Table of Contents

CH 7 Homework

1. Use the Wein displacement law to calculate the wavelength emitted by a blackbody that has been heated to 5000 K.

2. Use Stefan's law to calculate the total energy output in W/m^2 for the blackbody radiator in Q1.

3. How many lines per millimeter in a grating would be required for the first-order diffraction line for l = 400 nm to be observed at a reflection angle of 5 degrees when the angle of incidence is 45 degrees.

4. A monochromator has a focal length of 1.6 m and a collimating mirror with diameter of 3.5 cm. The dispersing device was a grating with 1500 lines/mm. For first-order diffraction, what is the resolving power of the monochromator if a collimated beam illuminated 3.0 cm of the grating?

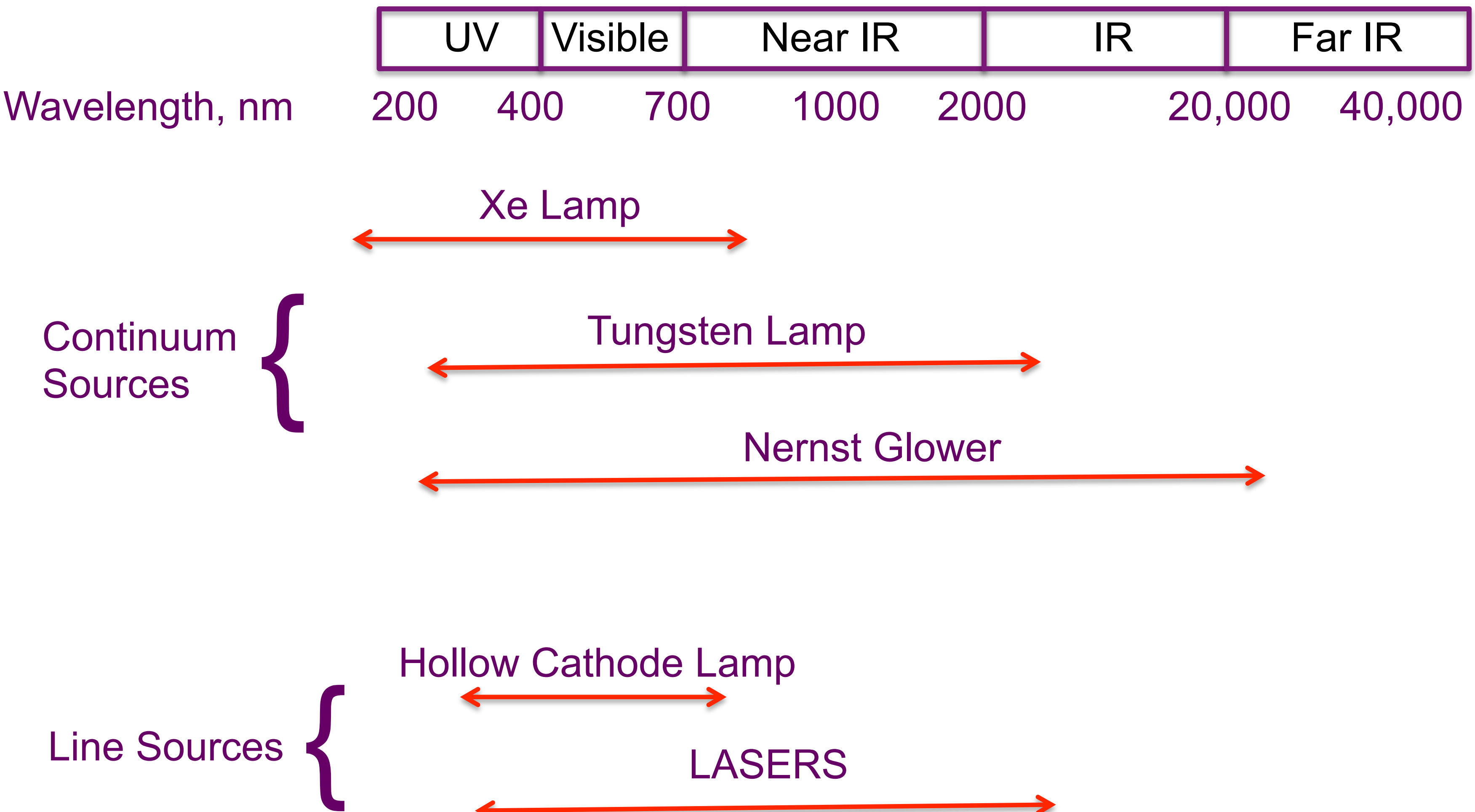
5. What length of mirror drive in a Michelson interferometer is required to produce a resolution sufficient to separate IR peaks at 4002.1 and 4008.8 cm^{-1}?

CH 7 Components of Optical Instruments

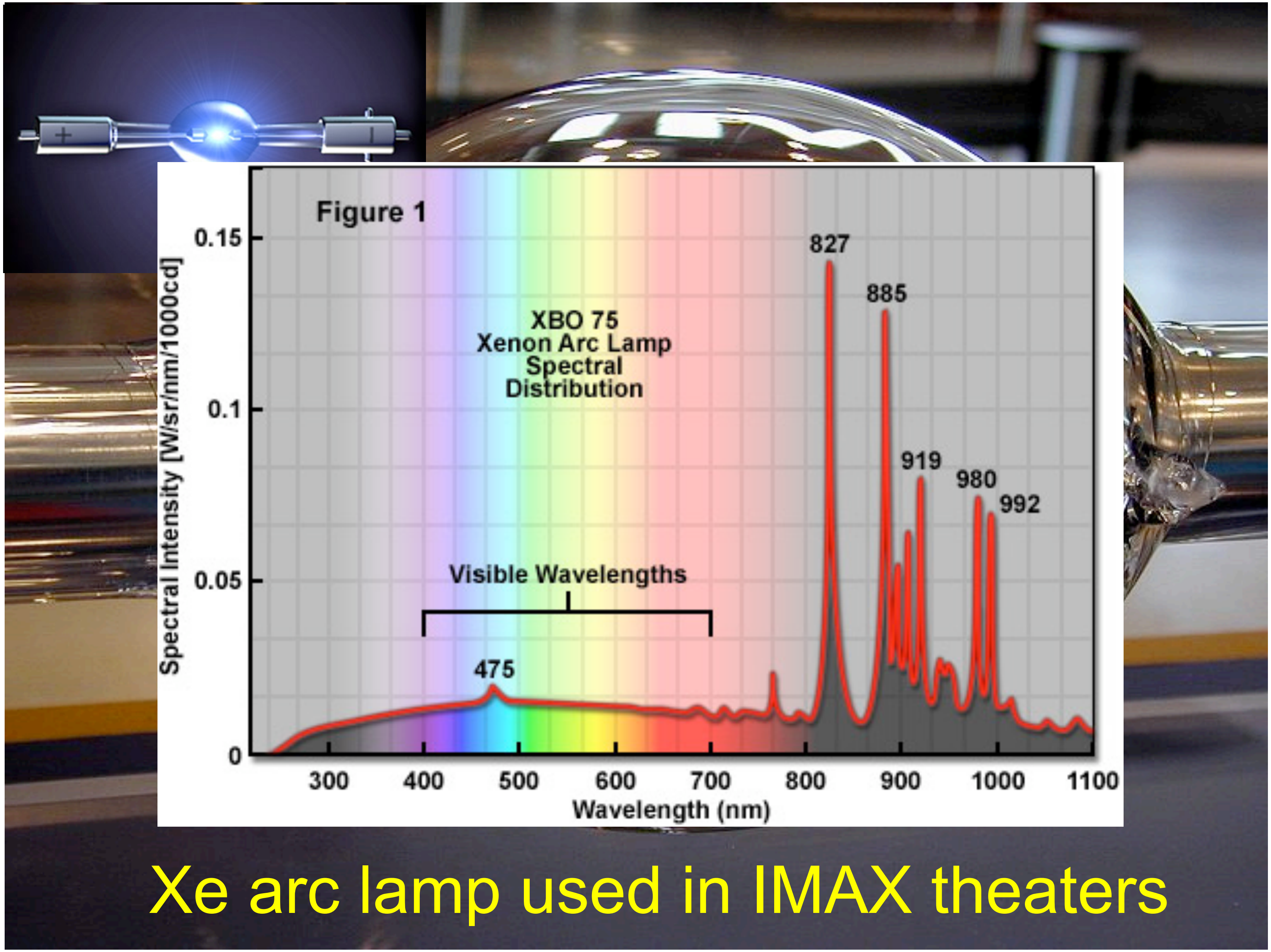
Instruments for measuring absorption, fluorescence, phosphorescence, and scattering contain similar components.

1. Source of light
2. Sample holder
3. Spectral isolator
4. Detector
5. Display

Sources of Radiation

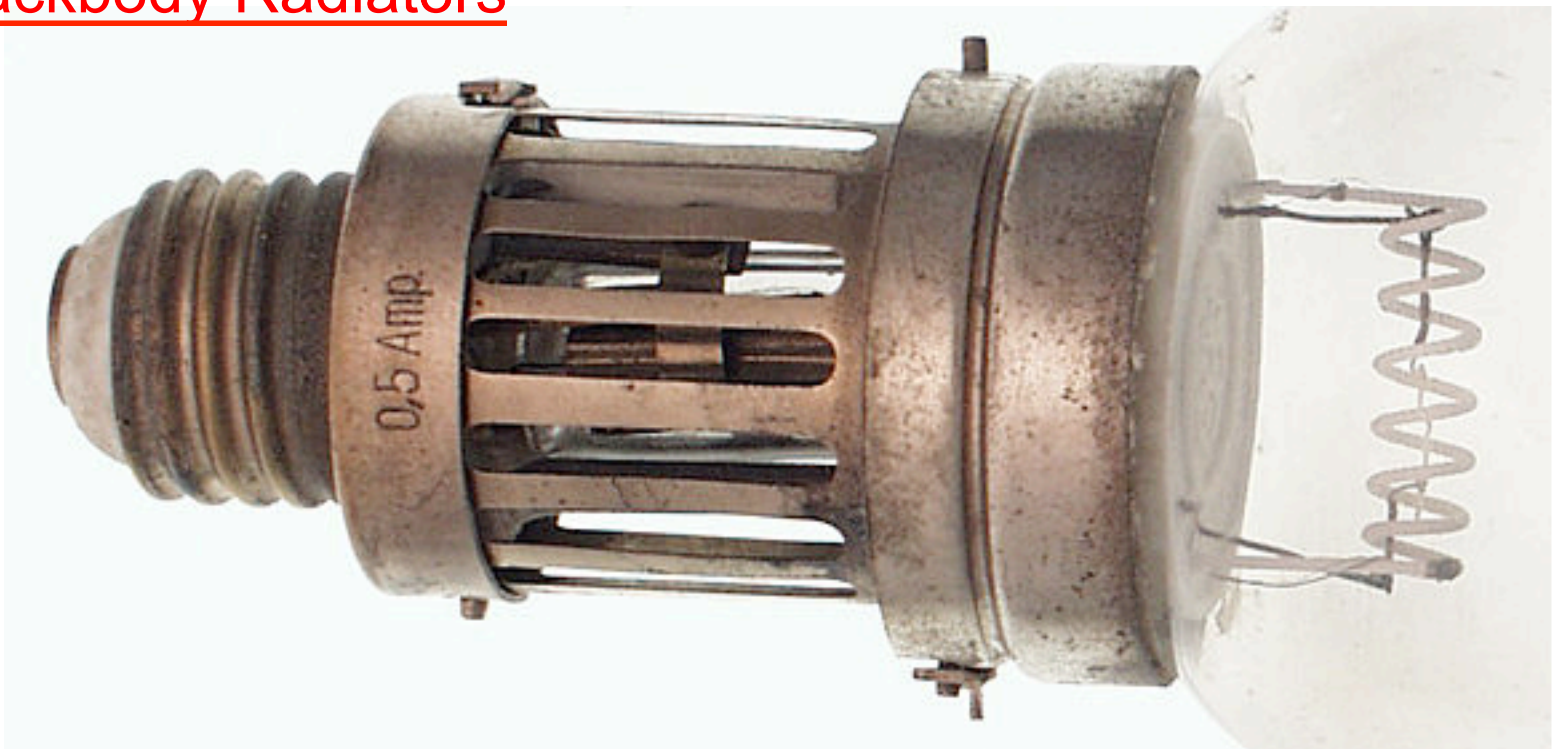


Sources of Radiation



Sources of Radiation

Blackbody Radiators



Invented by Nernst in 1897 and made out of a ceramic that wouldn't oxidized as it was heated so it didn't need a glass bulb.

