Welcome to Lecture 6

A few words about the last quiz

How many electrons and from which atoms are transferred in this reaction?

$$CH_3CH_2OH + O_2 \longrightarrow CH_3COOH + \boxed{H_2O}$$

The mass in this equation is not balanced!

Those who balanced the equation easily got to the right answer: 4 e^- from C to O

Oxygen on the left:	Oxygen on the right:
-2 for O in EtOH	-4 for O in acetic acid
0 for O_2	-2 for H_2O
Total Oxygen: -2	Total Oxygen: -6

You can see right away that there is no change for Hydrogen

Hence, Carbon must have lost 4 e^- to Oxygen

Primary structure

Define primary and secondary structure of proteins:

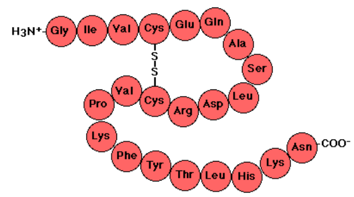
About 50% (!!!) answers were unsatisfactory

Primary protein structure is:

- a linear chain of amino acids held together by H–bond
- amino acids bind by CONH bonds and form a polypeptide
- a single long chain of polypeptides joined together
- the peptide that is connected by amino acids
- consists of many CO/NH/CR groups bonded by peptide bond
- formed between C and N terminus of two adjacent amino acids
- the formation of amino acid chains

Primary structure

is **__the sequence__** of amino acids in a peptide chain



- The simplest of protein structures
- A linear arrangement of amino acids
- The structure that is formed by peptide bond
- Describes the amino acids in the structure
- Contains AA sequences

Why is it important?

INFORMATION!

- Sequence of amino acids joined by H-bonds (and/or ionic in some answers)

Last time

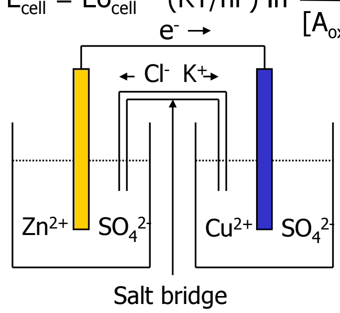
- Chemical bonds
- Redox reactions
- Electrolytic cells and electrodes
- The Nernst equation

Why is this important?

Electrodes are electro-chemical transducers i.e. interface between chemical and electrical energy

Some biosensors we discussed and others we will talk about are effectively bio-electrolytic cells e.g.

$$E_{cell} = Eo_{cell} - (RT/nF) \ln \frac{[A_{red}] \times [B_{ox}]}{[A_{ox}] \times [B_{red}]}$$

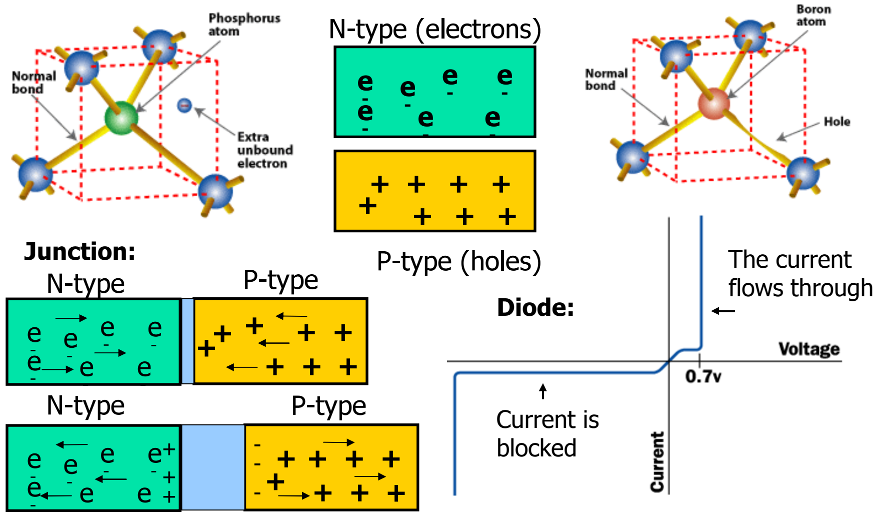


Potentiometry for enzyme reactions that generate or consume H^+

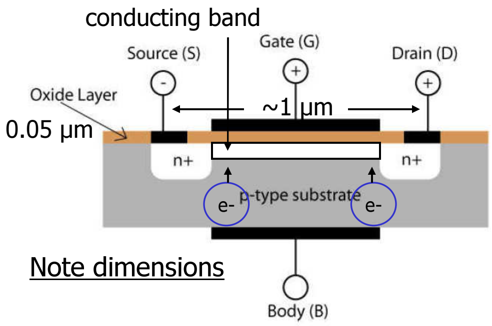
Amperometry for enzymes that generate or consume O_2 and/or H_2O_2 – cholesterol and __GOX sensors__

Also last time

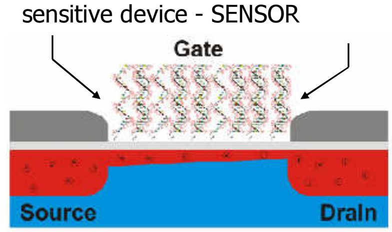
We briefly talked about semi-conductors



MOSFET



Creating a "reaction vessel" on top of the insulation layer converts MOSFET into an ion sensitive device - SENSOR

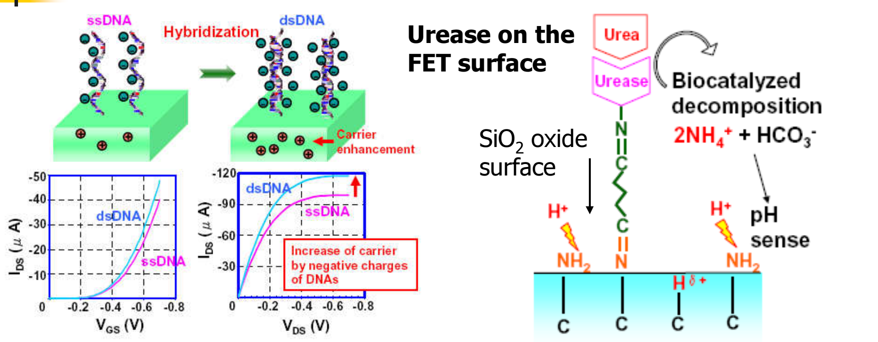


Application of a positive potential to the gate creates a strong electric field across the thin p-layer. It attracts e- and create a conducting channel, so that current can flow from source to drain electrodes

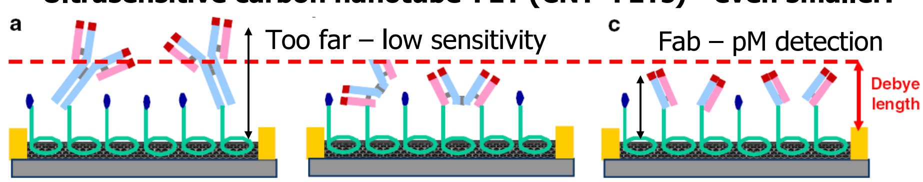
Because the device is so tiny, redistribution of charge on the surface of the oxide layer results in a change in the conducting band, and hence the electric current

Attaching an appropriate bioreceptor (Enz, DNA, Abs) – makes a BIOSENSOR

For example



Ultrasensitive carbon nanotube-FET (CNT–FETs) - even smaller!



Plan for today

Spectroscopy and optical transducers

- Electromagnetic radiation and properties of light
- Spectrometers and it's components
- Light detectors and semiconductors

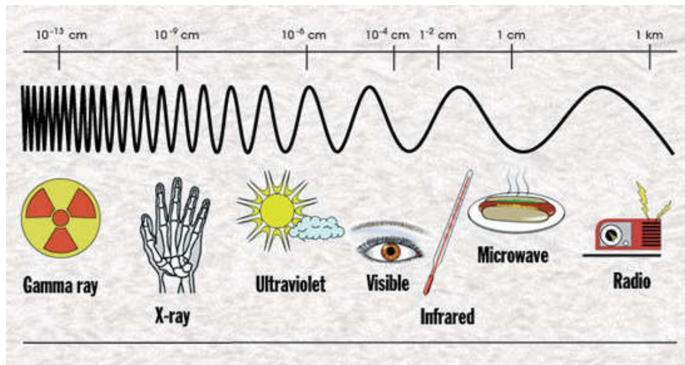
And as last time we will start with the basics

The electromagnetic spectrum

Higher frequency (ν), Shorter wavelength (λ)

$$\nu = \frac{c}{\lambda}^{*}$$

Lower frequency (ν), Longer wavelength (λ)



Higher energy (E) Lower energy (E)

*where c is the speed of light, and λ is its wavelength

The visible spectrum

γ-ray	Xray	Ultraviolet		Infrared	μwave	radio

0.1 nm 10 nm 200 μm 1 μm

Shorter wavelength: **400 nm**

Visible spectrum is only a TINY part

Longer wavelength: **750 nm**

Ultraviolet	Visible Light	Infrared

750 THz Higher frequency (ν)

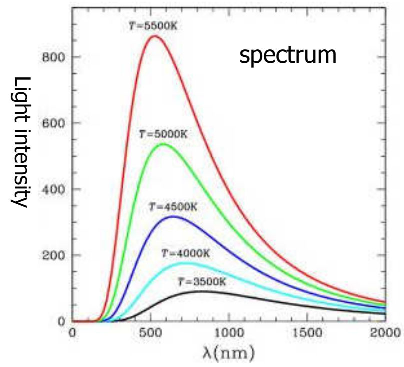
400 THz Lower frequency (ν)

