Phys 2310 Wed. Sept. 20, 2017
Today's Topics

- Detection of Light
  - Human Eye & Photography
  - Solid State Digital Detectors
    - Photoconductors for visible & infrared
  - Photoelectric (UV and x-rays)
  - Radio Waves
  - Signal Detection (Photon counting)
- Reading for Next Time

Homework this Week

French Chapter 3: 3-2, 3-13, 3-14, 4-3, 4-4, 4-5

SZ Chapter 32: #8, 9, 10, 11, 20, 29, 46

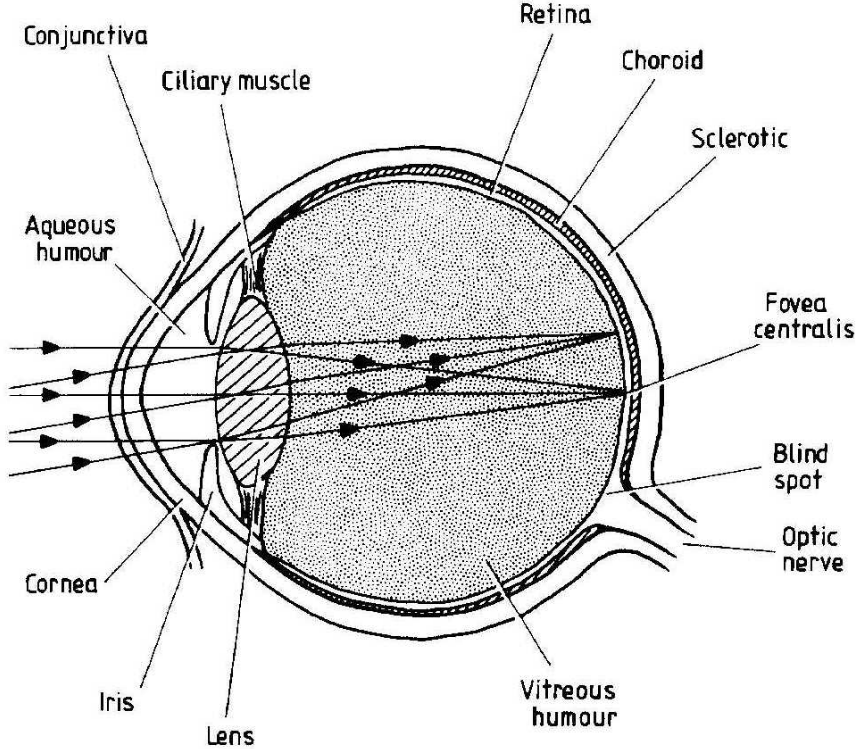
Due Mon. Sept. 26

Example Problems

- **Inverse Square Law:**
  - **A high-efficiency (50%) LED uses 1 watt of power to produce light from 500 – 550 nm. What is the surface brightness on a screen 2 meters away from the LED?**
- **Photon Nature of Light:**
  - **In the above example How many photons land on a 1-cm^2 detector in place of the screen? (Hint: recall that the energy of each photon $E_\chi = h\nu$)**

Supplementary Material: Detection of Light

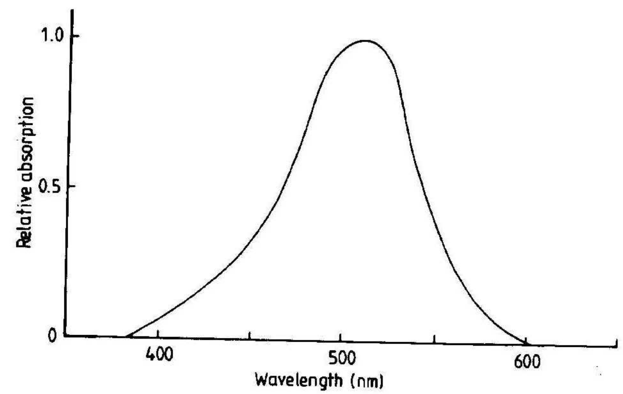
- **The Human Eye**
  - First detector of visible light
  - "Simple" structure easily understood
    - Image formation by lens
  - Inverted image originally highly controversial
  - Nature of retina unknown until microscope
    - Photosensitive cells