SiC now used.

Sources of Radiation

Blackbody Radiation

EM radiation is produced any time electric charges oscillate.

At any non-zero temperature, the atoms, molecules, and electrons are oscillating.

At any non-zero temperature, all matter will emit EM radiation.

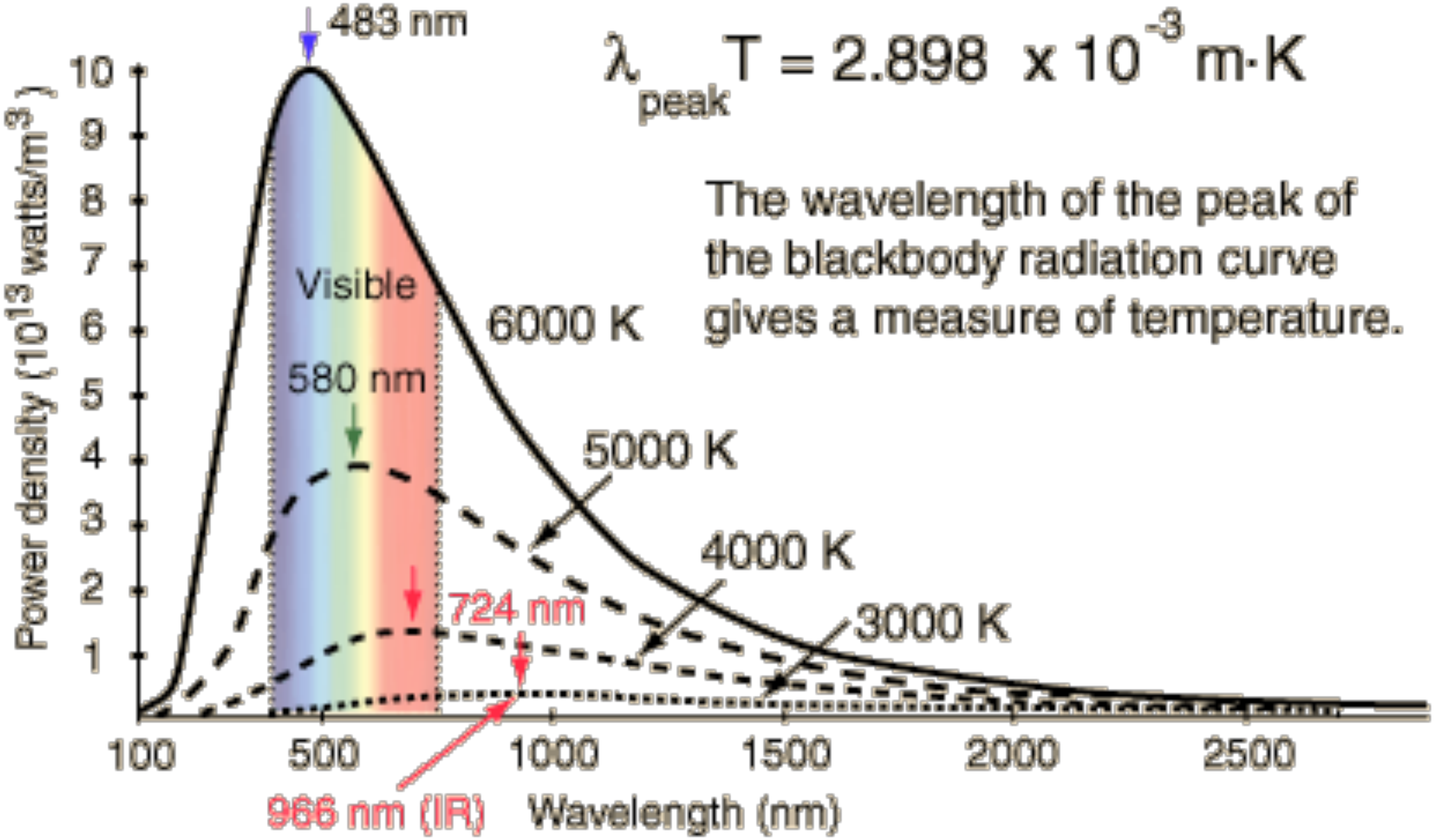
$$\lambda \bullet T = 2.898 \times 10^{-3}\ \mathrm{m} \bullet \mathrm{K}$$ Wein's Displacement Law

$$\text{Power } P = \sigma \varepsilon A T^4$$ Stefan's Law

σ is the Stefan-Boltzmann constant: 5.6703×10^{-8} W/m$^2 \bullet$K^4
ε is emissivity of the object; between 0 and 1; 1 for a true blackbody
A is area
T is temperature

Sources of Radiation

Blackbody Radiation



Sources of Radiation

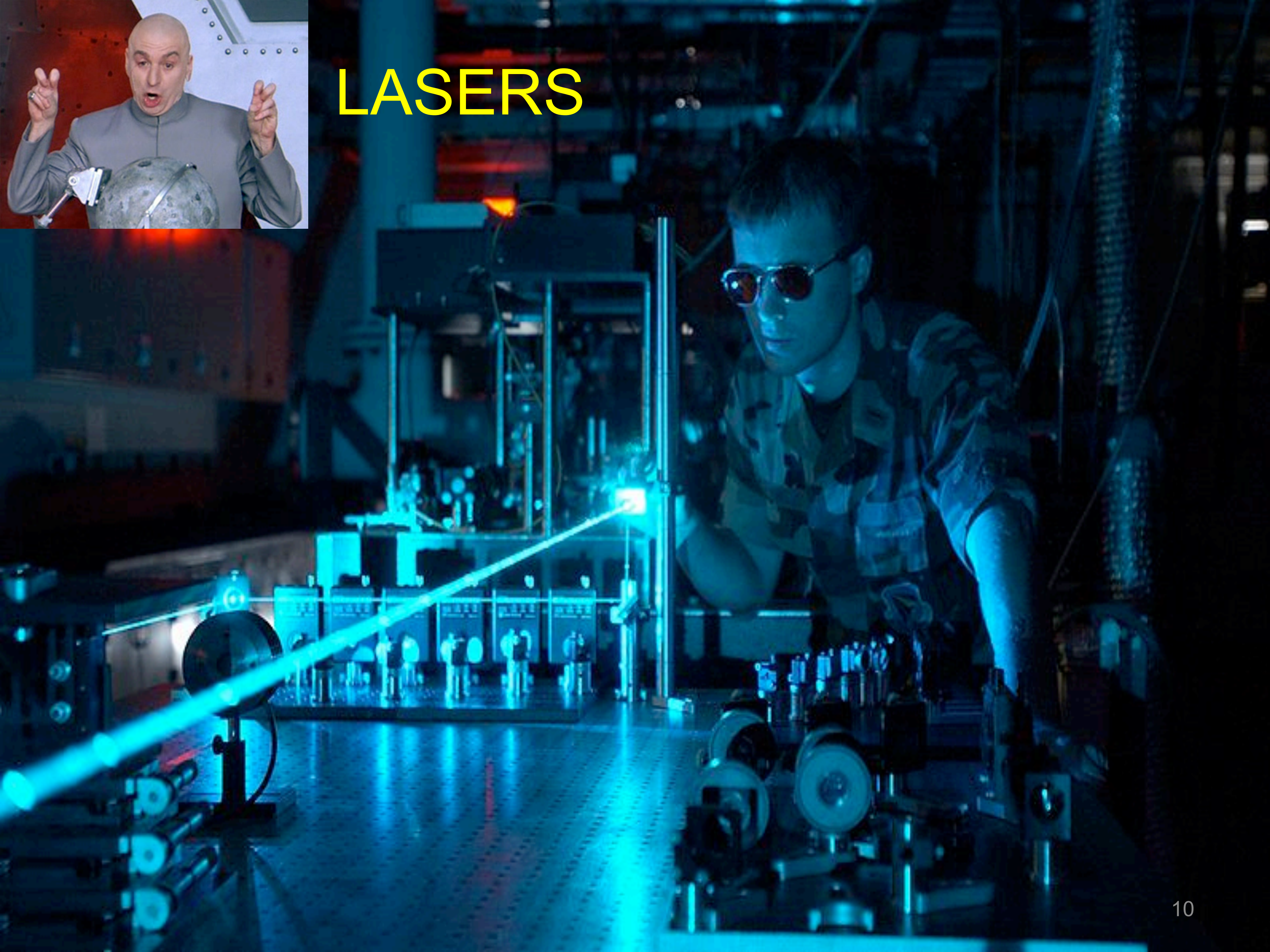
Concept Te$t

In 1965, microwave radiation peaking at a wavelength of 1070 um was discovered coming in all directions from space. This background radiation is believed to be left over from 15 billion years ago, soon after the universe formed.

Which temperature does this radiation correspond?

(A) 0 K (B) 2.79×10^{-6} K (C) 2.7 K

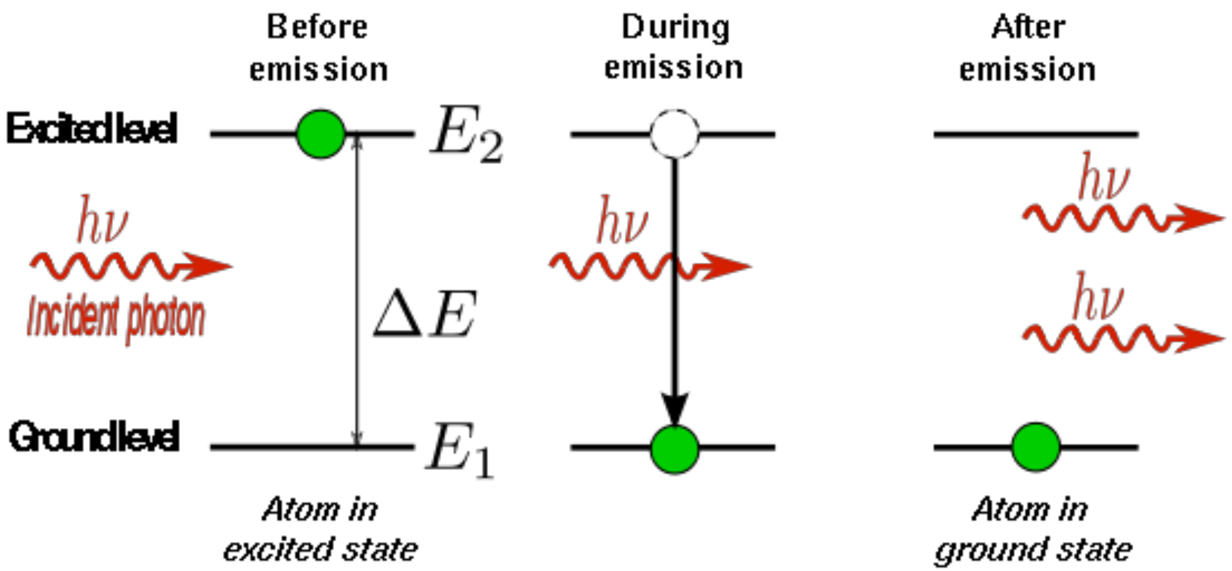
LASERS



Light Amplification by Stimulated Emission of Radiation

Basic Operating Principles

Consider a simple two level system.