4.97×10^{-19} J **Energy** 2.65×10^{-19} J

$E = h\nu$, where h is Planck's constant and ν is frequency

Light emission by matter

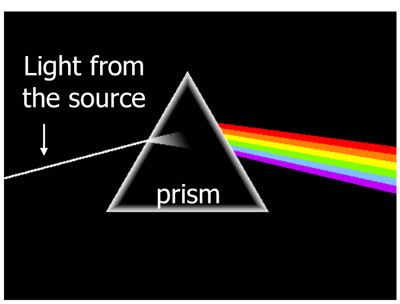
- When a material is heated, it loses the excess energy by several mechanisms, including emission of electromagnetic radiation
- If it is hot enough, we can see the "glow" as visible light is emitted



- This is a typical representation of the results of spectroscopic experiment
- The measured light intensity is plotted along the y-axis and the wavelength at which it was observed - on the x-axis

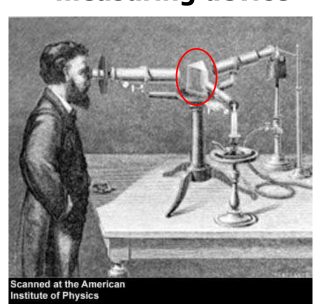
Generating a spectrum

To generate a spectrum the light from a source should be broken up to its spectral component ("dispersed")



- For light dispersion triangular prisms can be used
- The dispersion occurs because the angle of refraction depends on wavelength

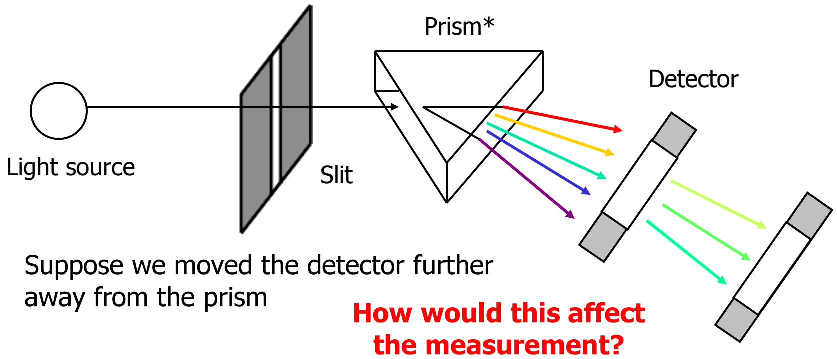
With a prism we can make a measuring device



The first instrument used to observe the component wavelengths of a glowing material was the spectroscope

The Spectrograph

An instrument that separates incoming light into a spectrum



Suppose we moved the detector further away from the prism

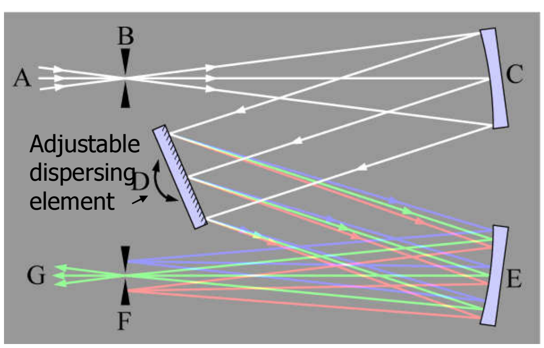
How would this affect the measurement?

Resolution will increase – ever wondered why some old, high quality instruments were so bulky ☺?

*A polychromator is an optical device for dispersing light in different directions to isolate parts of the spectrum: output multiple beams over a range of wavelength

The spectrophotometer

A key part of a spectrophotometer is a monochromator - an optical device made to transmit only a narrow band of light, while cutting off the rest of the wavelength spectrum



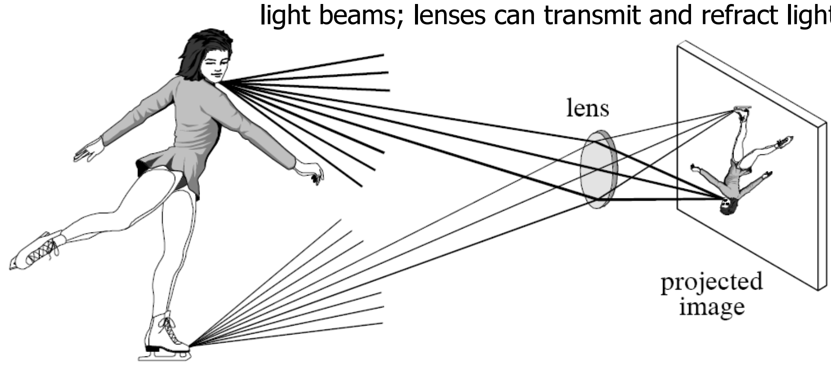
A – light source; B – entrance slit; C – collimator (curved mirror); D – prism or grating; E – another mirror; F – exit slit; G – light with selected λ

- Monochromators can also use a prism or grating (diffraction) to spatially separate the colors of light
- A collimator is a device that focuses light at infinity i.e. nearly parallel beams; typically it is a curved mirror/lens

Longer path – better resolution

Lenses

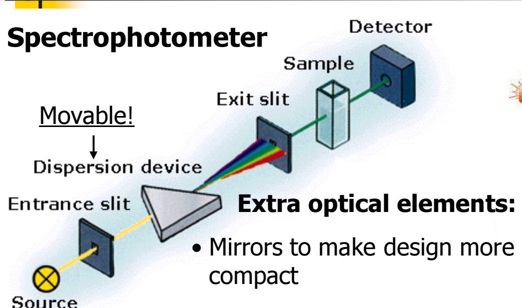
A lens is an optical device which converges (or diverges) incoming light beams; lenses can transmit and refract light



A lens gathers light expanding from a point source, and force it to return to a point at another location. This allows lenses to project images onto a surface

Instrumentation comparison

Spectrophotometer



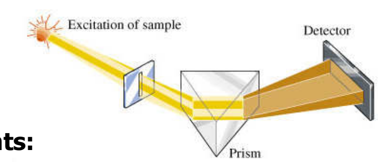
Extra optical elements:

- Mirrors to make design more compact
- Lenses to increase light input or to match geometry of sample or detector

Spectrometer advantages

- Higher resolution for the same price
- Easier sample quantification
- Simpler to miniaturize

Spectrograph

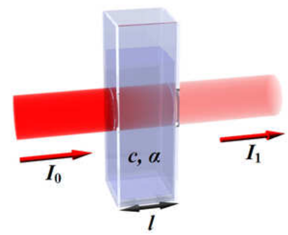


Spectrograph advantages

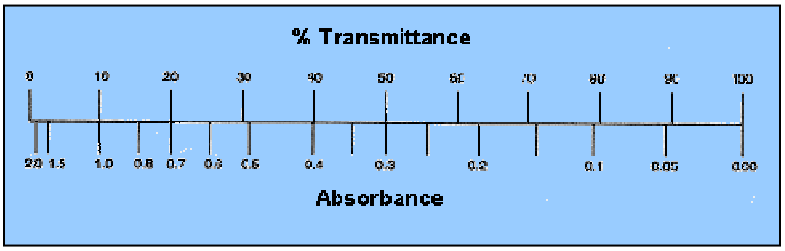
- Spectrum collected in one exposure
- Multiple scans can be done for better signal to noise
- More information collected per unit time

Doing the measurement

Transmittance, $T = I / I_0$
% Transmittance, $\%T = 100\ T$
Absorbance, $A = \log_{10} I_0 / I$

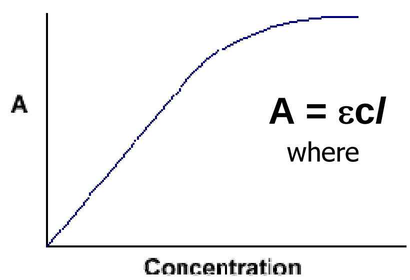


Note the log relationship between A and I: At optical density A=1 only 10% of light passes through



The Beer-Lambert law

describes a relationship between the absorption of light and the concentration of the light adsorbing substance(s) in a sample

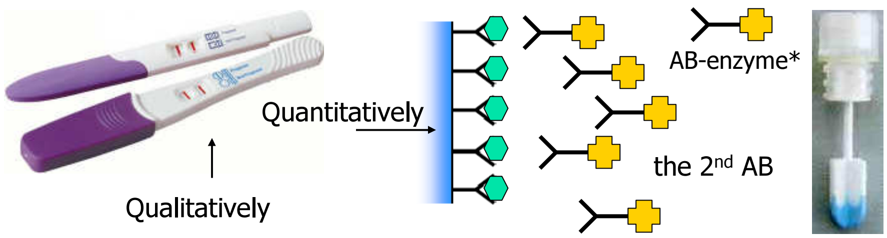


$A = \varepsilon c l$
where

A - absorbance
ε - the molar absorptivity with units of L mol^{-1} cm^{-1}
l - the path length of the sample
c - the concentration of the compound in solution, expressed in mol L^{-1}

Colorimetric reagents

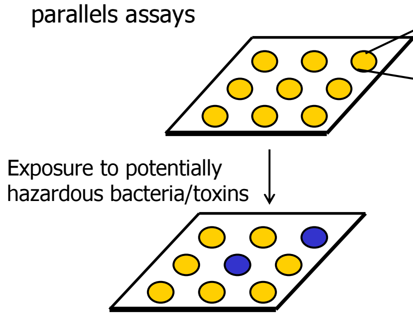
- Most organic molecule absorb light in the UV region of the spectrum. Hence, finding a wavelength clear of interfering transitions in the UV region is often difficult or impossible
- Many "colorimetric" reagents have been developed to react specifically with particular functional groups to form colored compounds or substrates to give a colored product in an enzymatic reactions so that their absorptions in the visible spectral region are clear of interference e.g.