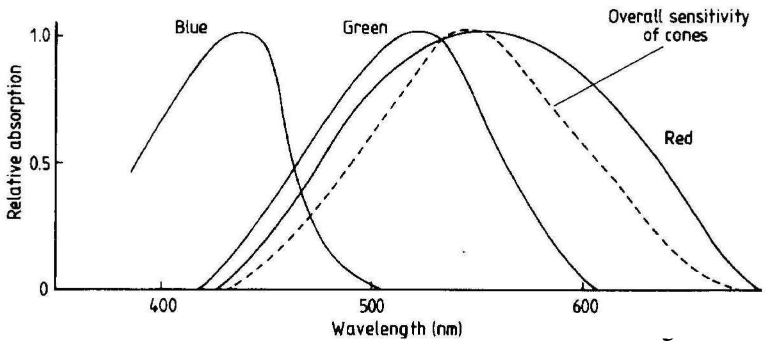


Supplementary Material: Detection of Light

- **The Human Eye**
  - **Nerve response from photochemical electrons emitted from molecules within the "rods" and "cones"**
  - **Wavelength response of rods constitutes color perception**
  - **Visible spectrum defined by response of human eye:**

$$400\text{nm} < \lambda < 700\text{nm}$$



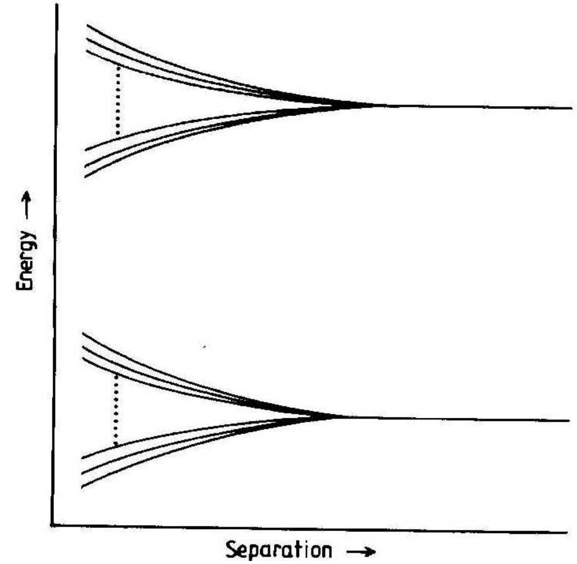


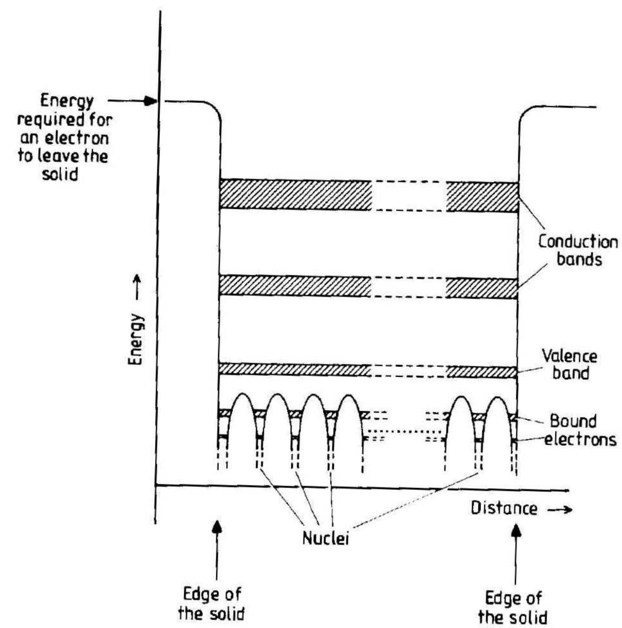
Supplementary Material: Detection of Light