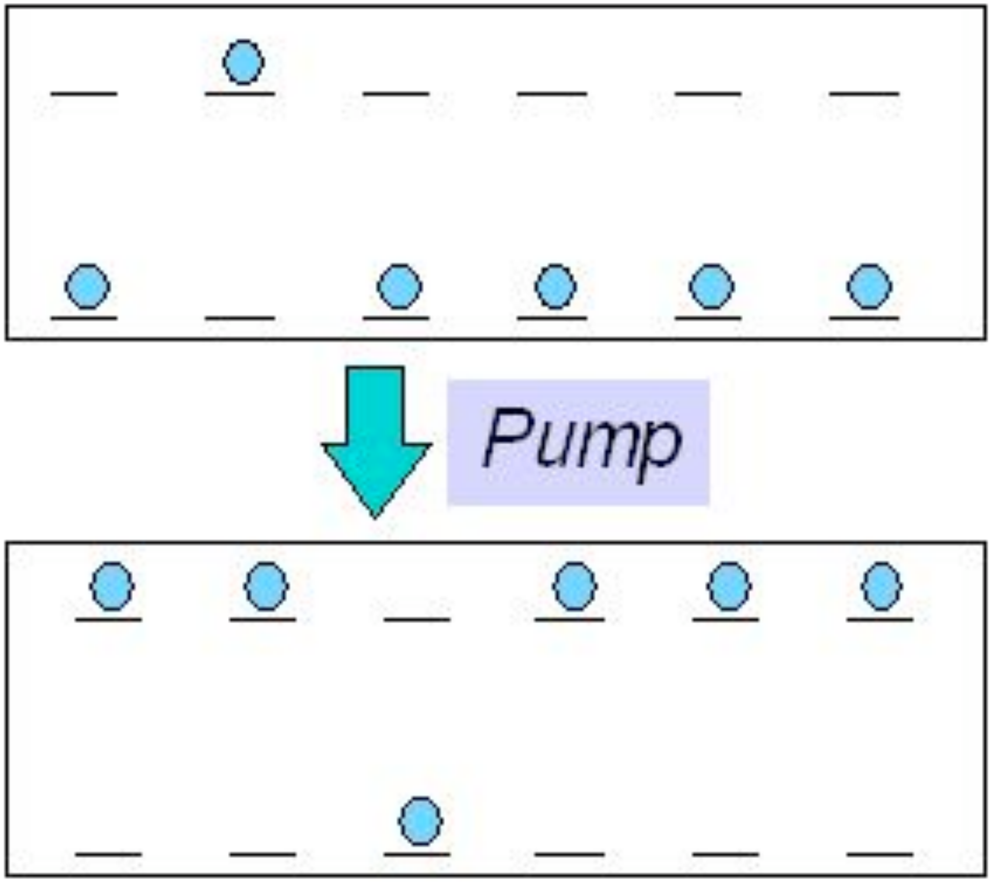
When an electron in the upper state interacts with a photon of energy $h\nu_o$, the particle can decay to the lower level, emitting a photon in the process.

The original photon is not absorbed in the process so 1 photon in results in 2 photons out, which travel in the same direction and are in phase.

Light Amplification by Stimulated Emission of Radiation

Basic Operating Principles

Population Inversion



Thermally populated systems will have a majority of their particles in the lowest energy state. We want a majority in an excited state.

*Key concept. This is accomplished using an electrical discharge or a very intense light source called a flash lamp. A system with a majority of particles in an excited state is said to have a population inversion.

More to the Story

Einstein showed that for a 2-level system, the population inversion can never be greater than 50%.

Since the probability of absorption and stimulated emission is 1, with a 50/50 distribution of electrons in the ground and excited states, photons are just as likely to be absorbed as emitted: No LASER!

Can a 2-level laser work at high T?

$$\frac{N_j}{N_0} = \frac{g_j}{g_0}\exp(-E_j/kT)$$

N_j/N_0 = ratio of electrons in excited and ground states

g_j; g_0 = # of quantum states having the same E at each level

E = E difference between ground state and excited state

k = Boltzmann's constant

Can a 2-level laser work at high T?

$$\frac{N_j}{N_0} = \frac{g_j}{g_0}\exp(-E_j/kT)$$

What T will yield a population inversion?

Assume a Na atom laser with the 3s ground and 3p excited states.

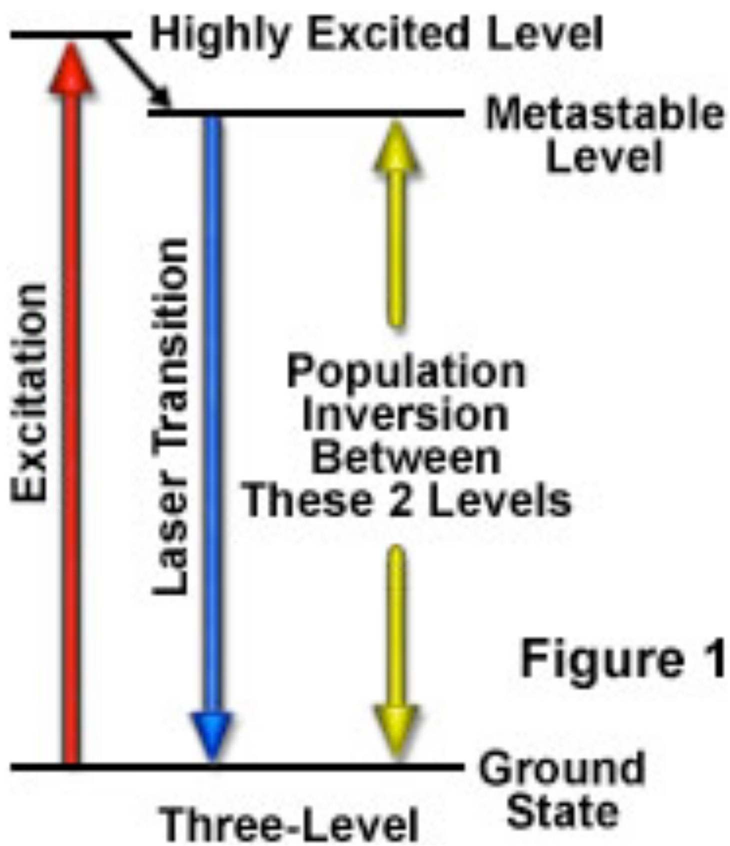
$g_j/g_0 = 6/2 = 3$ 3 orbitals with spin up + 3 with spin down = 6; 1 orbital spin up + 1 with spin down = 2

$E_j = 3.37 \times 10^{-19}$ J

$T = 14{,}438$ K

The Solution: 3-level Systems

A 3-level system



Pump electrons into the “highly excited level” and have them fall quickly (>ns) and radiationlessly to a “metastable level”.

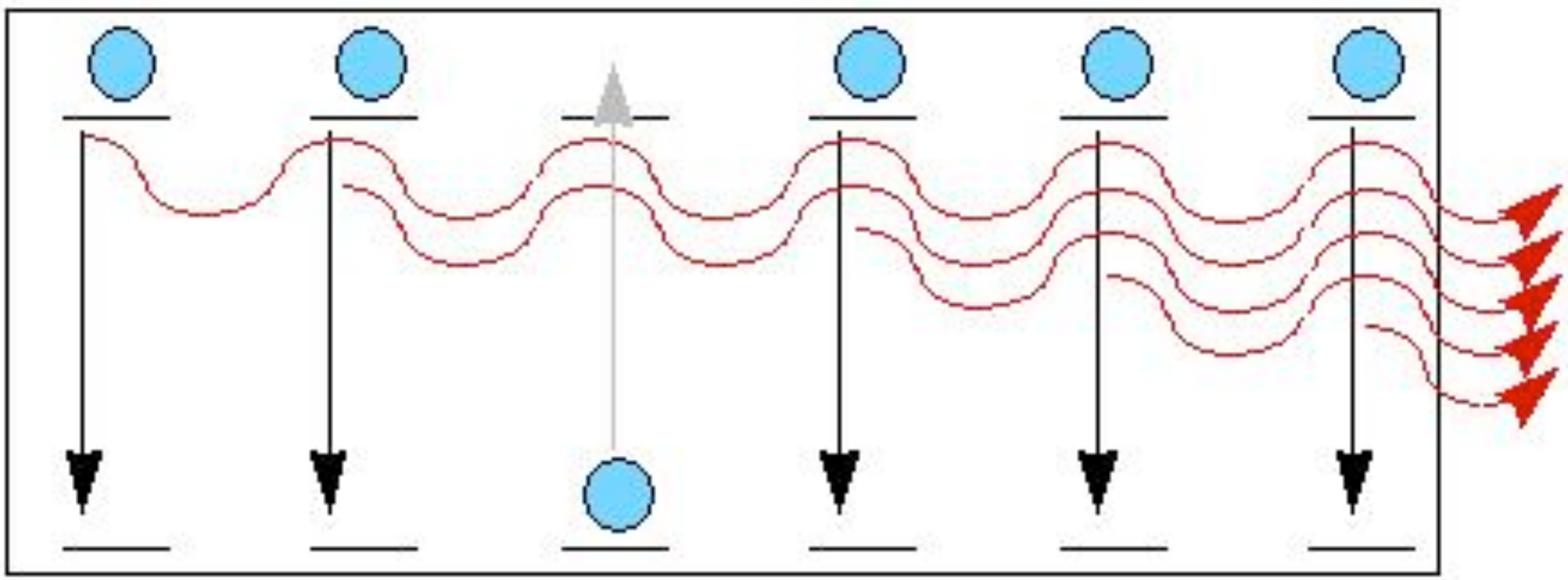
If the lifeltime of the electron in the metastable level is long (μs), a large Population Inversion (>>>50%) will be generated.

The photons that pump the electrons into the highly excited level are not the same E as the photons that cause the emission. Furthermore, there are never very many electrons in the ground state and the transition from the ground state to the metastable level are “forbidden” or low probability transitions. (More on that later.)

Light Amplification by Stimulated Emission of Radiation

Basic Operating Principles

Gain



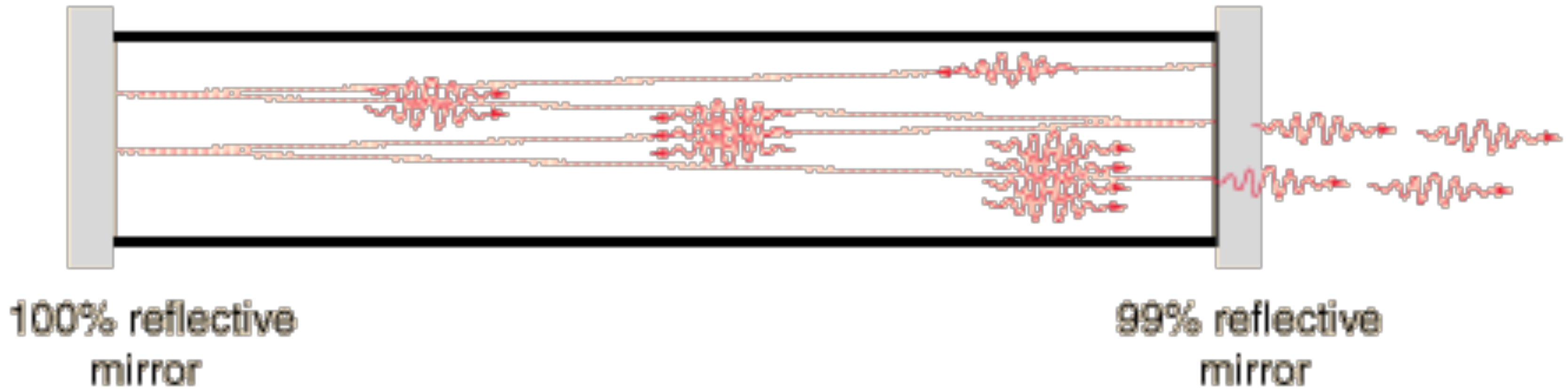
When the first particle falls a photon is emitted. This photon can stimulate the decay of other particles, which in turn will emit photons.