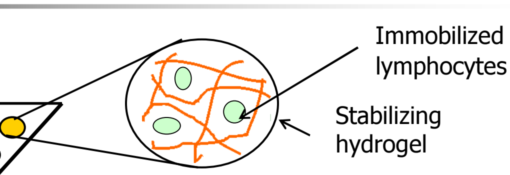


*Alkaline Phosphatase, peroxidase

Lymphocytes sense toxins

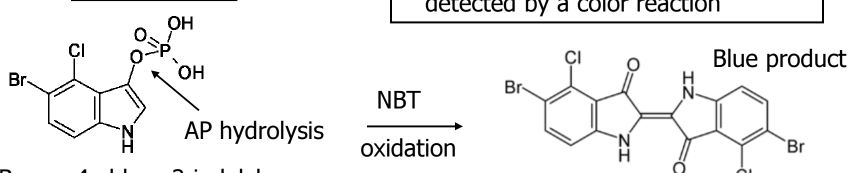
This setup allows multiple parallels assays





Operating principle:

- ➢ Detects whether a toxin or bacteria have "broken" the lymphocytes
- ➢ If damaged, lymphocytes release alkaline phosphatase, which can be detected by a color reaction

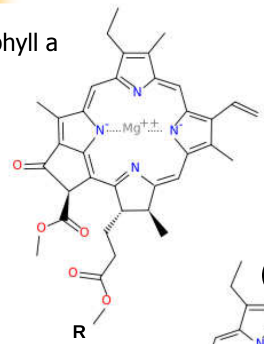


5-Bromo-4-chloro-3-indolyl phosphate (BCIP)

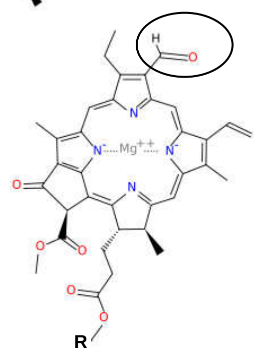
Is it better than pH detection?

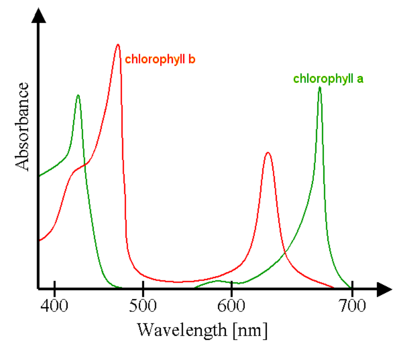
Sensitivity to substitutions

Chlorophyll a



Chlorophyll b





Absorbance spectra of free chlorophyll a (green) and b (red) in a solvent

The spectra are different due to a slight move of Mg^{2+} - different interactions with the porphyrin

The nature of light

- When a matter absorbs energy it can emit light and there is a fundamental relationship between the energy and **wavelength**
- The light can be split into constituent **wavelength** components e.g. with the help of a prism
- We can measure the properties of light using a relatively simple device and record a spectrum – dependence of light intensity on **wavelength**

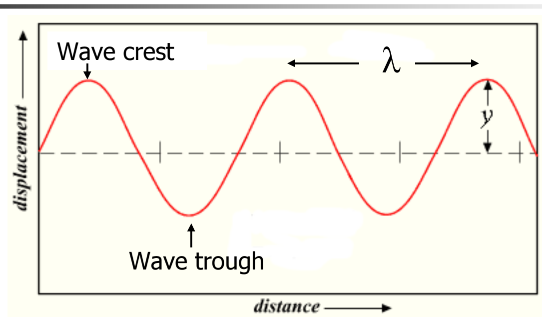
But what is a wave?

What is a wave?

- A **pulse** is a single disturbance moving through a medium from one location to another location
- A **medium** is a substance or material comprising a collection of interacting particles and it is the interactions of one particle with an adjacent one that allows the disturbance to propagate
- When such a disturbance is repeated periodically (i.e. propagates through space and time) it is referred to as a **wave**

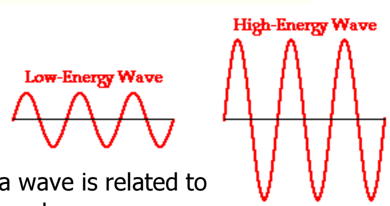
A wave is an energy transport phenomenon - individual particles in the medium are only displaced temporarily and then return to their prior positions

Basic properties



λ – wavelength

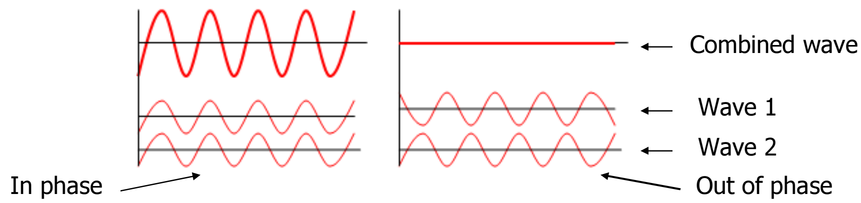
y – amplitude



The amplitude of a wave is related to the energy it transports

Superimposition principle

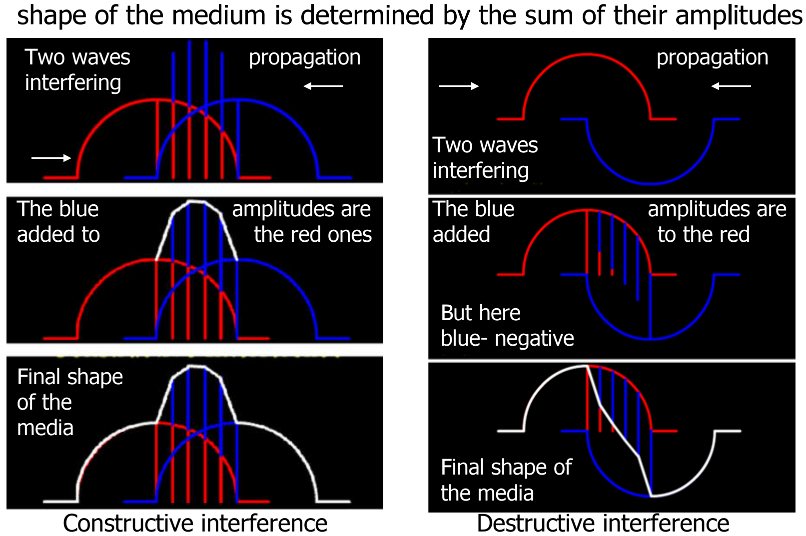
The principle of superposition states that displacement at any point is equal to the sum of the displacements of different waves at that point



- **constructive interference**: when the crest (trough) of one wave is superimposed upon the crest (trough) of another wave
- **destructive interference**: when the crest of one wave is superimposed upon the trough of another wave

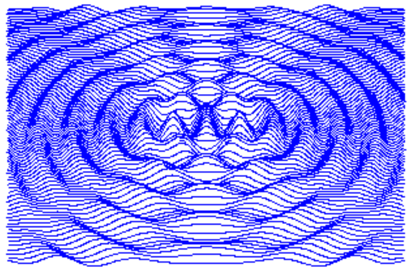
Interference

Interference occurs when one wave passes through another - the shape of the medium is determined by the sum of their amplitudes

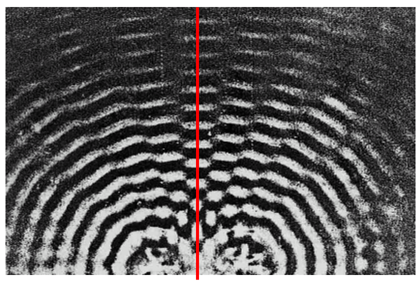


Visualizing interference

in 3D

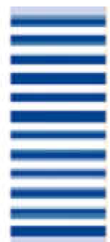


in 2D



What would it look like in 1D?

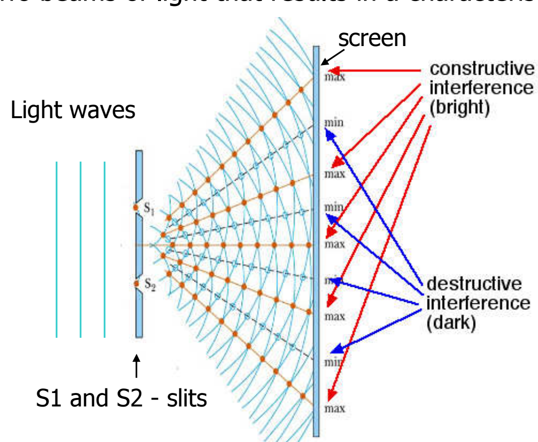
in 1D



Does light behave as mechanical waves?