- Photography
  - Silver chloride crystals suspended in gelatin
    - Photochemical reaction has poor efficiency but results in a permanent image.
    - Use of multiple layers of organic dye layers results in color film.
    - Primary means for detecting visible light for almost 100 years
    - Analog signal needs to be digitized for computer analysis and storage

Supplementary Material: Detection of Light

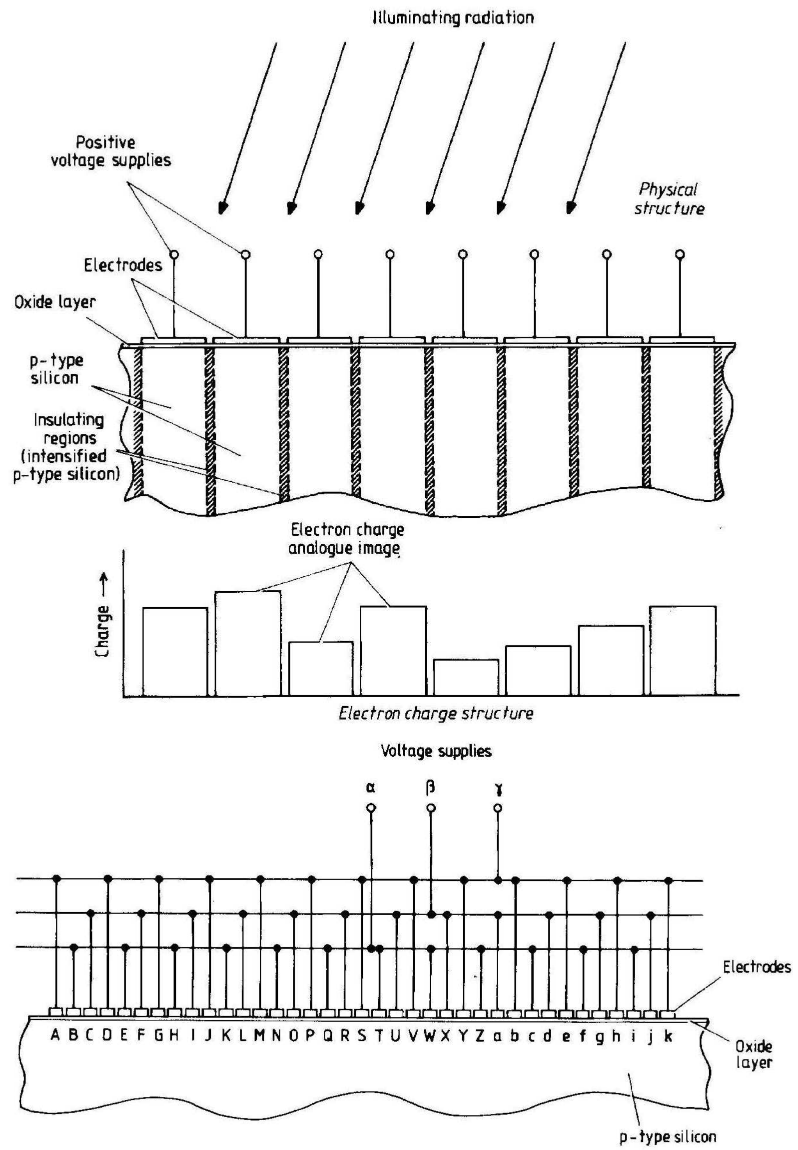
- **Modern Detectors are Solid State Devices (photoconductors)**
  - **Electrons in isolated atoms have discrete energy levels**
  - **Proximity of atoms in solids distort energy levels into bands**
  - **Semi-conductors behave like conductors if electrons have enough energy (via absorption of light**
  - **Band-gap (energy difference between valence and conduction band) determines wavelength response (tunable with selection of materials and "doping")**