Light Amplification by Stimulated Emission of Radiation

Basic Operating Principles

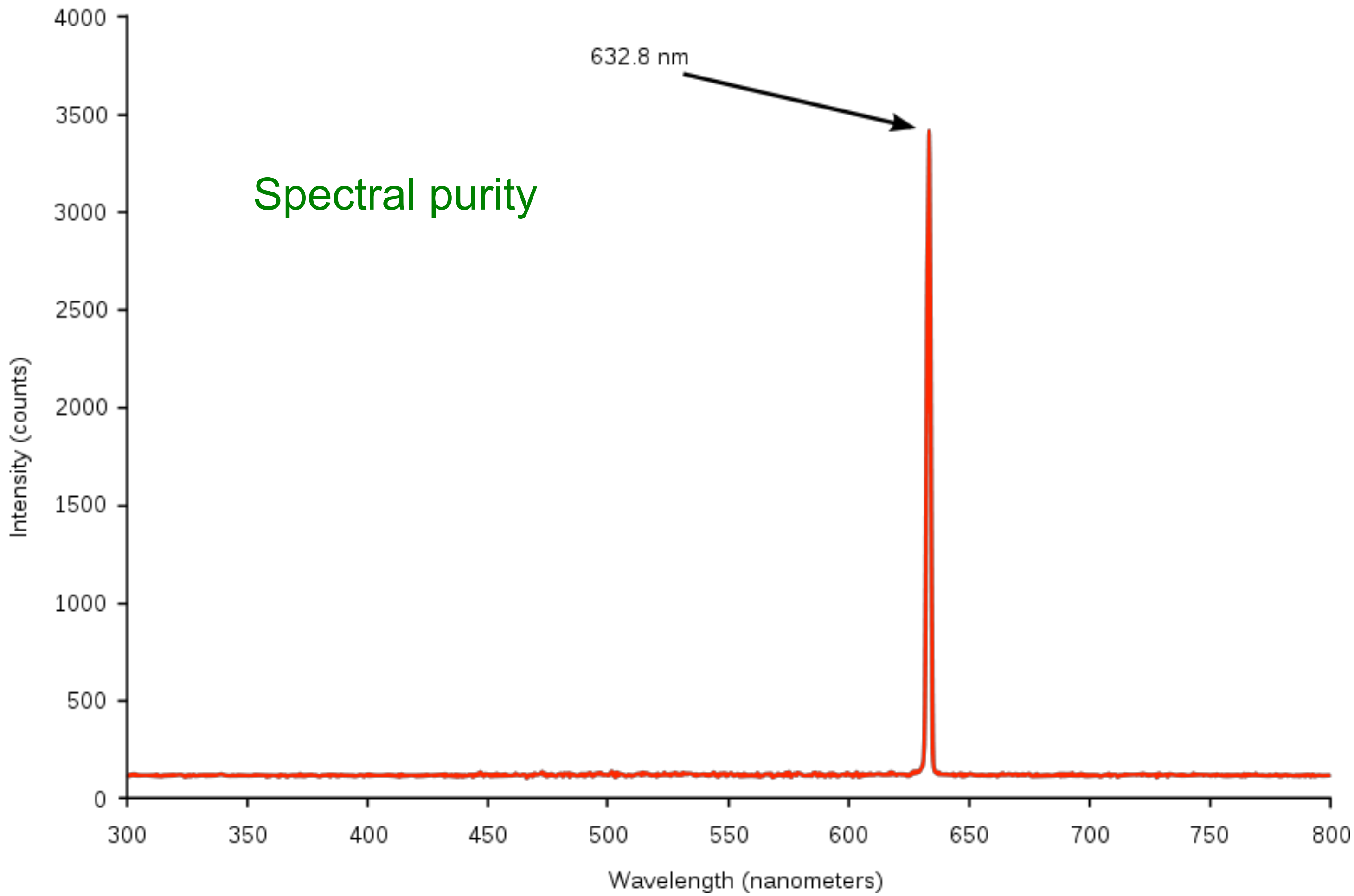
Gain is maximized using mirrors that force the light to rattle around in the laser for a while. Gain gives the exiting beam intensity.

The mirrors also make the light that emerges collimated.



Light Amplification by Stimulated Emission of Radiation

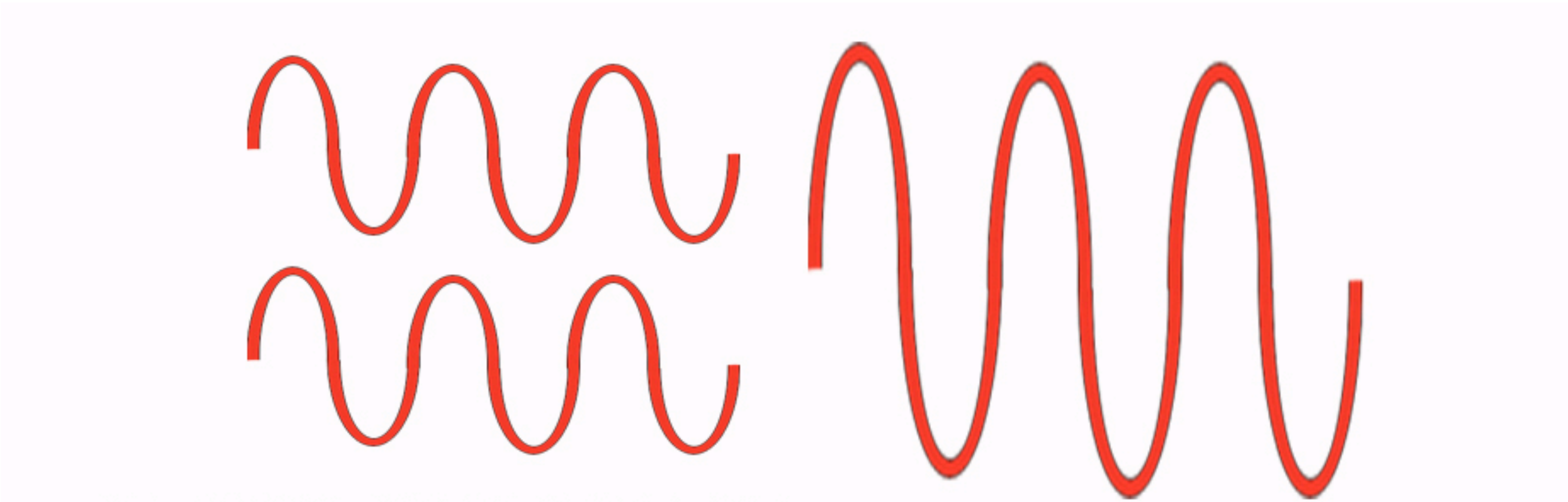
Characteristics



Light Amplification by Stimulated Emission of Radiation

Characteristics

Coherence



The stimulated emission occurs rapidly and in a cooperative manner. Light waves emerge in phase and add constructively.

In contrast, the atoms in a heated wire or undergoing fluorescence act independently and emit randomly.

Light Amplification by Stimulated Emission of Radiation

Characteristics

Can be focused to a point almost the same width as the wavelength of light. This is the origin of laser intensity. Intensities of 10^{17} W/cm^2 are easily obtained for lasers. An acetylene flame, in contrast, has an intensity of 10^3 W/cm^2.

Very little beam spreading; lasers are thus highly directional.

LASERS

Types of Lasers

Solid-State Lasers

Ruby Laser (1st successful laser): Al_2O_3 with 0.05% Cr^{3+}. Xe flashlamp coiled around a rod of Ruby. Cr^{3+} is responsible for the lasing.

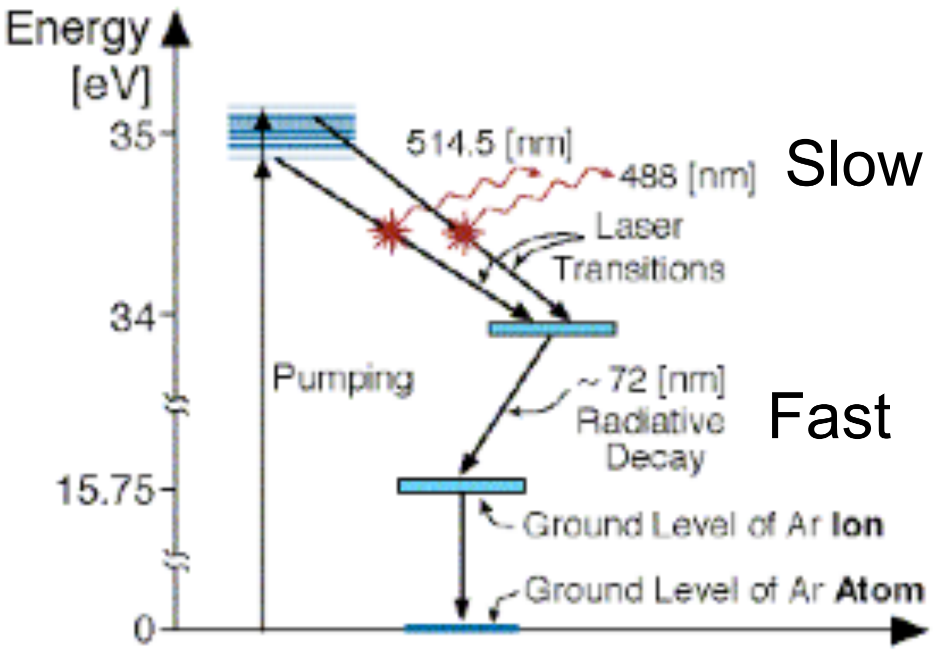
Nd-YAG Laser: Nd ion in a crystal of yttrium aluminum garnet. High power output at 1064 nm. (Garnet is the name for a class of minerals that contain silica mixed with other elements that give the minerals different colors.)

Gas Lasers

He-Ne (Red; 632.8 nm), Ar^+ (green; 514.5 and blue; 488.0 nm), or CO_2: Cheap and low power consumption.

LASERS

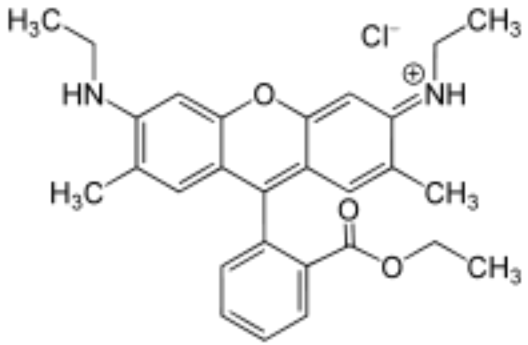
3 levels of the Ar^+ laser

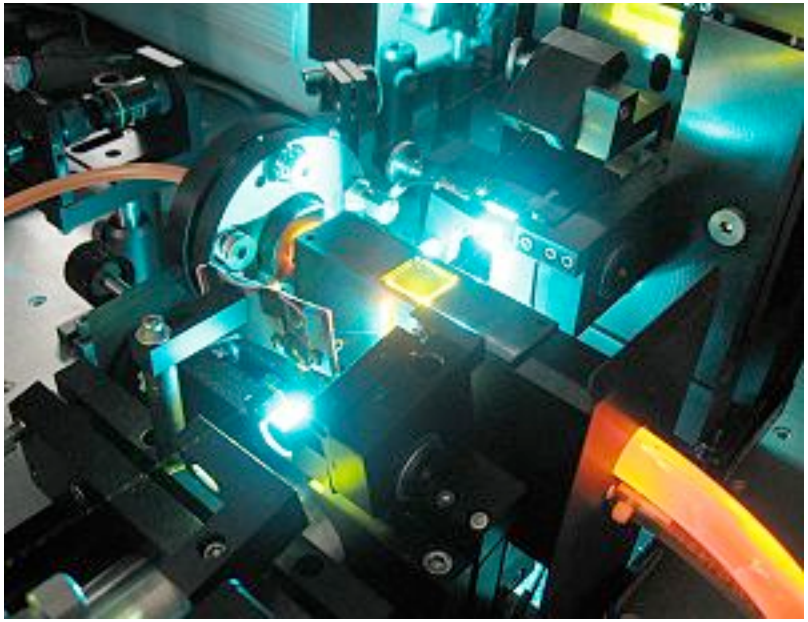


Types of Lasers

Dye Lasers

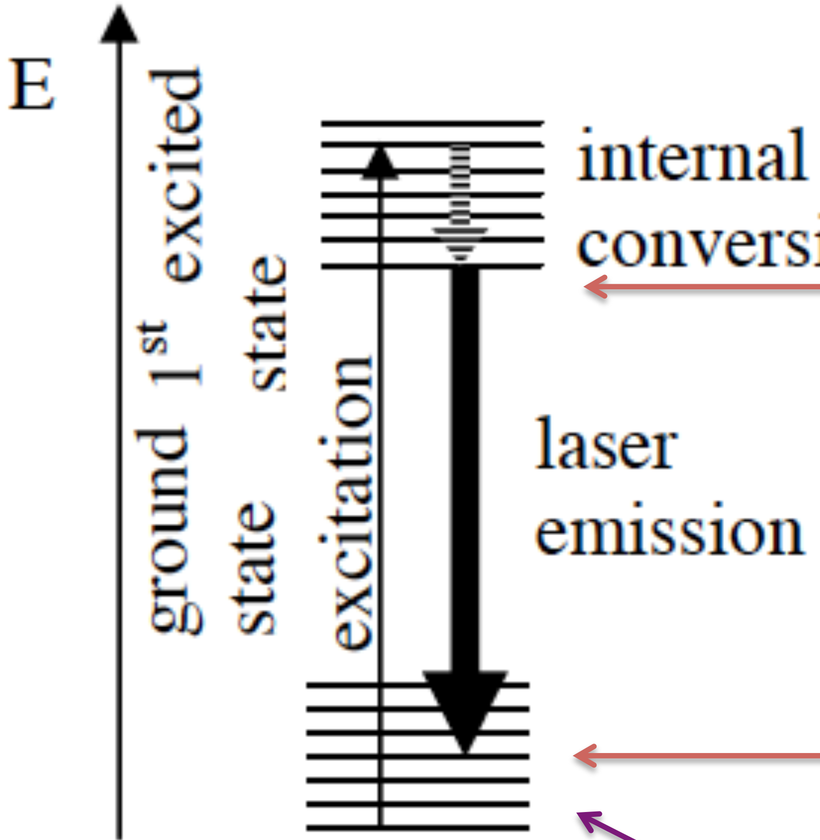
Liquids containing organic dyes such as Rhodamine 6g.