Double-slit experiment

Diffraction is the constructive and destructive interference of two beams of light that results in a characteristic pattern

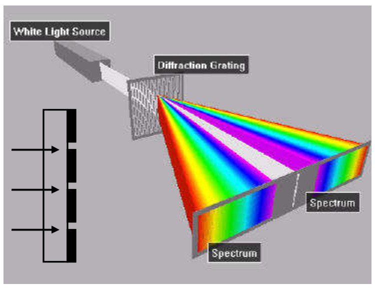


Interference pattern: The bright lines are constructive interference and the dark lines - destructive interference

Diffraction grating

A diffraction grating is an optical device which can disperse light into spectrum - just like a prism

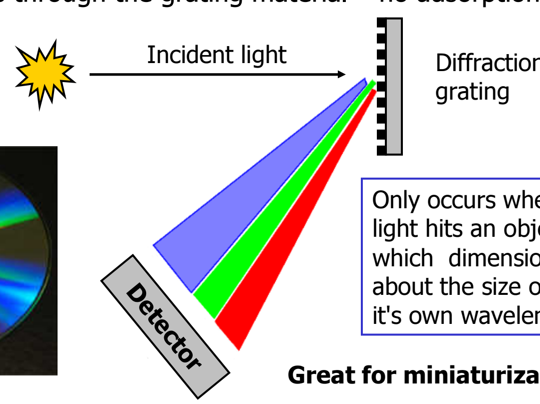
It has a regular pattern of closely-spaced parallel grooves or slits, typically several thousand per cm, that produce interference patterns in a way that separates the components of the incoming light



- A transmission grating has grooves on top of a transparent material (e.g. glass), so that when a beam of light passes through it is partly split into so-called sets or orders with spectra on either side of it
- The orders of spectra increase in dispersion and faintness with distance from the direct beam

Diffraction grating

A **reflection grating** has grooves assemble onto a reflective coating. Its advantage over a transmission grating is that it produces a spectrum extending from ultraviolet to infrared, since the light doesn't pass through the grating material – no adsorption



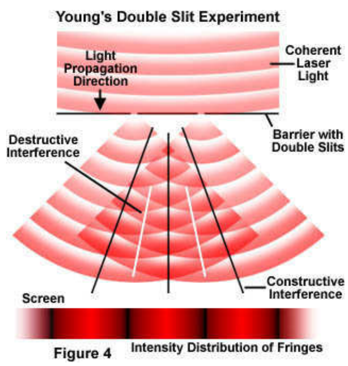
Only occurs when light hits an object which dimensions about the size of it's own wavelength

Great for miniaturization

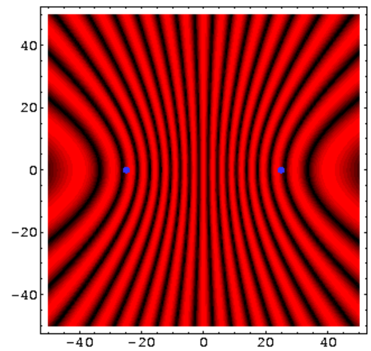
Light vs sound

Clearly the same phenomenon

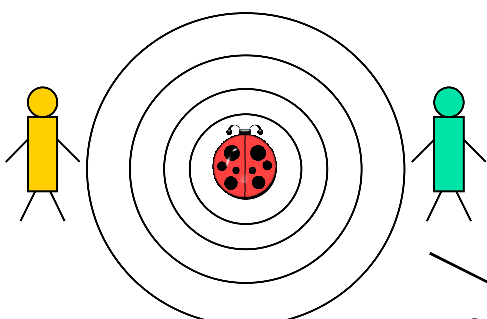
Diffraction of light



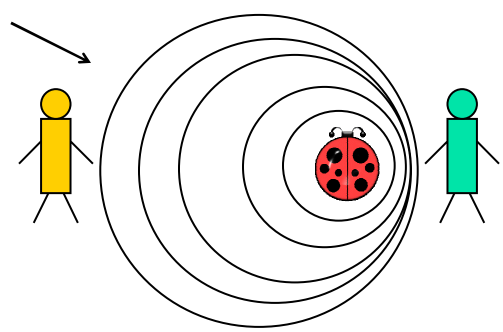
Diffraction of mechanical waves



The Doppler effect



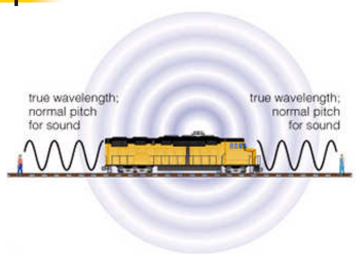
Waves coming at the two observers with the same frequency



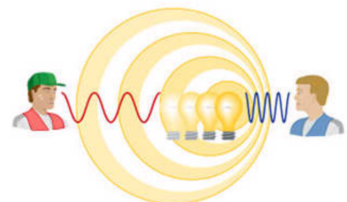
The bug moves from the center to the side

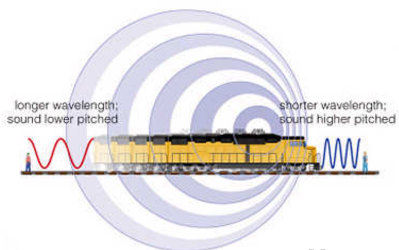
Now the two observers experience waves of different frequency

Light is just like sound…



The Doppler effect can also be observed with light





Sound and light waves seem to behave in exactly the same way…

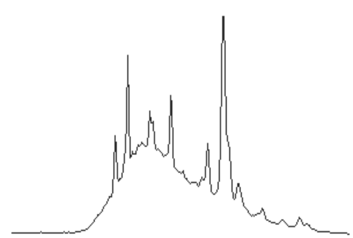
Why do you see the sun but do not hear it?

Sound doesn't travel in vacuum but light does

How can a wave propagate in vacuum?

Light is different

- This spectrum was generated on a telescope focused on a star in the constellation Cygnus
- It has the general shape of a typical spectrum, but also contains sharp "spikes" (peaks) that are clearly from some other origin
- The explanation of these features were the focus of research of many prominent physicists in the early XXth century

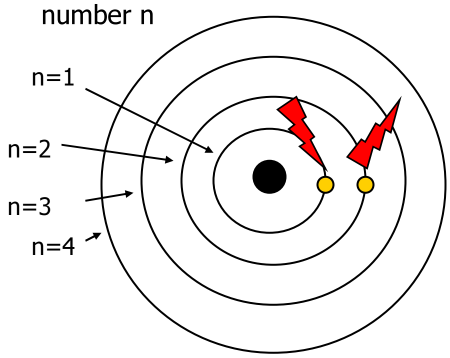


After comparison to spectra of various materials, most of the "mysterious" peaks* occurred at the same wavelength in the spectrum of excited hydrogen

*The positions of these peaks can be calculated from a simple formula E = k(1/n2 – 1/m2), where n and m are integers. The H atom appeared to have a series of "quantized" energy states…

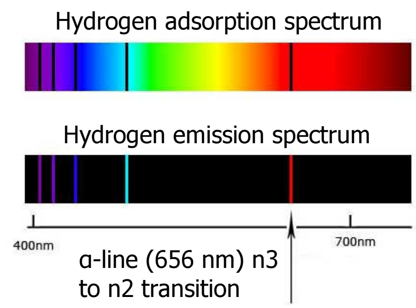
Atomic quantum theory

- H-atom has a single e that can only spin around the nucleus in specific orbits, each of which is given a number n



When an electron absorb a particular amount of light energy, it "jumps" from the lower to the higher orbital

- This can be observed in the absorption spectrum
- When it falls back, the energy is released and we can observe this in the emission spectrum



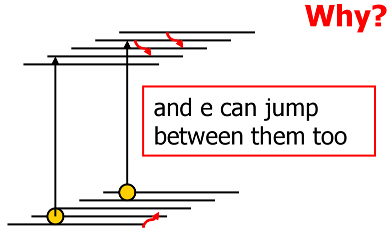
β-line (486 nm) n4 to n2 transition

Molecular quantum theory

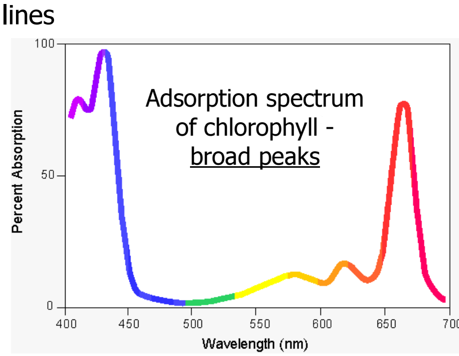
For more multi e- atoms energy schemes are more complicated – this is why Hydrogen has so few lines

Molecules are bonded arrangements of atoms but their spectra ate typically broad bands, not lines

Why?

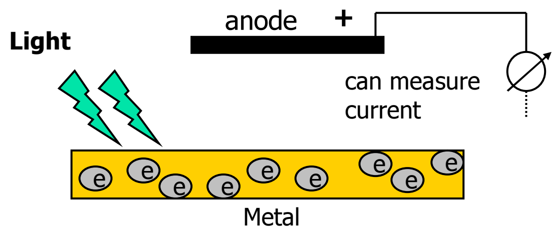


A number of energetically close orbitals mainly due to vibrations



Photoelectric effect

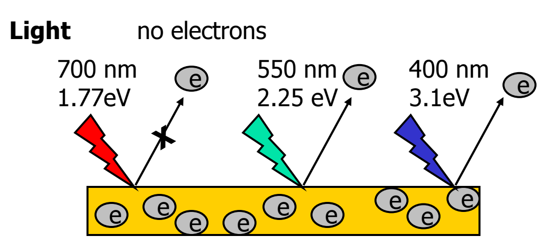
When a metallic surface is exposed to electromagnetic radiation the light is absorbed and electrons are emitted



- Photoelectric effect can be observed with a variety of metals (and other materials) and in a range of radiation frequencies
- For a given metal and frequency of incident light radiation, the rate of photoelectrons ejection was directly proportional to the light intensity

But there was something odd…

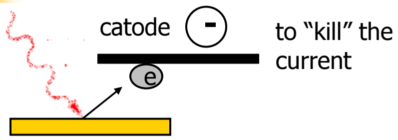
For any particular metal the photoelectric effect was only observed above a certain threshold frequency light…

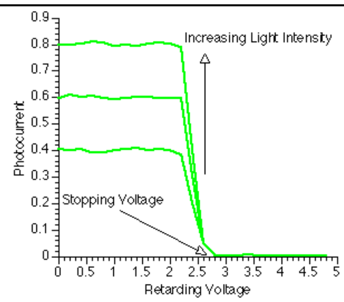


For potassium 2.0 eV needed to eject an e

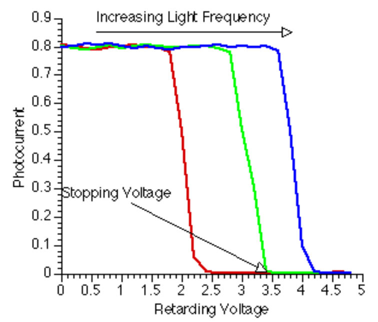
and the energy of the emitted electrons increased with the frequency of the light but not with the intensity of radiation **as would be predicted by the wave theory of light**

