sampling Theorem

- A theorem, developed by H. Nyquist, which states that an analog signal waveform may be uniquely reconstructed, without error, from samples taken at equal time intervals. The sampling rate must be equal to, or greater than, **twice the highest frequency** component in the analog signal.

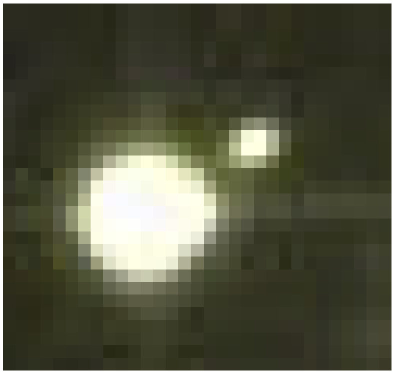
If we sample at twice per sample (i.e., at Nyquist rate), we can pretty much get the original signal.

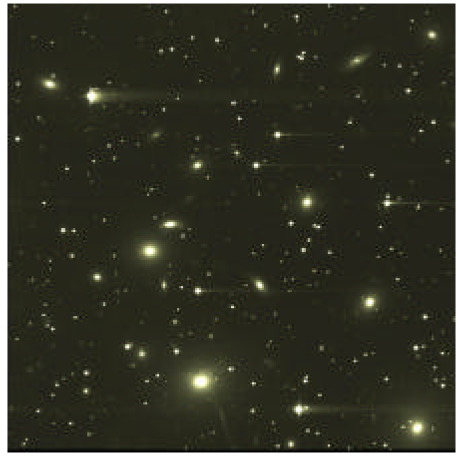


The more sampling, the better…Over sampling

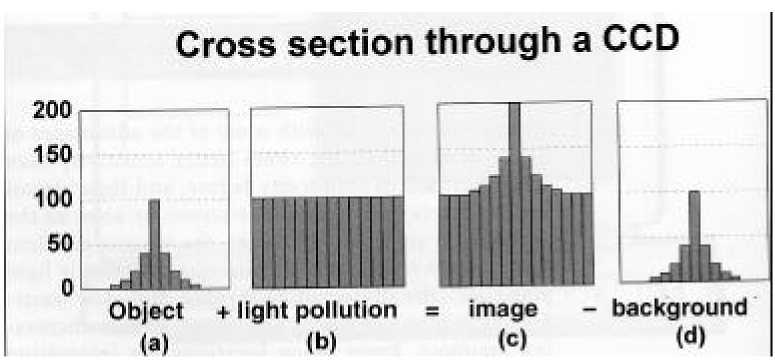


所以，想要不失真，取樣速率必須起碼是最高頻率的兩倍！





Pixelization not obvious if there are enough pixels (fine resolution)



The image we record = <u>object</u> + light pollution

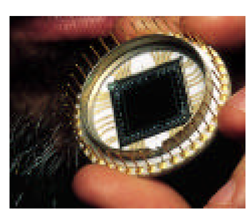
This is what we want
= [image] – [background]

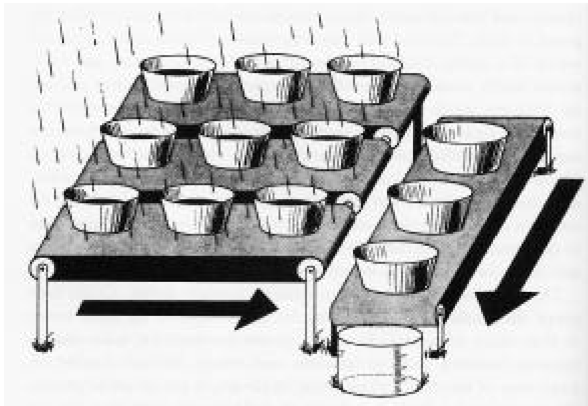
- The intensity of the object can be retrieved because our image is of **digital** nature
- Objects fainter than the sky can be imaged
- Dynamical range is a concern