Continuously tunable over a range of 20 nm to 50 nm rather than just single wavelength.

LASERS



Many electrons in this state

Population Inversion

Few electrons in the state

Many levels the electron can fall back into. Broad wavelengh emission rather than a single line.

Concept Te$t

Which of the following is true of “normal” fluorescence (non-stimulated or spontaneous) light emission?

(A) Emitted photons are incoherent

(B) Emitted photons are highly collimated

(C) Emitted photons are higher in E than absorbed photons

(D) Both A and B are true

Waves emitted during fluorescence are not in phase with each other as they travel.

Concept Te$t

Which of the following statements represents an accurate comparison of 2-level vs. 3-level lasers?

(A) 2-level lasers require less power than 3-level lasers

(B) 2-level laser emission is more spectrally pure

(C) Both A and B are true

(D) 2-level lasers do not exist

Concept Te$t

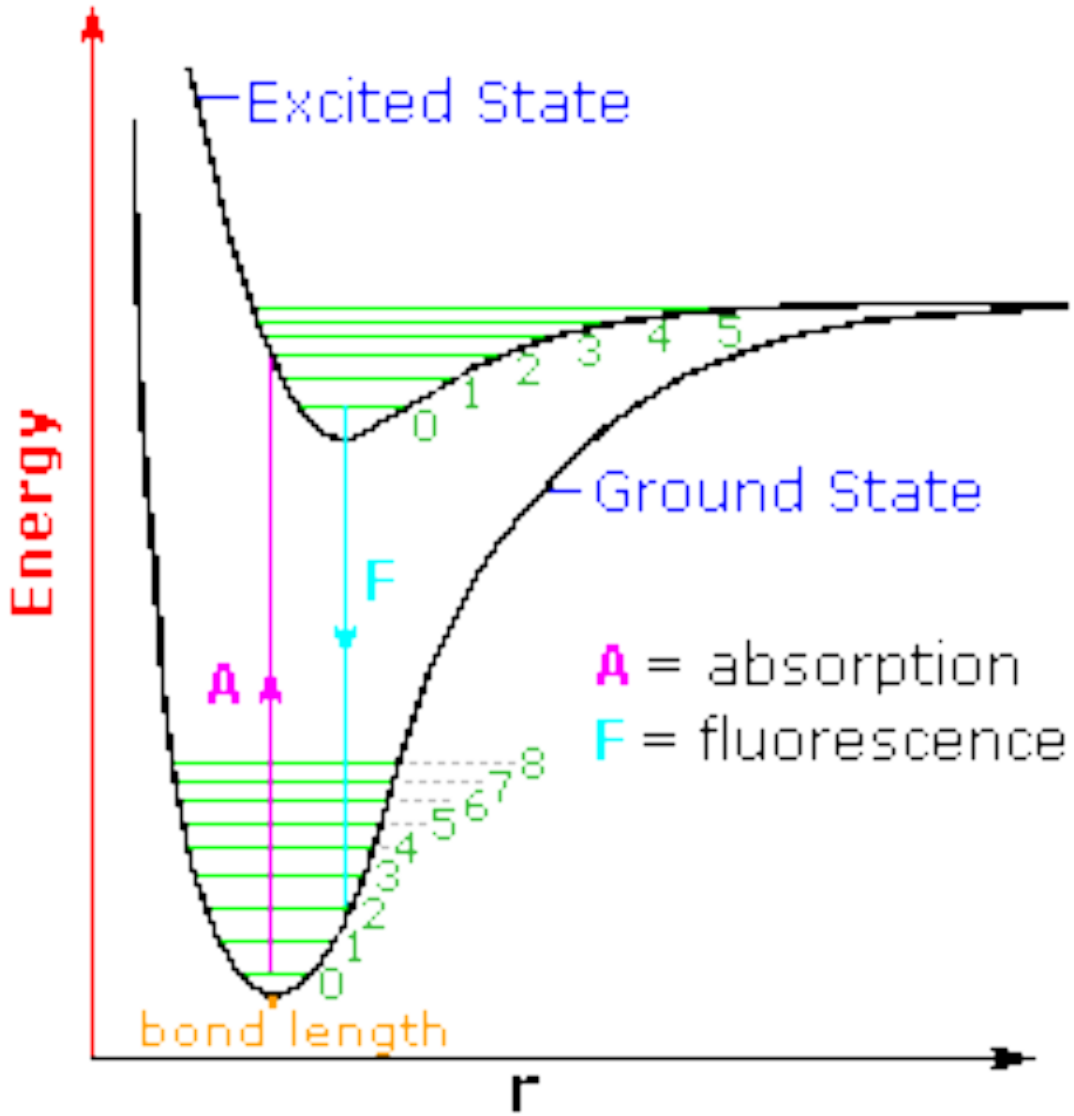
Dye Lasers emit over a broad wavelength range because

(A) Population inversion is easier to achieve in molecules compared to atoms or ions.

(B) The excited electronic state has many vibrational levels associated with it.

(C) Molecules have more electronic states than atoms or ions.

(D) The ground electronic state has many vibrational levels associated with it.

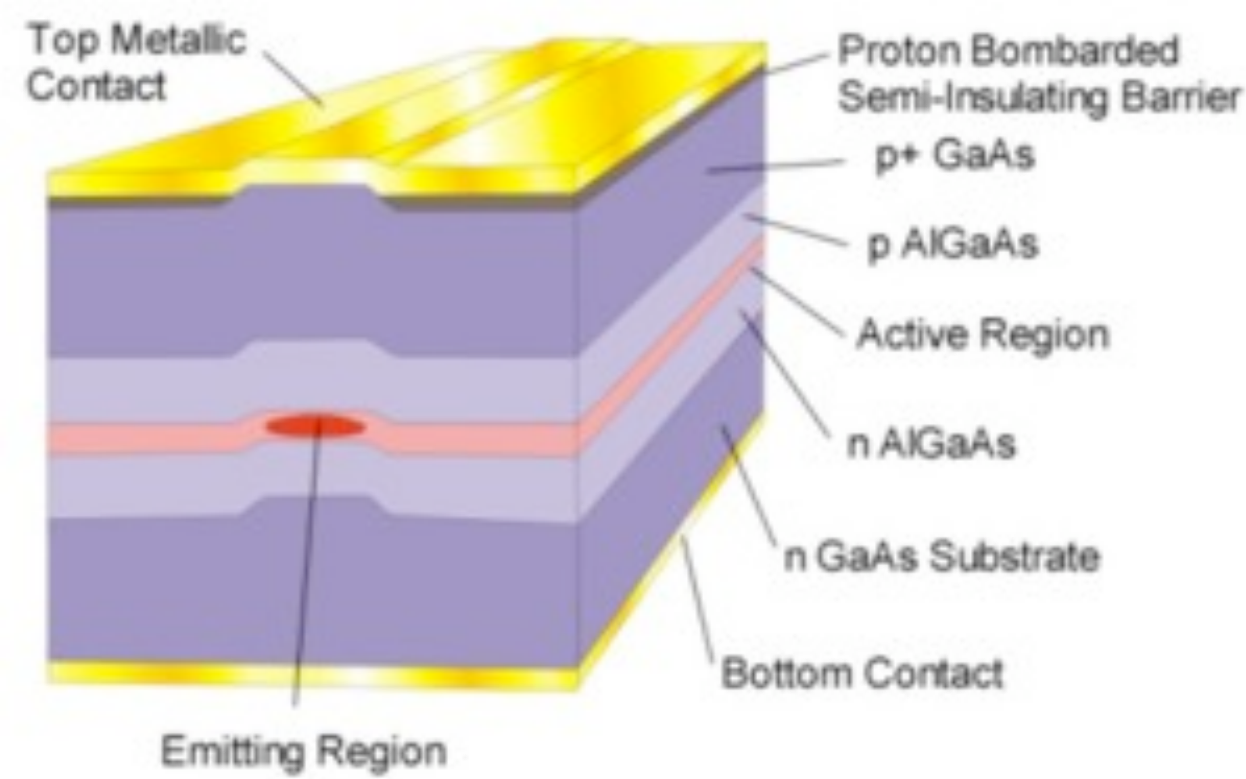


Excited State
0
1
2
3
4
5
Ground State
Energy
F
A
A = absorption
F = fluorescence
8
7
6
5
4
3
2
1
0
bond length
r

LASERS

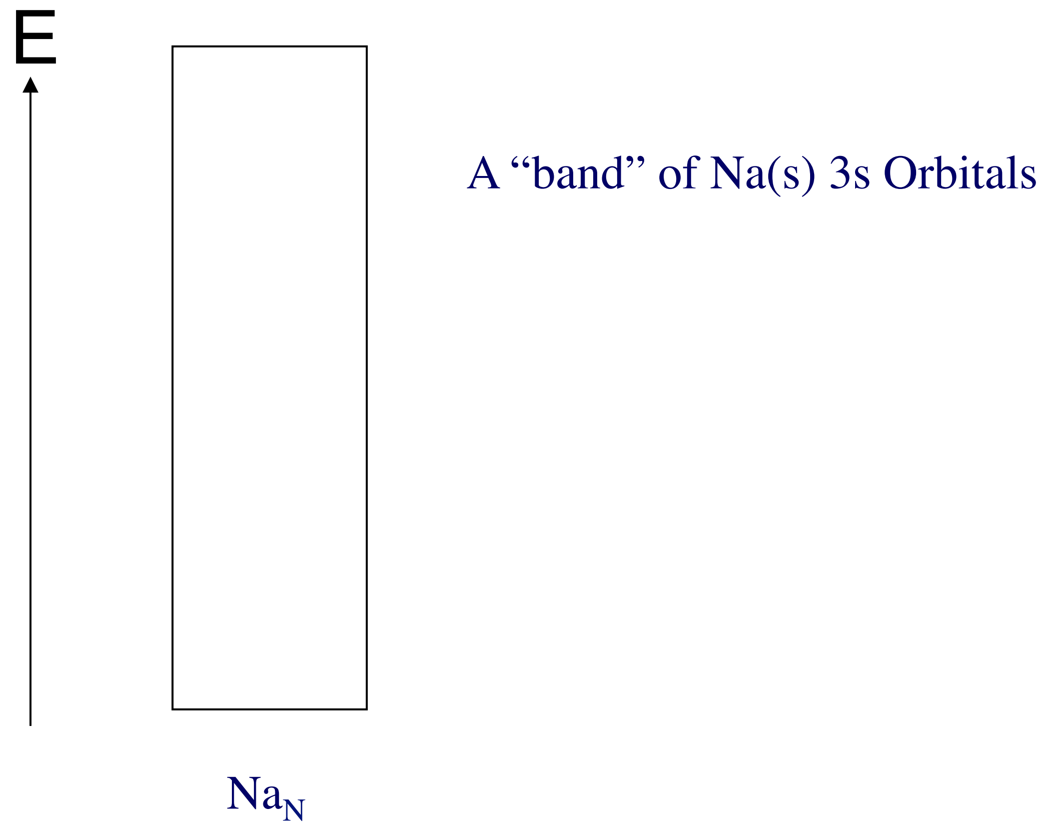
Semiconductor Lasers

p-n junction devices



Energy Bands in Solids

Atoms have atomic orbitals, molecules have molecular orbitals, so what do solids have?