Experimental data





Photocurrent increases when the light intensity increases but the wavelength is held constant



When a higher energy light source is used (higher frequency, shorter wavelength), the ejected electrons have greater energy i.e. the potential needed to prevent photoelectric effect is larger

The explanation

- This paradox was resolved by Einstein (1905) who proposed that light is composed of discrete "quanta" of energy - **photons**, rather than being a continuous wave
- Einstein also postulated that the energy of the ejected electrons should increase linearly with the frequency of light:

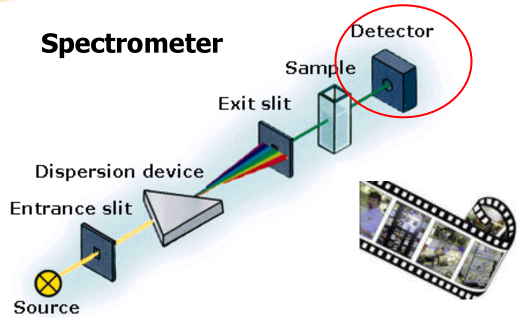
$$E = h \times \nu$$

where h is Planck's constant and ν is frequency

- The photoelectric effect helped to establish the then-emerging concept of the **dualistic nature of light** i.e. at different times and under different conditions light can display characteristics of **either waves or particles**
- And there were numerous technological implications too…

Detectors

Spectrometer



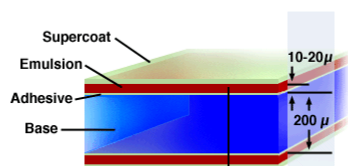
How do light detectors work?

Most spectrometers in use before 1960 relied on this form of photodetection

A photographic film
– the simplest detector

Detectors: photographic film

A photographic film transduces light into chemical energy



- It is a plastic film coated with silver salt crystals, the size of which determines the film's sensitivity to light
- Upon light exposure, silver is photo-reduced to very fine grains of Ag metal and the development process simply washes away the gel medium and unexposed silver salts
- Most spectrometers before 1960 used this form of photodetection - the dark lines on the film had to be converted to a spectral plot by eye or using a film scanner
- The quantum efficiency is only ~10%

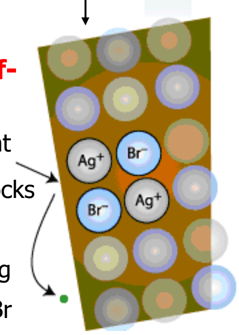
Other half-reaction?

Light

Light knocks off an e^-

$Ag^+ + e^- = Ag$

$Br^- - e^- = Br$



But the world has changed

There are much cooler photo-detector in use today

What do camera cell phones have to do with biosensors?

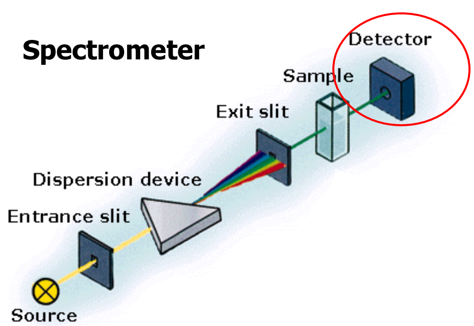
All this and much more…

after the break

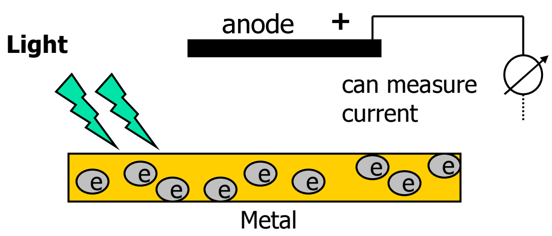
Light detectors

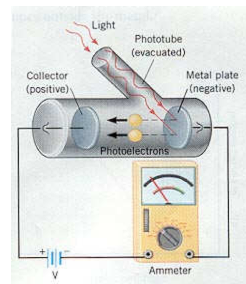
How do modern photodectors work?

Spectrometer



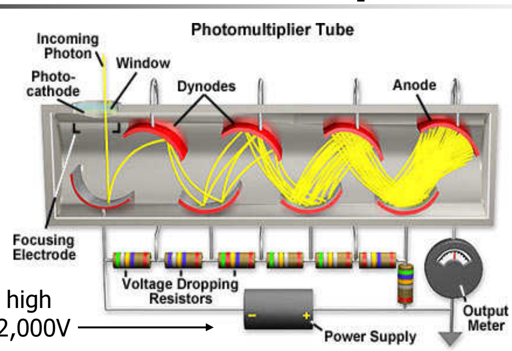
Phototubes





- Phototubes utilize the photoelectric effect to detect light
- Photons with sufficient energy eject electrons from the surface of thin metallic films and the resulting current, which is proportional to the light intensity (the number of photons), is then measured

Photomultipliers



Typically use high voltage 500-2,000V →

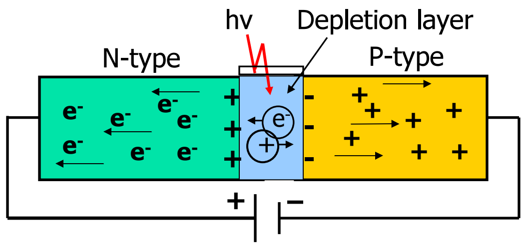
In practice, phototubes often contain cascaded metal electrodes at high potential differences - the accelerated photoelectrons knock off additional electrons at each stage, thus amplifying the photocurrent

Tubes with 8-10 stages can reach quantum efficiencies of 90%

Great but bulky and power hungry

Photodiode

Photodiode are photodetector that converts light into either current or voltage, depending upon the mode of operation



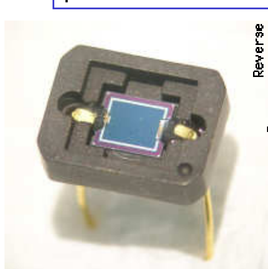
Similar to regular diodes but there is a "window" to allow light to reach the photo sensitive part of the device

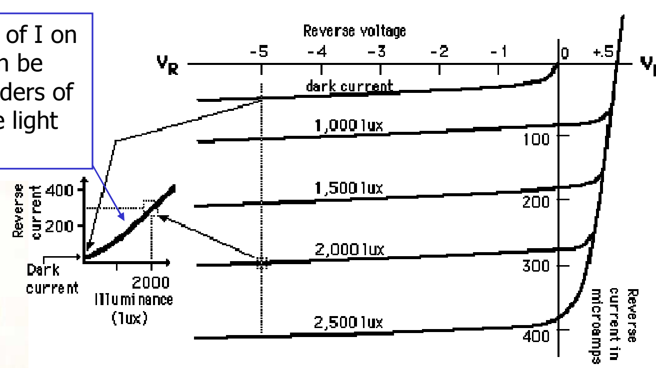
Light absorbed in the depletion region generates electron-hole pairs, which contribute to photocurrent

Operation mode

Photoconductive mode: a reverse voltage (i.e. voltage in the direction where the diode is not conducting) is applied and the resulting photocurrent is measured

The dependence of I on light intensity can be linear over six orders of magnitude of the light power

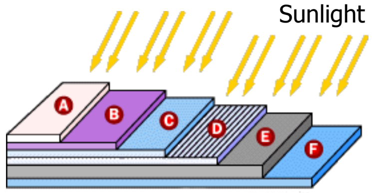




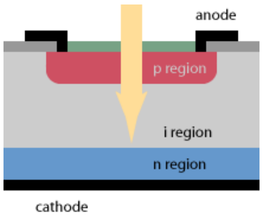
A photodector can be constructed from a transistor too ("phototransistor") - are more sensitive

Just for your information

Photovoltaic mode: the photodiode can generate voltage too; this is, by the way, how solar panels work



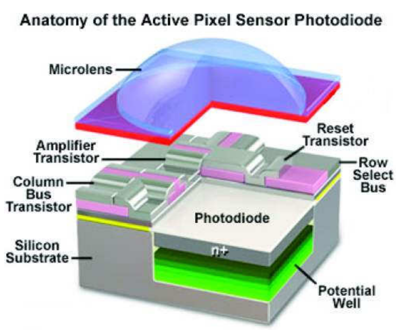
A: cover glass
B: antireflective coating
C and F: electrodes
D: N-type
E: P-type

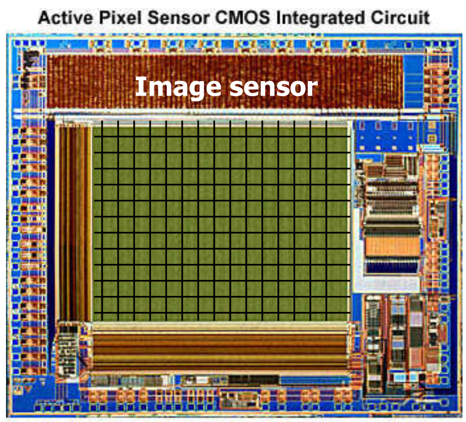


PIN (p–i–n) photodiodes: To increase performance an intrinsic (un-doped) layer can be incorporated between n and p layers – same principle but electron–hole pairs are generated in the i-layer

CMOS sensors

Complementary metal-oxide-semiconductor (**CMOS**)





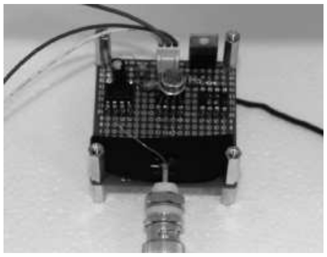
Based on FET (field-effect transistors)

All we need to do is to arrange them in a grid

More than 90% of camera phones sold today rely on CMOS image sensing technology

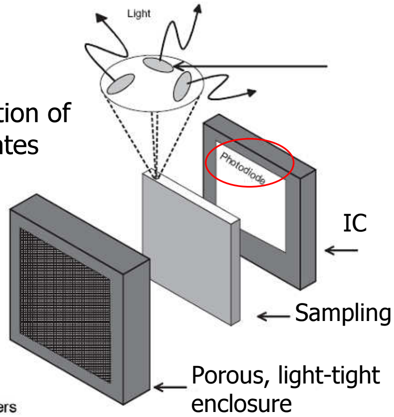
What does it have to do with biosensors?