Number of bits	**Resolution (shades of gray)**
8	256
10	1,024
12	4,096
14	16,384
16	65,536

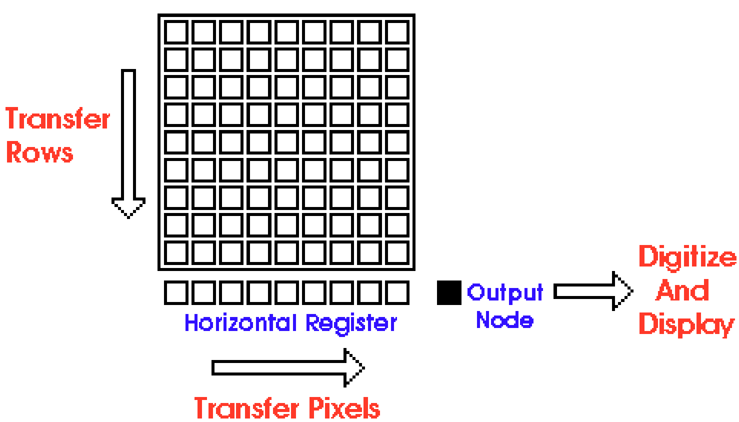
CCD Operation

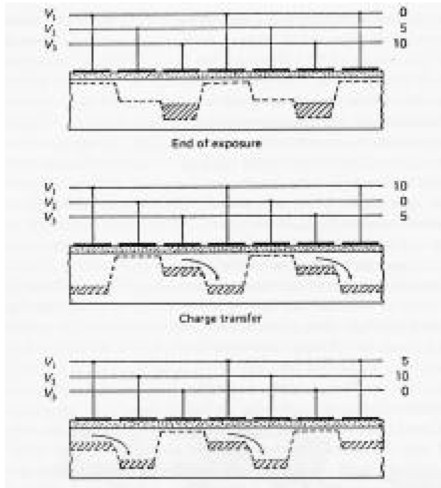
- **Generate charge**
  photoelectric effect
  Photons → photoelectrons
- **Collect charge**
- **Transfer charge**
  applying differential voltage
- **Detect charge**
  charge → output voltage →
  (A/D converter)
  digitally recorded





The physically larger the pixel (area and thickness), the more charge it can collect and store. E.g., A Kodak 9-micron pixel has a full-well capacity of 85,000 electrons; cf. a SITe 24-micron pixel has > 350,000 electrons.





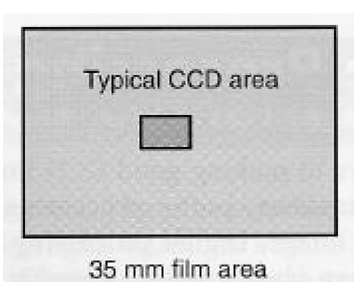
Schematic voltage operation of a typical 3-phase CCD. Each clock cycle causes the stored charge within a pixel to be transferred to its neighbor pixel.

Advantages of CCD Detectors

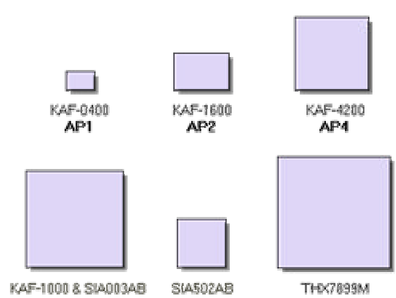
- **High QE** (> 80%)
- **Linearity** between incident light and measured output; i.e., no reciprocity failure
- **High dynamical range** (>10^4)
  cf. ~100 for photographic plates
- **Digital form** --- easy storage and manipulation of data
- **Geometric stability** ∵ pixels structurally fixed; cf. possible emulsion shifts during development