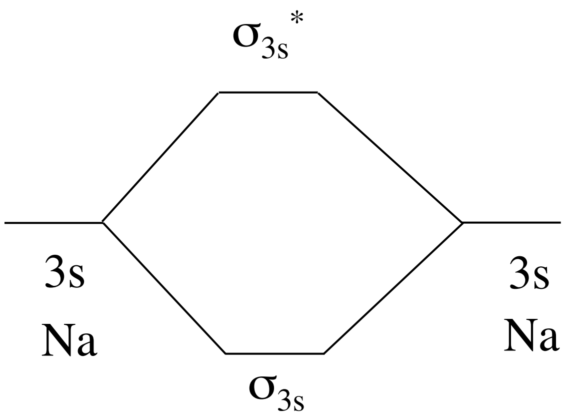
What does this mean and where did it come from?

From atoms to molecules to solids: Band Theory

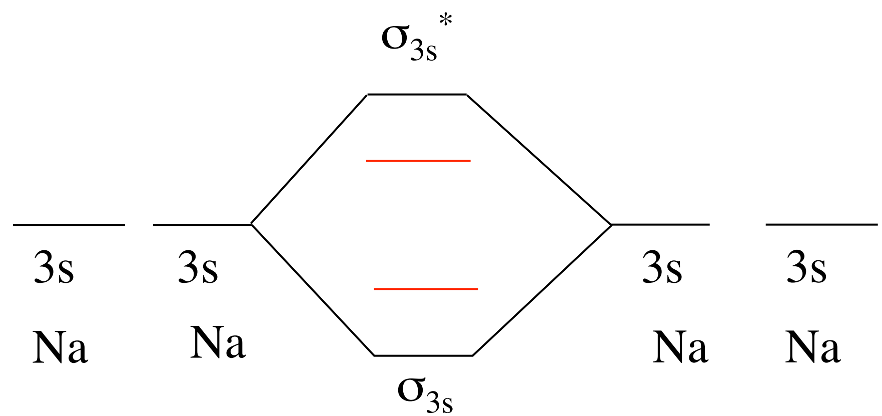
Band diagrams are energy level diagrams for solids.

What do the molecular orbitals of solids look like?

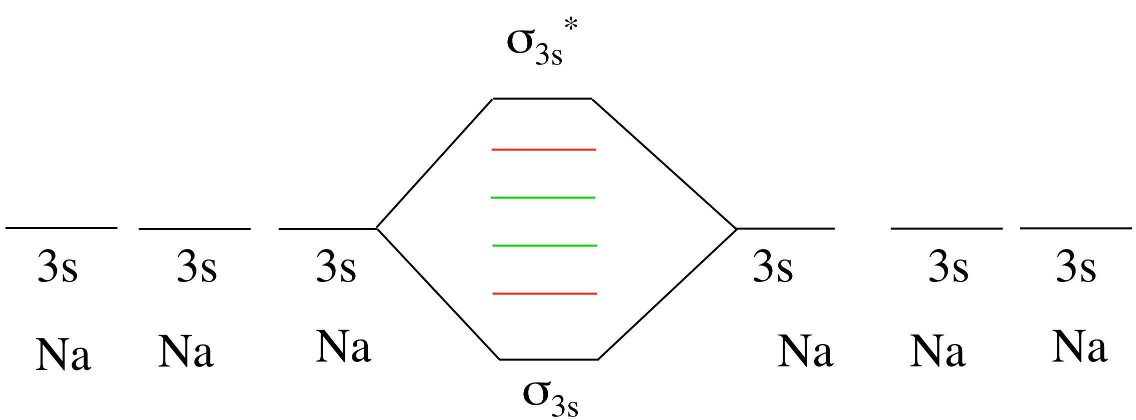
Let’s look at a hypothetical 1D chain of Na atoms.



Na_2

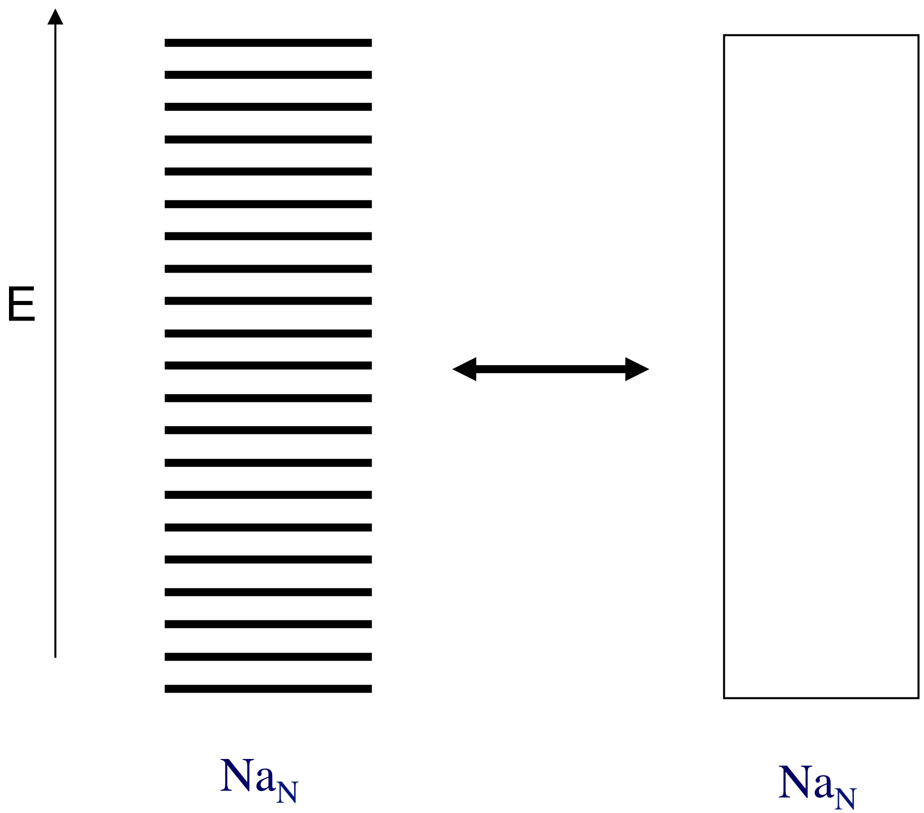


Na_4



Na_6

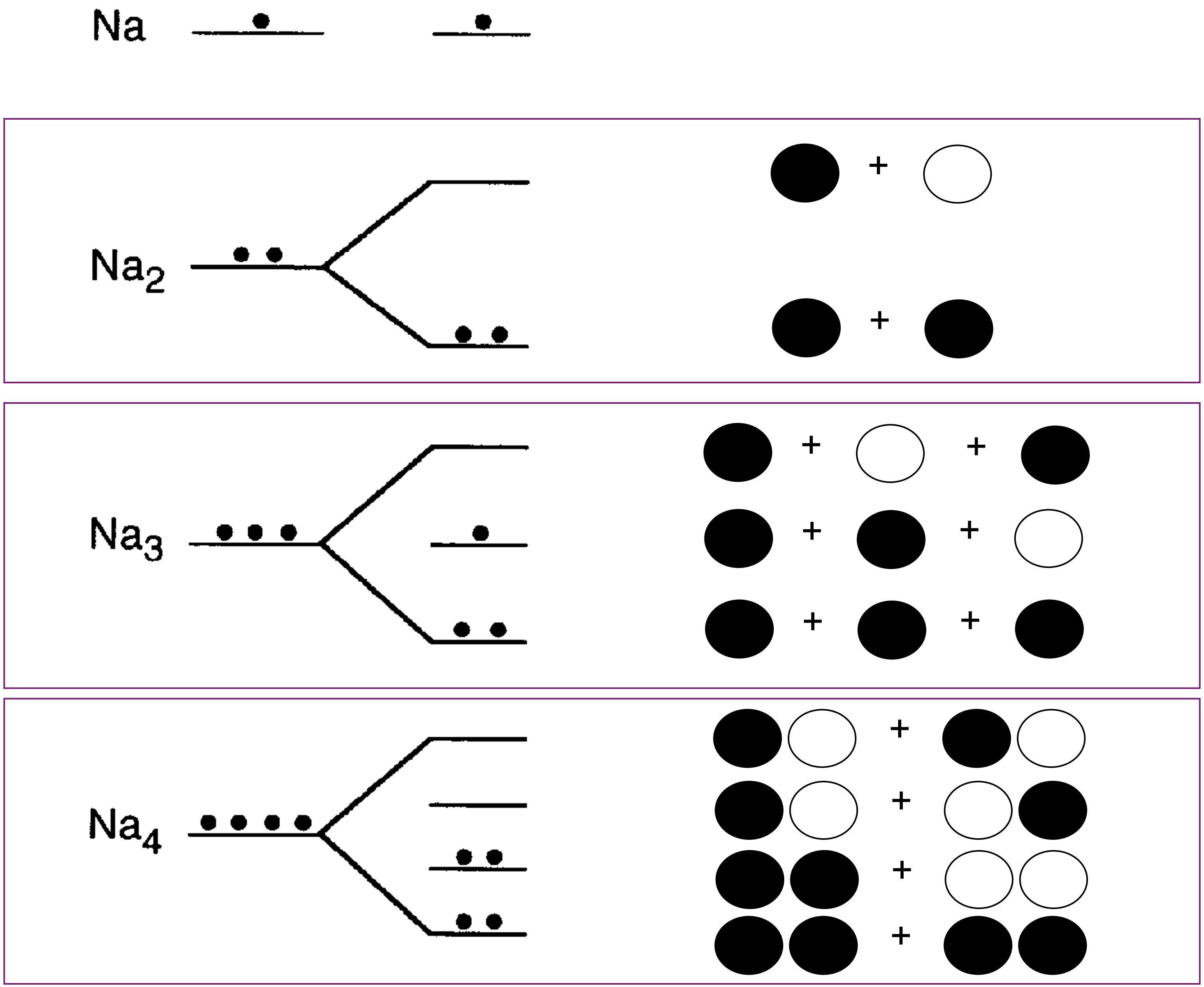
How About N Atoms?



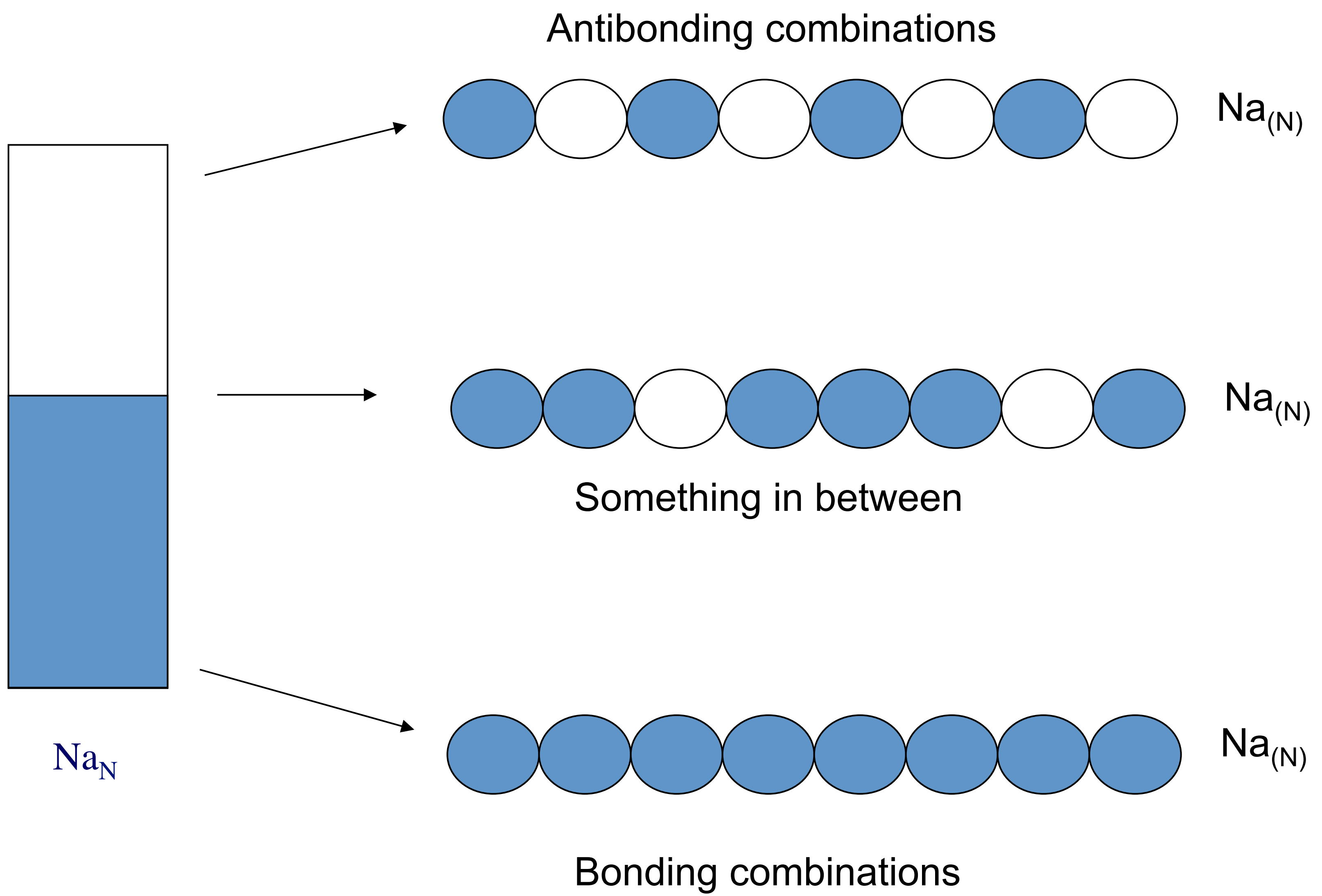
A "band" of Na(s) 3s Orbitals

A band consists of a large # of orbitals spaced so close in energy as to be indistinguishable from each other.