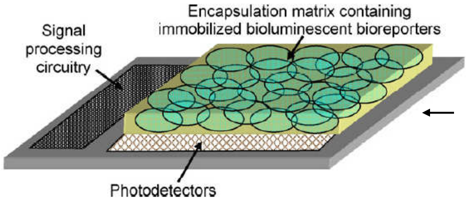
Detection of airborne bacteria



Photodiode sensor

Detection of salicilates





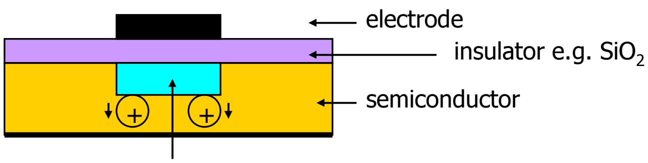
Or a multi-channel system on a CMOS

MOS detectors

CMOS sensors - consume little energy, integrate seamlessly into modern electronic device, but can be noisy – low quality image

MOS: Metal-Oxide-Semiconductor

Electrode is attached on top of the SiO_2 (dielectric) layer on the semiconductor substrate surface

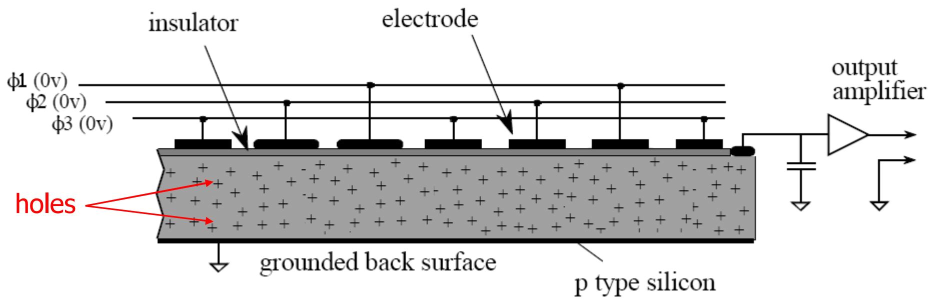


When voltage is applied a depletion layer is formed in the region near the interface of SiO_2 and semiconductor interface

Arranging these guys in a grid makes a CCD sensor which are also used widely i.e. digital cameras, spectrometers, etc, etc, etc

Charge coupled device (CCD)

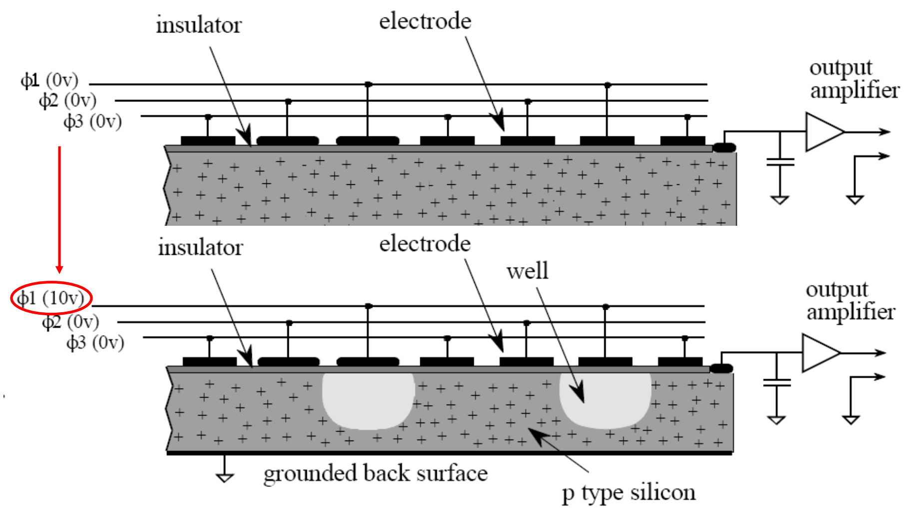
Basically CCD is a thin wafer of p-type silicon covered with an insulating layer on top and an array of electrodes in a repetitive pattern. The electrodes are connected in groups of 3, so that 3 separate voltages can be applied.



- In p-type there is an excess of positive charge carriers (holes) that can be pushed around by applying voltage

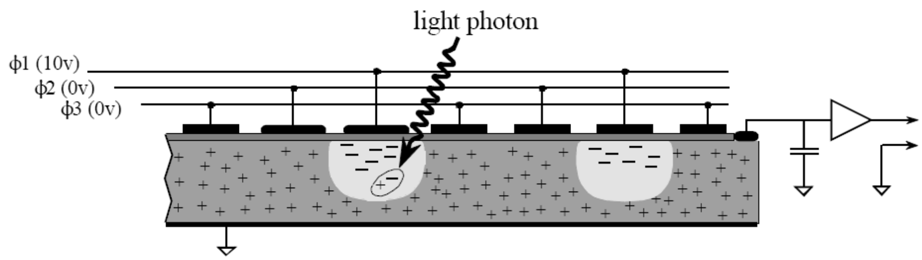
How CCDs work 1

When a positive voltage is applied to an electrode, the holes are pushed away and depleted areas (wells) appear under the electrode



How CCDs work 2

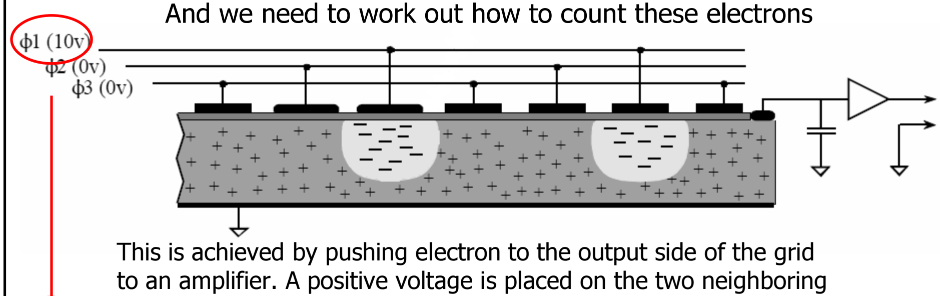
Each well in the CCD is a very efficient light sensor



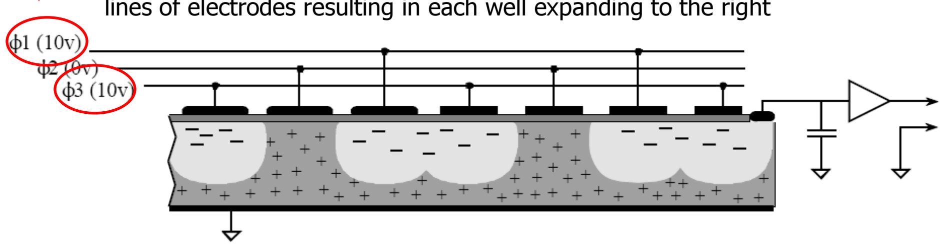
- When a photon of light strikes the silicon, its energy is converted into one e^- and one hole. The hole moves away, leaving the electron stuck in the well, where it is held by the positive voltage on the electrode
- If CCD is exposed to light for some time (integration period), the pattern of light striking is transferred into a pattern of charge within the CCD wells

How CCDs work 3

And we need to work out how to count these electrons

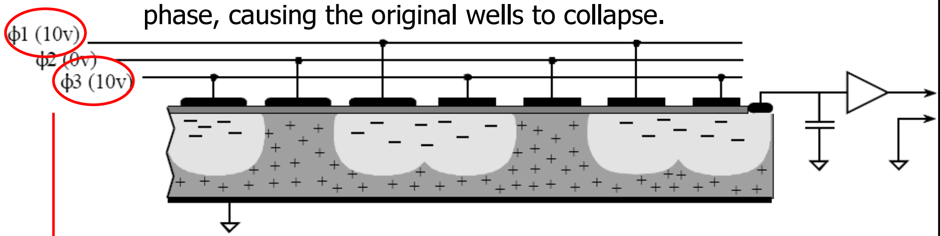


This is achieved by pushing electron to the output side of the grid to an amplifier. A positive voltage is placed on the two neighboring lines of electrodes resulting in each well expanding to the right

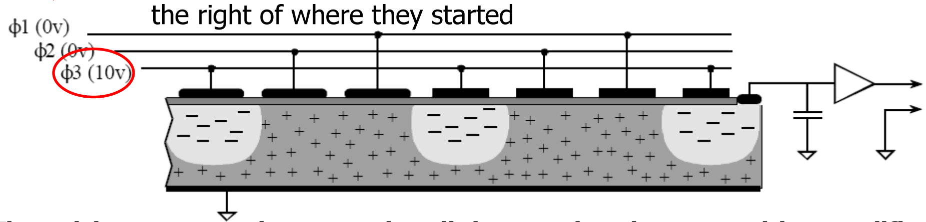


How CCDs work 4

The next step is to remove the voltage from the first phase, causing the original wells to collapse.