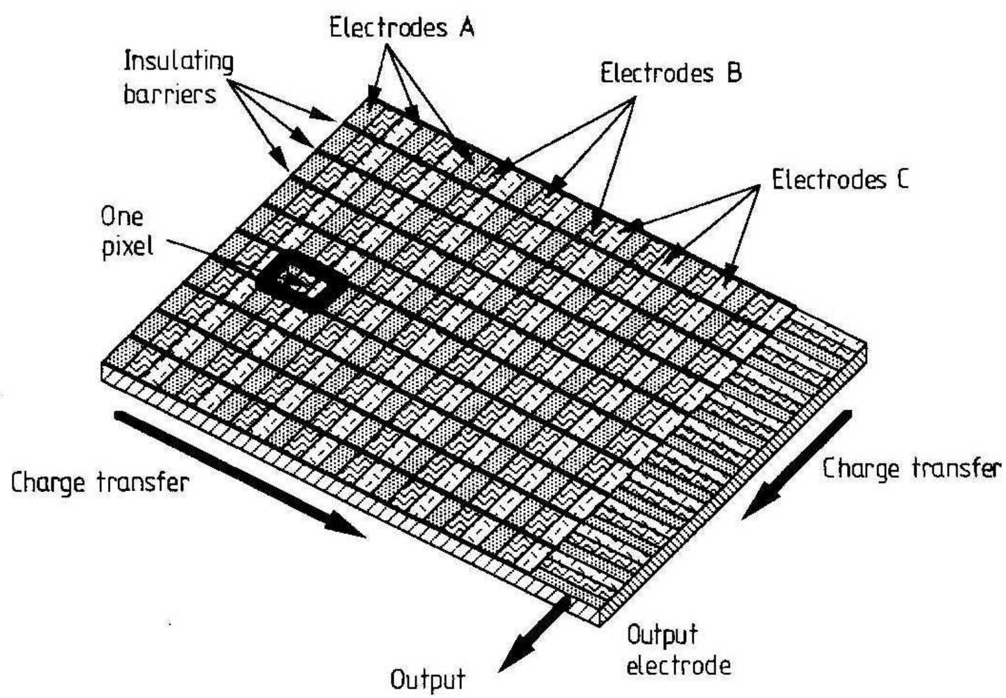
Supplementary Material: Detection of Light

- **Digital Detectors for Visible Light (CCDs)**
  - **Charge-Coupled-Devices originally developed for computer memory storage**
  - **High efficiency and digital output make them the detector of choice**
  - **Response from 0.30 μm < λ < 1.00 μm**
  - **High frequency electrical pulses (clocks) used to shift charge out to high sensitivity read-out circuitry**



Supplementary Material: Detection of Light

- **CCD Performance**
  - Formats currently up to 16 Mpixels (4K x 4K)
  - Readout noises of only 3-5 electrons
  - Low dark (thermal) noise requires cooling to low temperature (e.g., LN2 @ 77 K)



CMOS vs. CCD Detectors

- **The Choice of CMOS vs. CCD Detector Depends on Application**
  - **CCDs have generally higher performance but require more off-chip electronics**
  - **CMOS sensors have higher noise but can be read out slightly faster and can be "windowed" more easily.**
  - **See the following:**

    http://www.teledynedalsa.com/corp/markets/ccd_vs_cmos.aspx

    http://www.teledynedalsa.com/public/corp/Photonics_Spectra_CCDvsCMOS_Litwiller.pdf