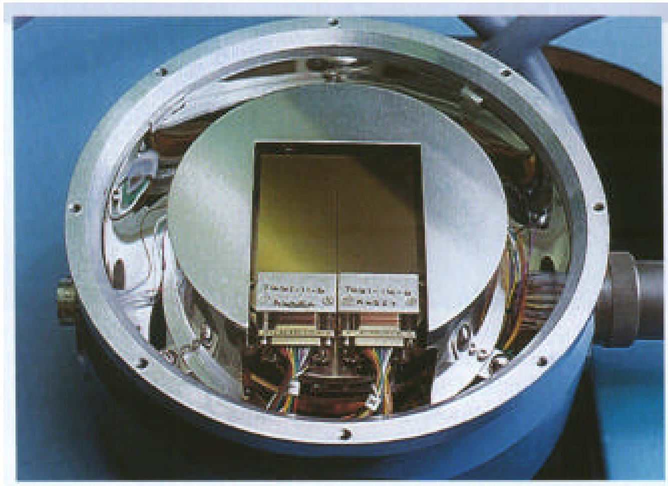
Disadvantages of CCD Detectors

- **Small size** compared to photographic plates
  → poor resolution; small field of view
- **poor blue response**
  → use some coating to rectify
- Vulnerable to **cosmic rays**
  particularly bad in long exposures
  → medium-filtering the image

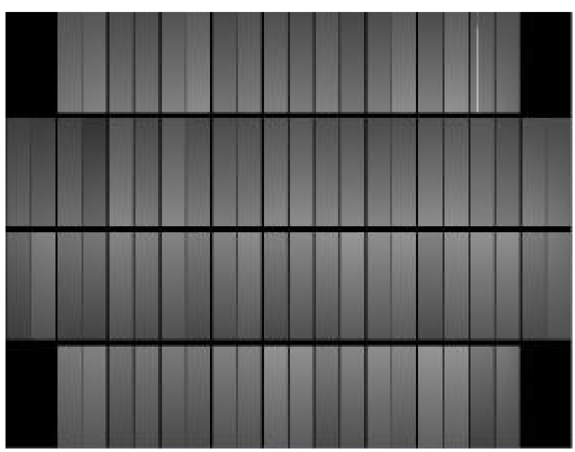


Relative Chip Sizes

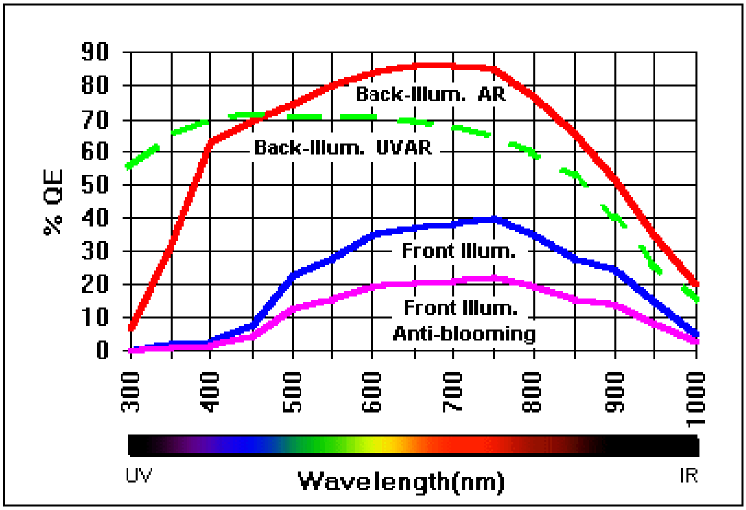




Prime Focus camera for the William Herschel Telescope, with 2 EEV-42-80 thinned and AR coated CCDs to give a 4k x 4k mosaic. Pixel size=13.5 micron → FOV 16.1’.



Canada-France-Hawaii Telescope (CFHT)
MegaPrime Camera: mosaic of 40 CCDs,
2k x 4.5 k each → 1 degree square, with 0.18”/pixel



90
80
70
60
50
40
30
20
10
0
% QE
Back-Illum. AR
Back-Illum. UVAR
Front Illum.
Front Illum.
Anti-blooming
300
400
500
600
700
800
900
1000
UV
Wavelength(nm)
IR