This leaves the accumulated electrons in one well to the right of where they started

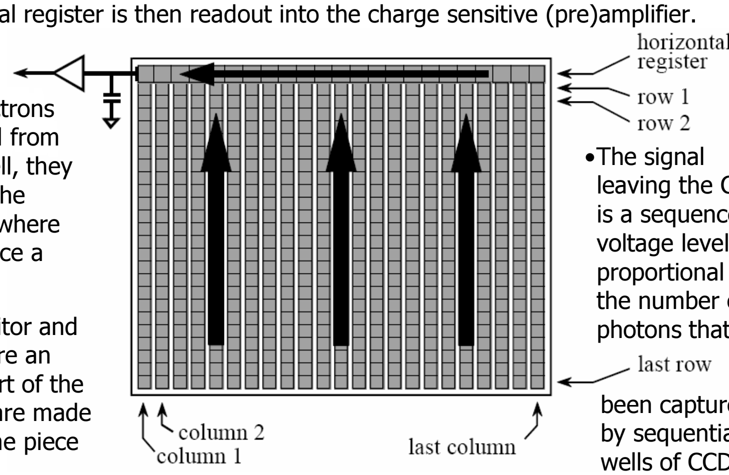


The pulsing sequence is repeated until they reach a charge sensitive amplifier

CCD architecture

The imaging wells of the CCD are arranged in columns. During readout, the charge from each well is moved up the column into a horizontal register. The horizontal register is then readout into the charge sensitive (pre)amplifier.

- As the electrons are pushed from the last well, they flow onto the capacitor, where they produce a voltage
- This capacitor and amplifier are an integral part of the CCD, and are made on the same piece of silicon



- The signal leaving the CCD is a sequence of voltage levels proportional to the number of photons that has been captured by sequential wells of CCD

CCD output

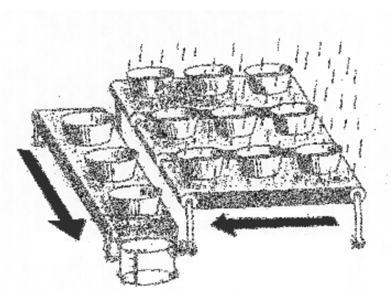
Column

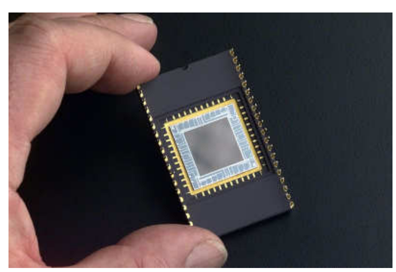
Row	150					155					160					165
50	183	183	181	184	177	200	200	189	159	135	94	105	160	174	191	196
	186	195	190	195	191	205	216	206	174	153	112	80	134	157	174	196
	194	196	198	201	206	209	215	216	199	175	140	77	106	142	170	186
	184	212	200	204	201	202	214	214	214	205	173	102	84	120	134	159
	202	215	203	179	165	165	199	207	202	208	197	129	73	112	131	146
55	203	208	166	159	160	168	166	157	174	211	204	158	69	79	127	143
	174	149	143	151	156	148	146	123	118	203	208	162	81	58	101	125
	143	137	147	153	150	140	121	133	157	184	203	164	94	56	66	80
	164	165	159	179	188	159	126	134	150	199	174	119	100	41	41	58
	173	187	193	181	167	151	162	182	192	175	129	60	88	47	37	50
60	172	184	179	153	158	172	163	207	205	188	127	63	56	43	42	55
	156	191	196	159	167	195	178	203	214	201	143	101	69	38	44	52
	154	163	175	165	207	211	197	201	201	199	138	79	76	67	51	53
	144	150	143	162	215	212	211	209	197	198	133	71	69	77	63	53
	140	151	150	185	215	214	210	210	211	209	135	80	45	69	66	60
65	135	143	151	179	213	216	214	191	201	205	138	61	59	61	77	63

Essentially a grid of number corresponding to # of photons in each well/pixel

CCD: summary

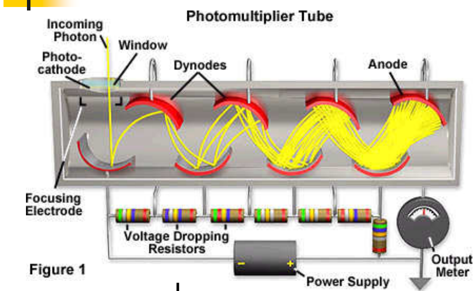
CCD imaging is performed in a three-step process:

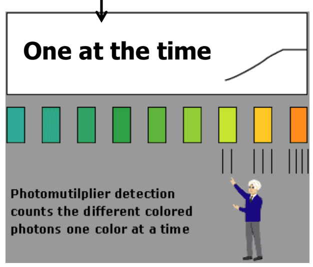




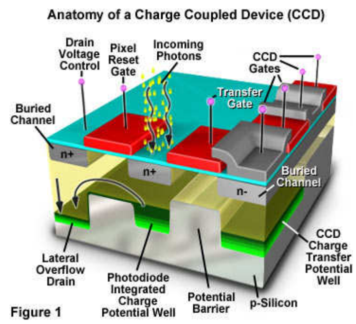
1. Exposure to light which converts light energy into an electronic charge at discrete wells (pixels)
2. Charge transfer to move the packets of charge in wells along thestructure
3. Charge-to-voltage conversion and output amplification

Photomultipliers and CCDs





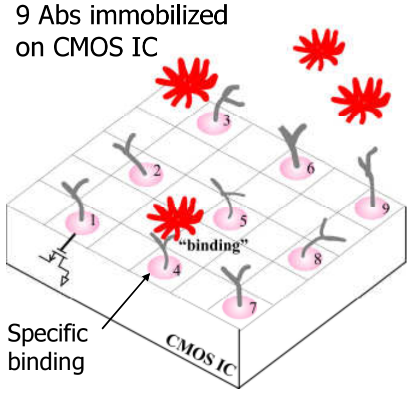
What is the difference between photo-multipliers and CCDs?



while CCD can capture millions simultaneously

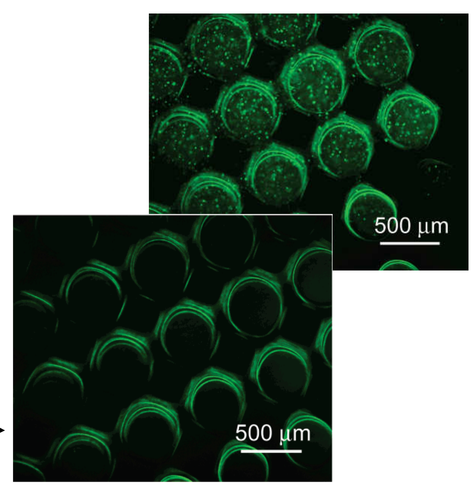
CMOS/CCD biosensors

9 Abs immobilized on CMOS IC



Specific binding

Whole mammalian cell biosensors for the optical monitoring of cell viability



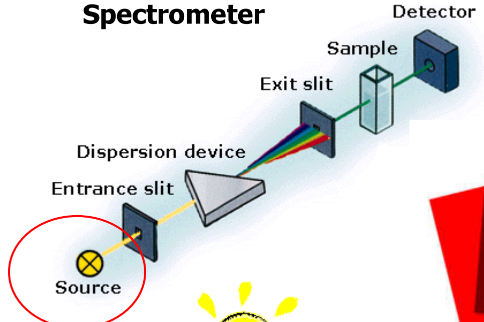
Before (top) and after (bottom) exposure to a toxin →

Why is it important?

- Miniaturization/portability
- High throughput – massively parallel analysis is possible
- Cost of large scale manufacturing
- Signal digitization/ease of integration with modern electronics

And finally…

Spectrometer

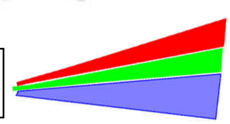


What is there left to discuss?

The light source

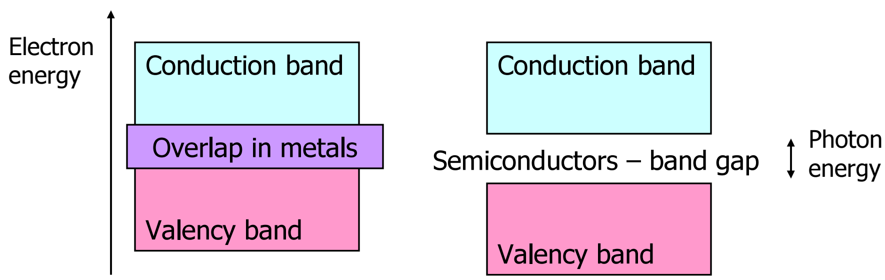
Optical filters

Mono-chromator



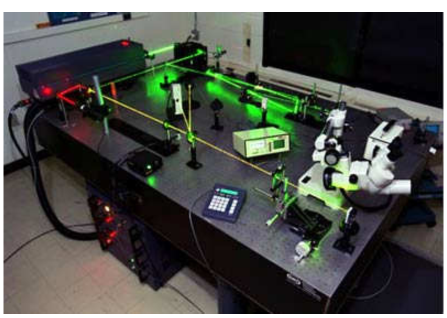
Light emitting diode

- A LED is a semiconductor diode that emits light when an electrical current is applied in the forward direction
- Like a normal diode, a LED has a p-n junction where electrons and holes recombine – the energy released is emitted in the form of a photon
- Wavelength of the emitted light (typically very narrow) depends on the material (silicon is not used)



Lasers

"Laser" stands for **light amplification by stimulated emission of radiation;** it is a device that controls the way that energized atoms release photons