What do the LCAOs look like?

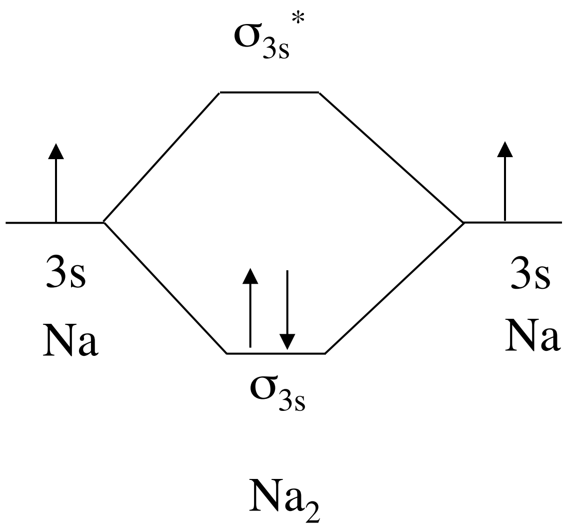


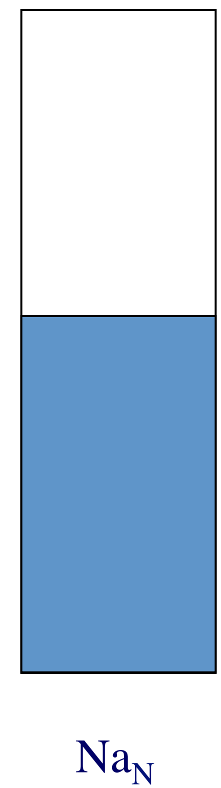
What do the orbitals of the band look like?



How Do We Fill the Band?

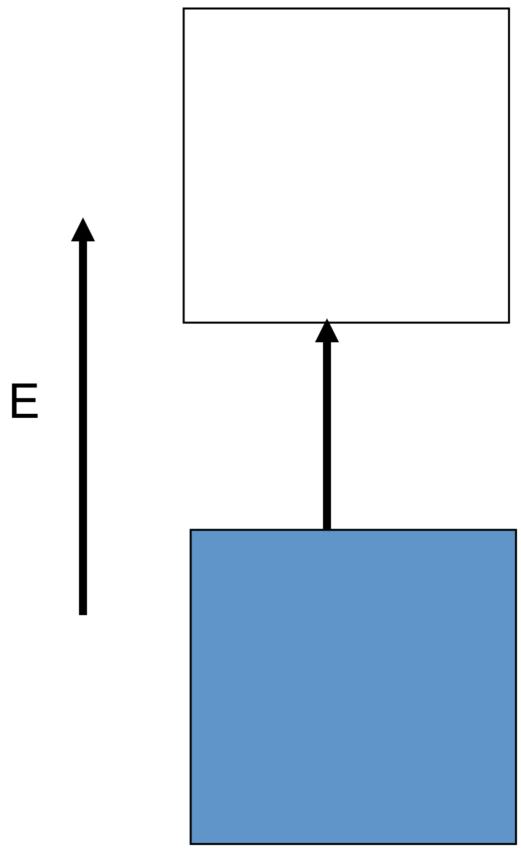
First consider how we would fill the simplest diatomic molecule





Note, this diagram is 1/2 filled........ → and so is the band diagram.

Solids have many bands, just like atoms and molecules have many orbitals.



Lowest Energy Empty Band at 0 K (Conduction Band)

Band gap (E_g): forbidden energies

Highest Energy Filled Band at 0 K (Valence Band)

What bands tell us: electronic properties of solids

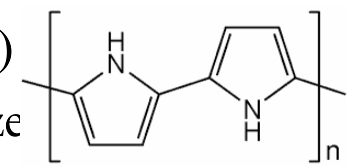
ohm^{-1} cm^{-1} 10^{-20} 10^{-16} 10^{-12} 10^{-8} 1 10^{4} 10^{6}

Quartz NaCl glass doped Si Fe, Cu

porcelain Si, Ge

poly(pyrrole)

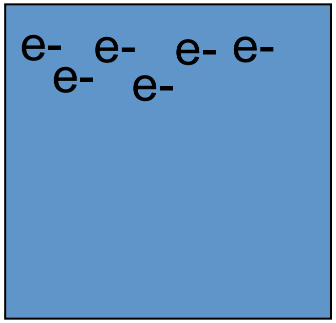
2001 Nobel Prize



Insulators Semiconductors Metals

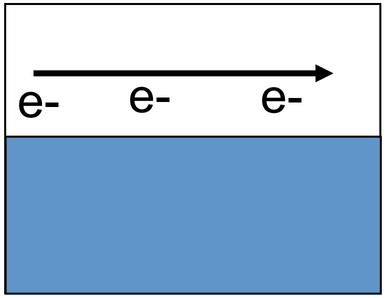
What are the rules for conductivity?

A filled band is like a filled freeway.

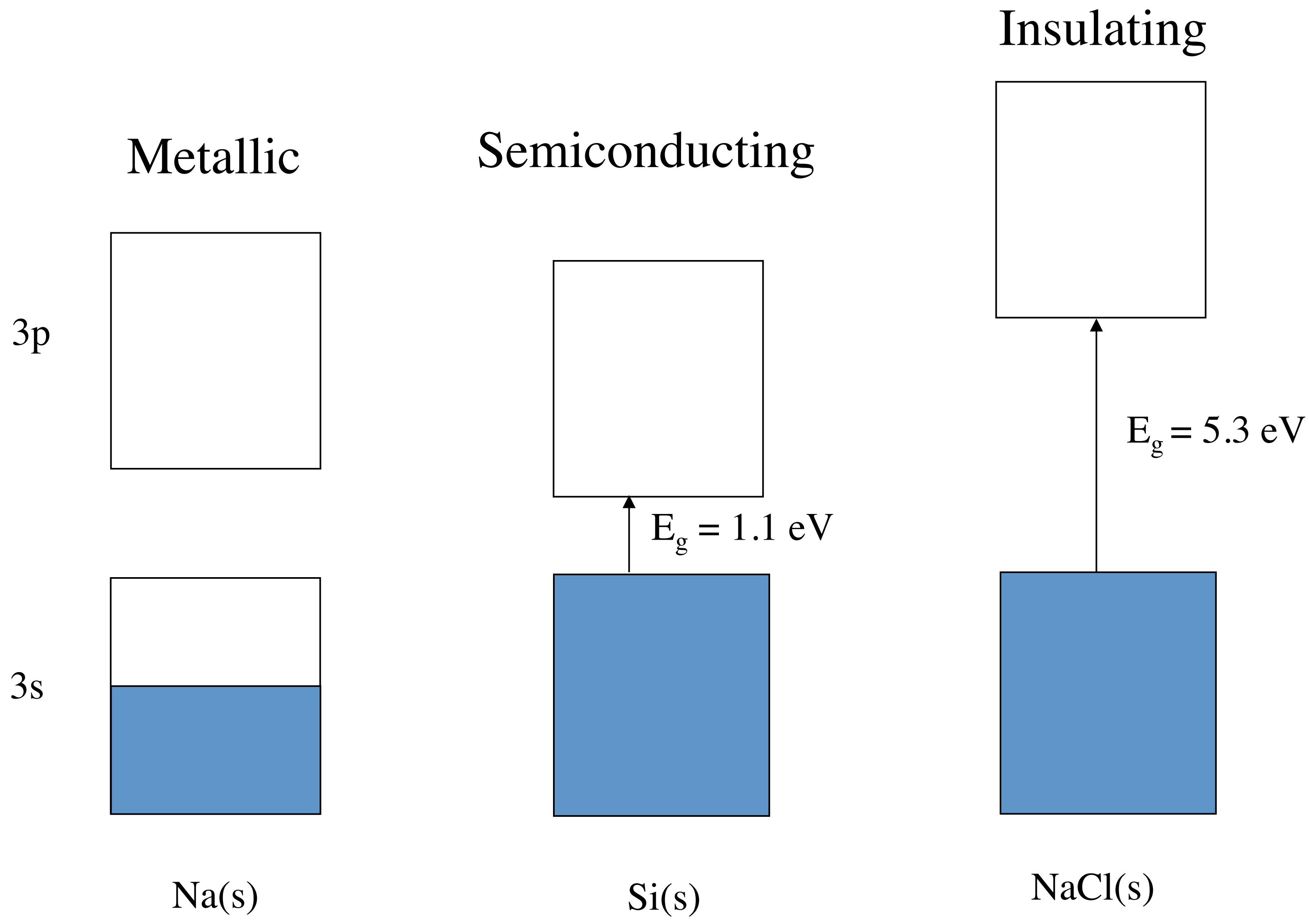


The electrons can't move!

A partially filled or empty band is like an empty freeway.

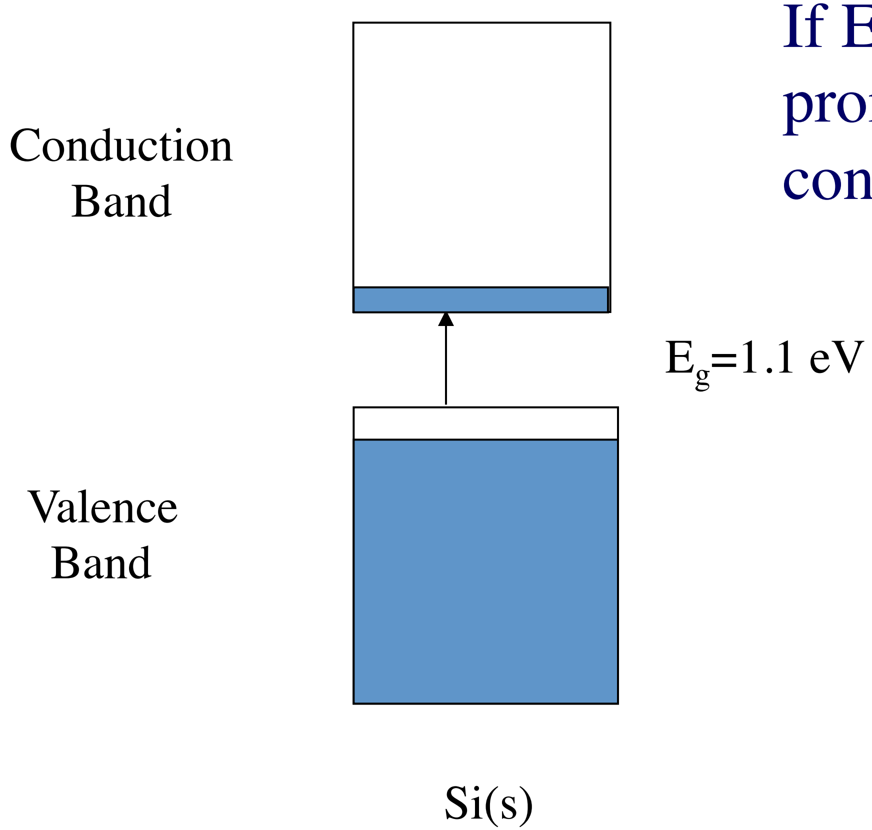


Electrons can move!