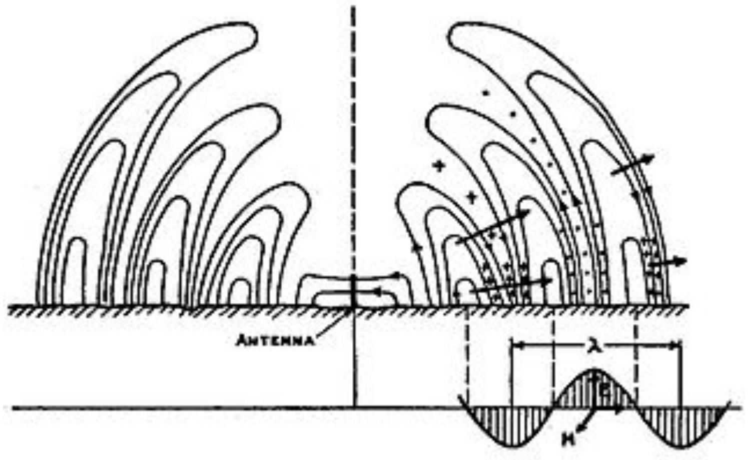
    http://www.teledynedalsa.com/public/corp/CCD_vs_CMOS_Litwiller_2005.pdf

Supplementary Material: Detection of Light

- **Detectors for Infrared Wavelengths**
  - Similar to CCDs at $\lambda < 25\ \mu m$
  - Largest formats are 2K x 2K
    - High Cost (~ $500K)
  - Use at $\lambda > 3\ \mu m$ requires liquid He cooling (4 ^oK)
  - Longer wavelength detectors ($\lambda > 25\ \mu m$) require use of bolometers
    - Electrical resistance depends on temperature below 4 ^oK
      - Measurement of minute temperature (resistance) changes due to photon absorption.

Supplementary Material: Detection of Light

- **Detectors for Microwave and Radio Wavelengths**
  - **Electric field in radio wave excites oscillatory electrons in antenna**
    - **Amplification produces detectable signal**
  - **Modern electronics technology sufficiently <u>fast</u> to detect and amplify signals.**
  - **Both phase and amplitude of photons can be detected**
    - **What about at optical λs?**



Let's assume we need to sample a wave at (say) 10 points to determine amplitude and phase.

What is the minimum wavelength (λ) that can be sampled?

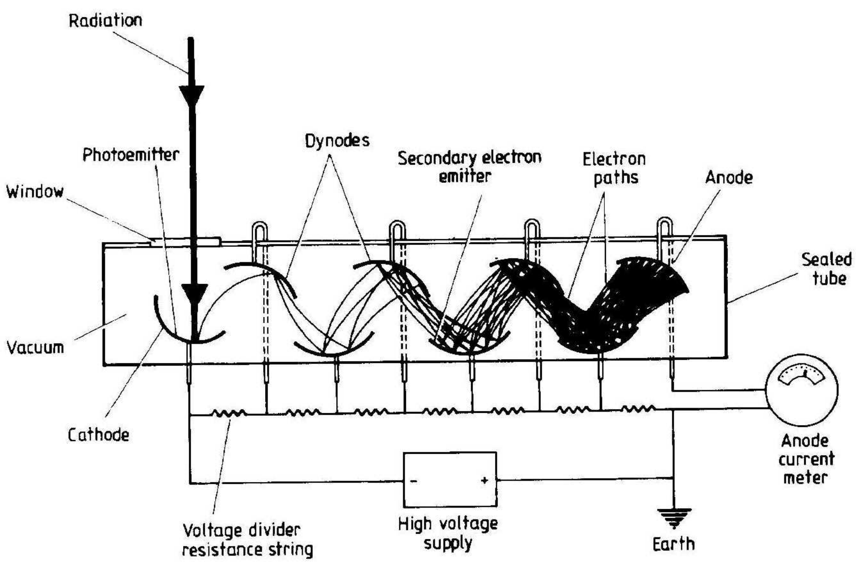
$c = 3.0x10^{8}\, m/\sec$ so if the fastest electronics can sample at 1000 Ghz frequencies then the minimum λ will correspond to a frequency (ν) of $(10^{12}/10)\sec^{-1}$. Recall that $\nu = c/\lambda$ so:

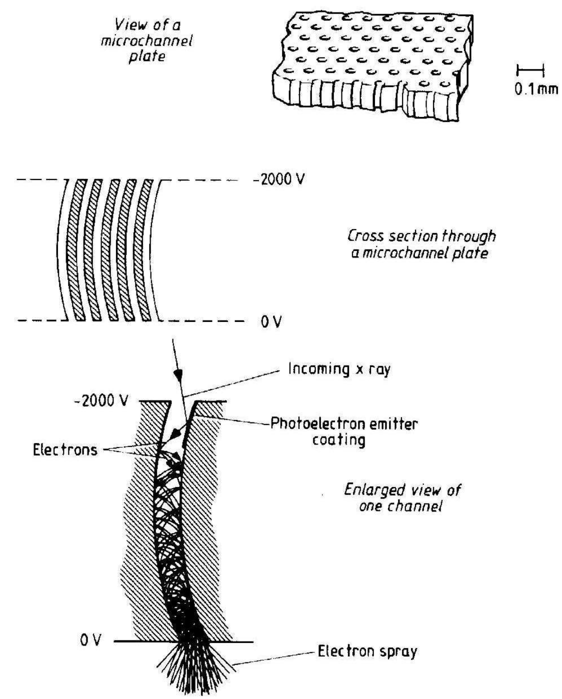
$\lambda_{\min} \approx (3.0x10^{8}\, m/\sec)/(10^{11}\sec^{-1}) = 3x10^{-3}\, m = 3mm.$ These are microwaves and so we cannot record both the amplitude and phase of optical or even infrared light.

Supplementary Material: Detection of Light

- **Detectors for Ultraviolet and X-ray Wavelengths**
  - **High energy of photons results in strong photoelectric effect**
    - **Electrons emitted from solids when photons absorbed**

      (secondary electrons detected)





Supplementary Material: Signal Detection

- **Photon rate from a source (N) is never constant**
  - **Signal is an average rate over a given time interval**
  - **Can't detect a fraction of a photon**
    - **Some time intervals contain little more or little less**
  - **Poisson (counting) statistics:**

    $\sigma_N = \mathrm{sqrt}(N)$
  - **Signal is seldom (never) without some sort of background**
  - **Almost all detectors has some intrinsic noise**
  - **Uncertainty in any detection is the combination of all these effects**
  - ***Any measurement has an associated uncertainty***

Supplementary Material: Signal Detection

- **Uncertainty in any signal can be estimated**
  - **Without detailed information we assume any source of errors is distributed as a Gaussian distribution:**

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Uncertainty(s) can be estimated via a Gaussian fit to a histogram made from lots of individual measurements. Compute Mean, Standard Deviation. Alternatively just estimate. Errors from each source don't add in same sense

They are random and (usually) uncorrelated. So, add in quadrature:

$$\sigma_T = \sqrt{\left(\sigma_1{}^2 + \sigma_2^2 + \sigma_3^2 + \ldots\right)}$$

Photon (Counting) Statistics

- **The discrete nature of photons means that any signal is subject to fluctuations from counting statistics.**
  - **When sampling over a finite time interval we will see fluctuations in the number (N) of photons detected, i.e., in the brightness of a light source.**
  - **The corresponding uncertainty in the signal can be modeled via Poisson statistics.**
    - **See web or statistics books for derivation.**
    - **Bottom Line: The uncertainty in the signal (N) is = SQRT(N) and so the precision of the measurement (Noise/Signal) is:**

N/S = 1/SQRT(N) and S/N = SQRT(N)

If I detect 100 photons in a given measurement this has an intrinsic uncertainty from counting statistics alone of 10%. To improve this to 1% I would need 100x as many photons (longer exposure, better detector, bigger telescope, brighter source, etc.)

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Summary and Key Concepts

- **Detection of Light Though Photochemistry**
  - Human eye and old-school photography is analog (chemical)
- **Most Modern Detectors are Digital**
  - Electrons excited into a conduction band (within a semi-conductor) or released via the photoelectric effect
  - One exception is radio (analog signal)
  - Digital detection of photons (photo-electrons) subject to counting (Poisson) statistics