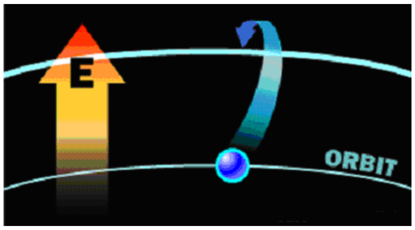
Lasers can now be found in an amazing range of products from CD players to Starwar defense systems

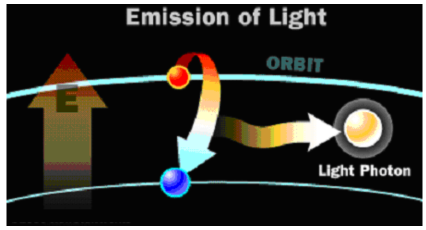
Laser light is different from other light sources:

- The laser light is mono-chromatic
- The laser light is coherent i.e. it is "organized" in such a way that photons move in step with the others
- The laser light is directional i.e. a powerful and "concentrated" beam

Pumping

In a laser, the medium is "pumped" by very intense flashes of light or electrical discharges to create a large proportion of excited-state atoms. In general, the atoms are excited to a level that is two or three levels above the ground state



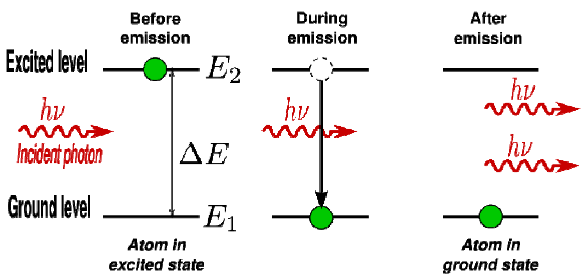


When electrons in the exited atoms return to the lower energy level, the light is emitted

But there is an interesting twist – **stimulated emission**

Stimulated emission

The energy of emitted photons depends on the energy difference between the excited and the ground state. When an emitted photon encounters another atom that has an electron in the same excited state, **stimulated emission** occurs



$$E_2 - E_1 = \Delta E = h\nu$$

The first photon induces atomic emission in such a way that photon emitted from the second atom has exactly the properties (frequency, phase, polarization, direction) as the incoming photon

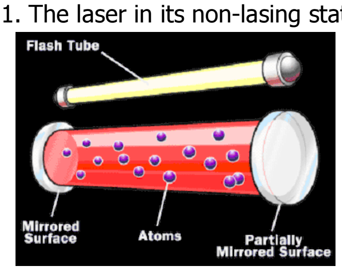
Mirrors

- The other key feature of lasers is a **pair of mirrors**, one at each end of the lasing medium. Photons, with a specific wavelength and phase, reflect off the mirrors and travel back and forth through the lasing medium to cause the emission of more photons of the same wavelength and phase creating a cascade effect
- One end of the laser often has a "half-silvered" mirror - it reflects some light and lets some light through, depending on intesity
- **The light that makes it through is the laser light**

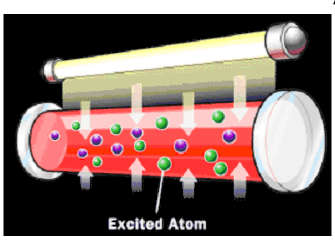
How lasers work

- A ruby laser (694 nm) consists of a flash tube, a ruby rod and two mirrors (one half-silvered)
- The ruby rod is the lasing medium and the flash tube pumps it

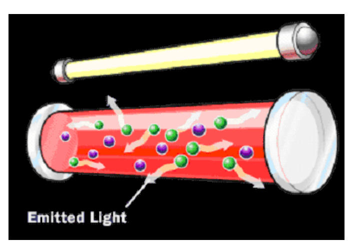
1. The laser in its non-lasing state



2. The flash tube fires light into the ruby rod which excites atoms in the ruby

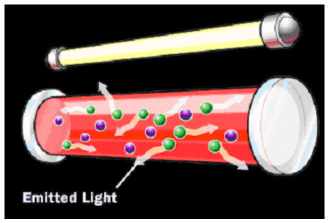


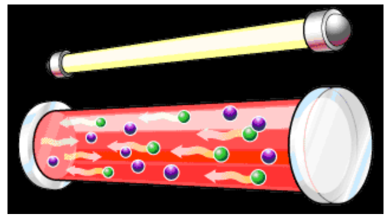
3. Some of these atoms emit photons



How lasers work

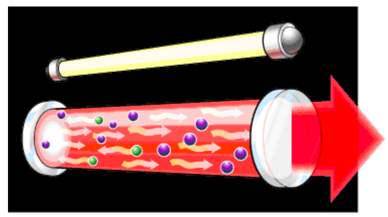
The photons running in a direction parallel to the ruby's axis bounce back and forth off the mirrors and, as they pass through the crystal, stimulate emission in other atoms



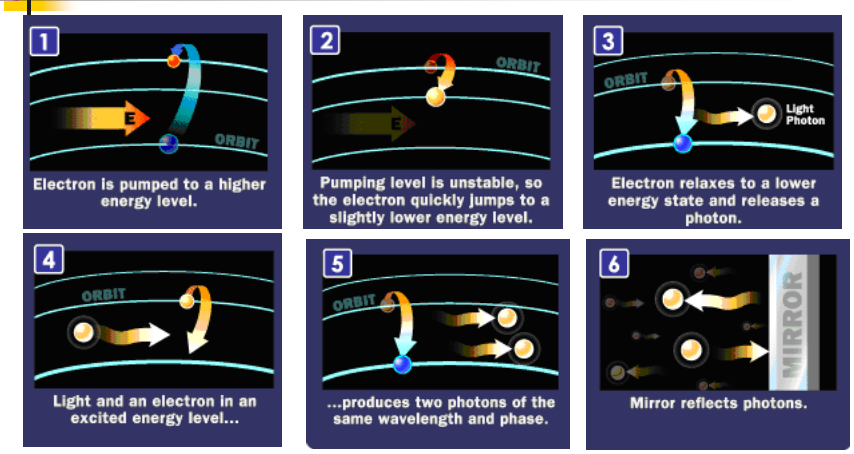


Once there is enough photons monochromatic, single-phase light leaves the ruby through the half-silvered mirror

This is laser light



A three-level laser



A burst of energy excites electrons from their ground state to a higher state. The electrons then drop into a longer lived state with slightly less energy (the level down), where they can be stimulated to quickly shed the excess energy - **a laser burst -** returning to the stable ground state

Types of lasers

- Solid-state lasers have lasing material distributed in a solid matrix e.g. the ruby laser
- Semiconductor lasers or diode lasers (not solid-state lasers) are electronic devices - generally small and use low power e.g. CD players
- Gas lasers e.g. helium and helium-neon have a primary output of visible red light. CO_2 lasers emit energy in the far-infrared, and are used for cutting hard materials
- Dye lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths

Types of lasers

Laser Type	Wavelength (nm)
Argon fluoride (UV)	193
Krypton fluoride (UV)	248
Xenon chloride (UV)	308
Nitrogen (UV)	337
Argon (green)	514
Argon (blue)	488
Helium neon (green)	543
Helium neon (red)	633
Rhodamine 6G dye (tunable)	570-650
Ruby (CrAlO3) (red)	694
Nd:Yag (NIR)	1,064
Carbon dioxide (FIR)	10,600

Canary

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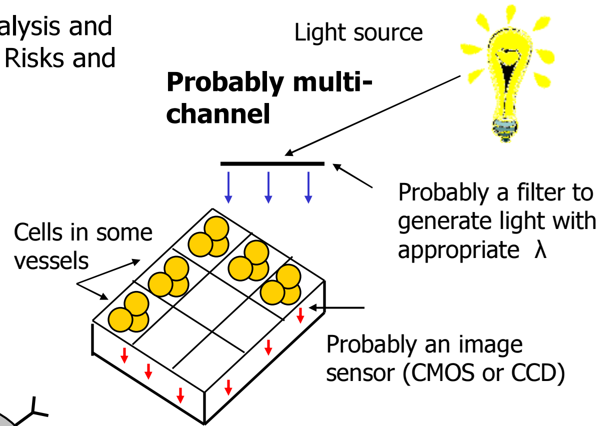
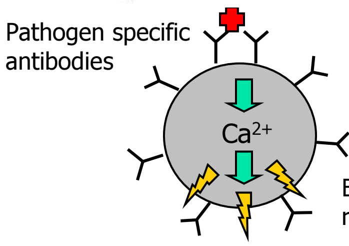




What could be inside this box?

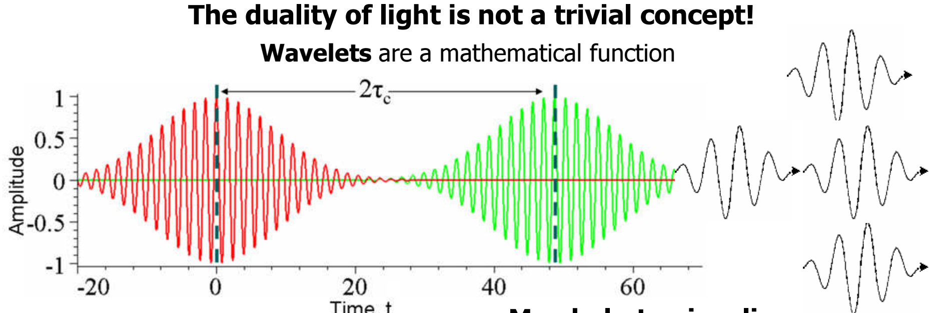
In conclusion

We have covered some ground today ☺

- Mechanical waves vs electromagnetic radiation
- Duality of light
- Spectrometers, spectroscopes, photomultipliers, CCDs, and lasers

The duality of light is not a trivial concept!

Wavelets are a mathematical function



May help to visualize…