Note: 1 eV is a λ of 1240 nm (Near-Infrared)

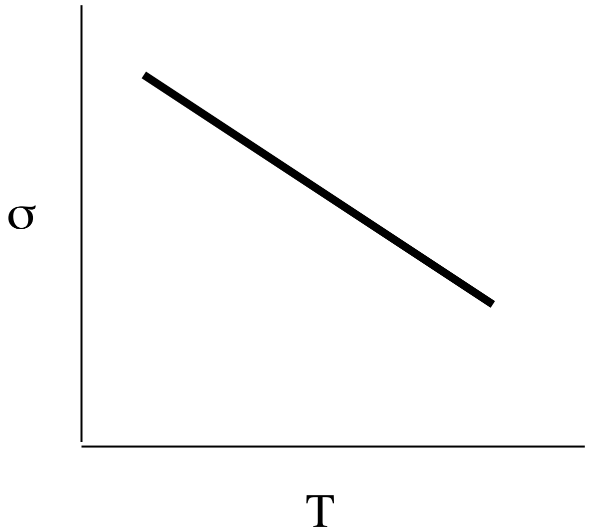
Semiconducting



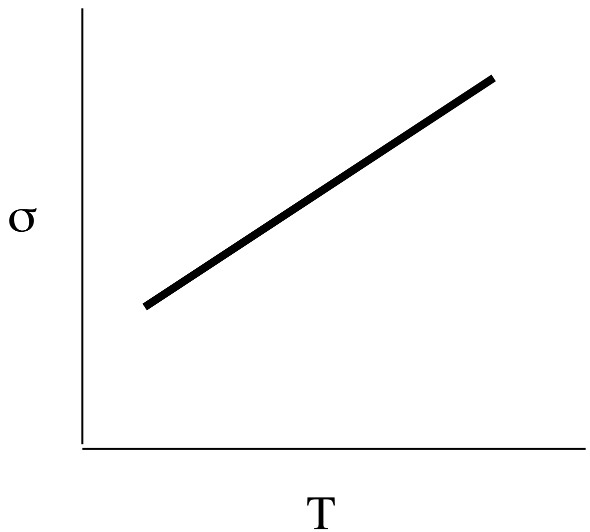
If E_g is small, heat or light will promote some electrons into the conduction band.

Temperature Dependence of Conductivity

σ = conductivity (Ω^{-1} cm^{-1})



Metals



Semiconductors

σ proportional to # of free charge carriers and how easily they can move through the crystal.

Concept Te$t

Why does the conductivity of metals decrease as T increases?

(A) As T increases the bandgap of metals increases.

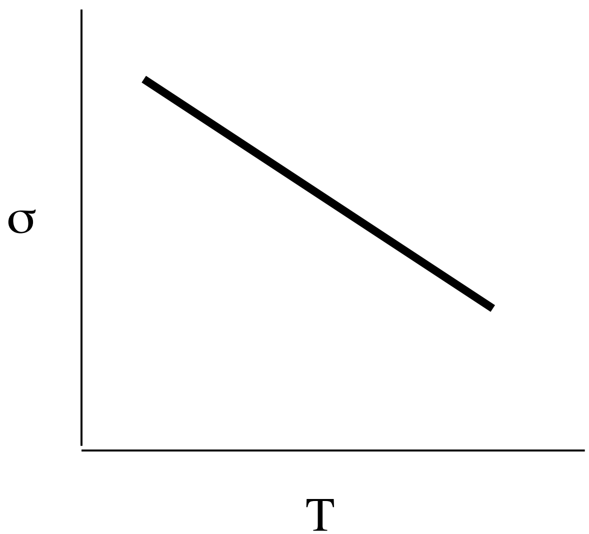
(B) As T increases the number of charge carriers decreases.

(C) As T increases the rate at which electrons can move through metals slows because of atomic vibrations.

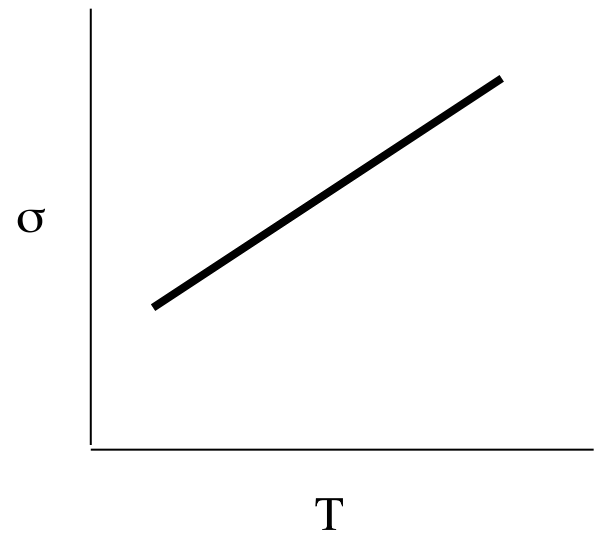
(D) A and B are true.

Temperature Dependence of Conductivity

σ = conductivity ($\Omega^{-1}\ cm^{-1}$)



Metals

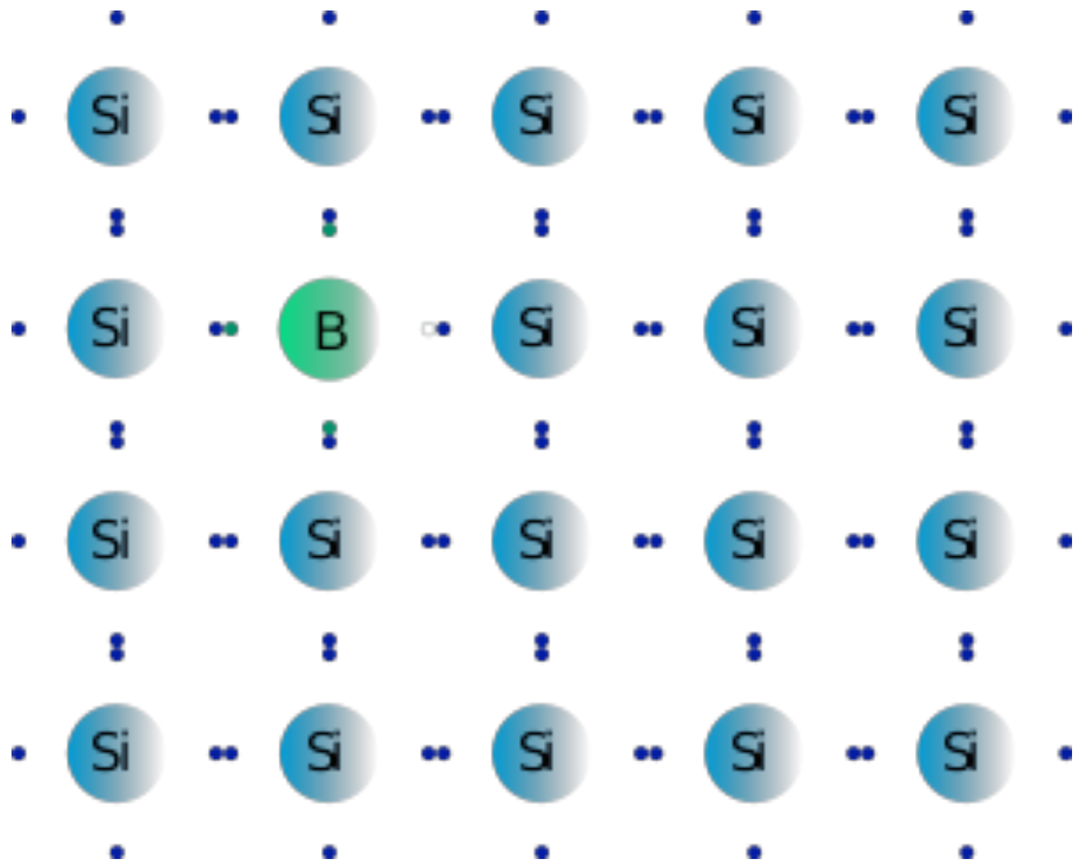


Semiconductors

Metals: Plenty of charge carriers already so increasing T doesn't help. Increasing T does make atoms vibrate more, which slows down the electrons as they try to travel through the crystal.

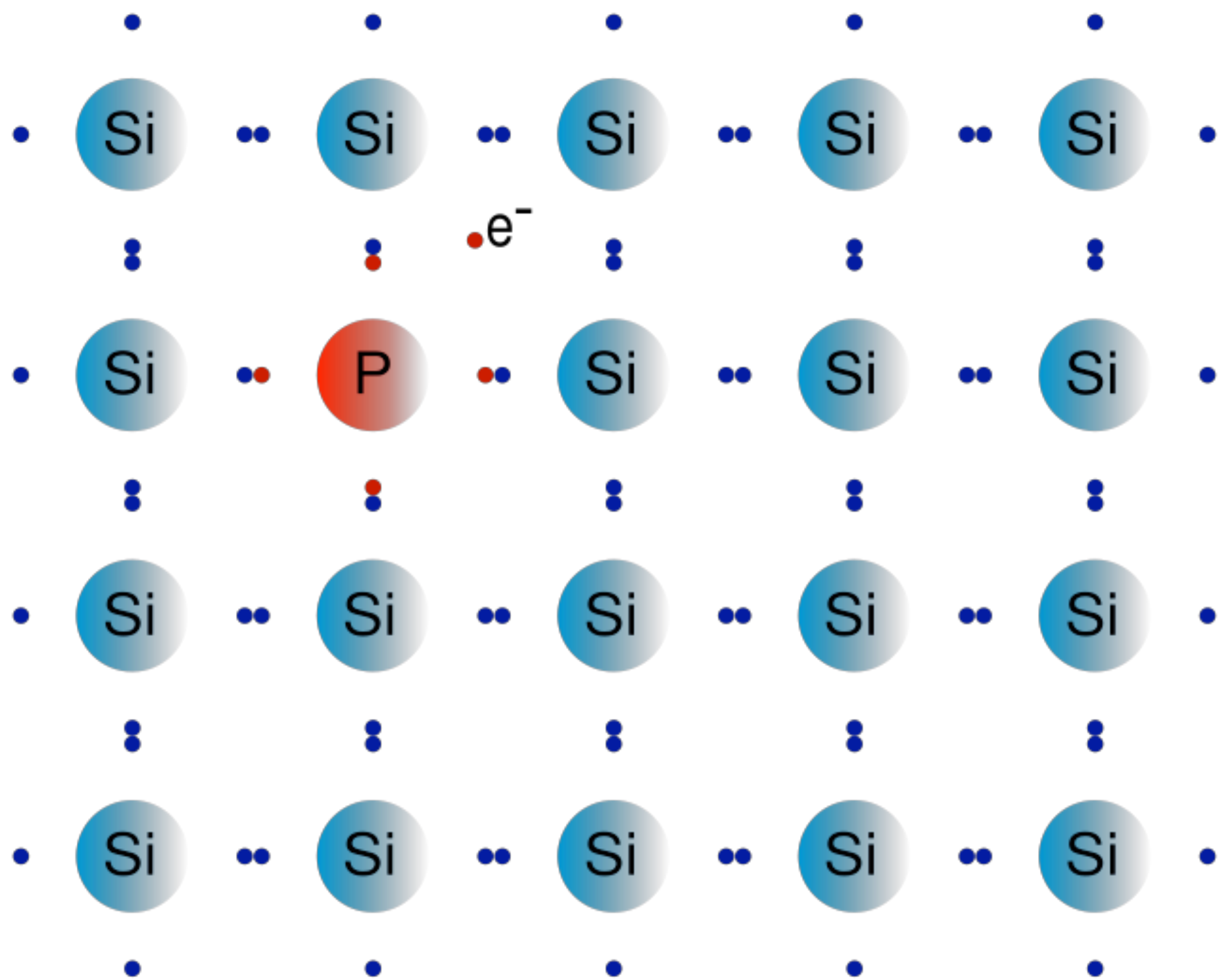
p and n doped Semiconductors

p doping: Addition of a small amount of atoms with fewer valence electrons



p and n doped Semiconductors

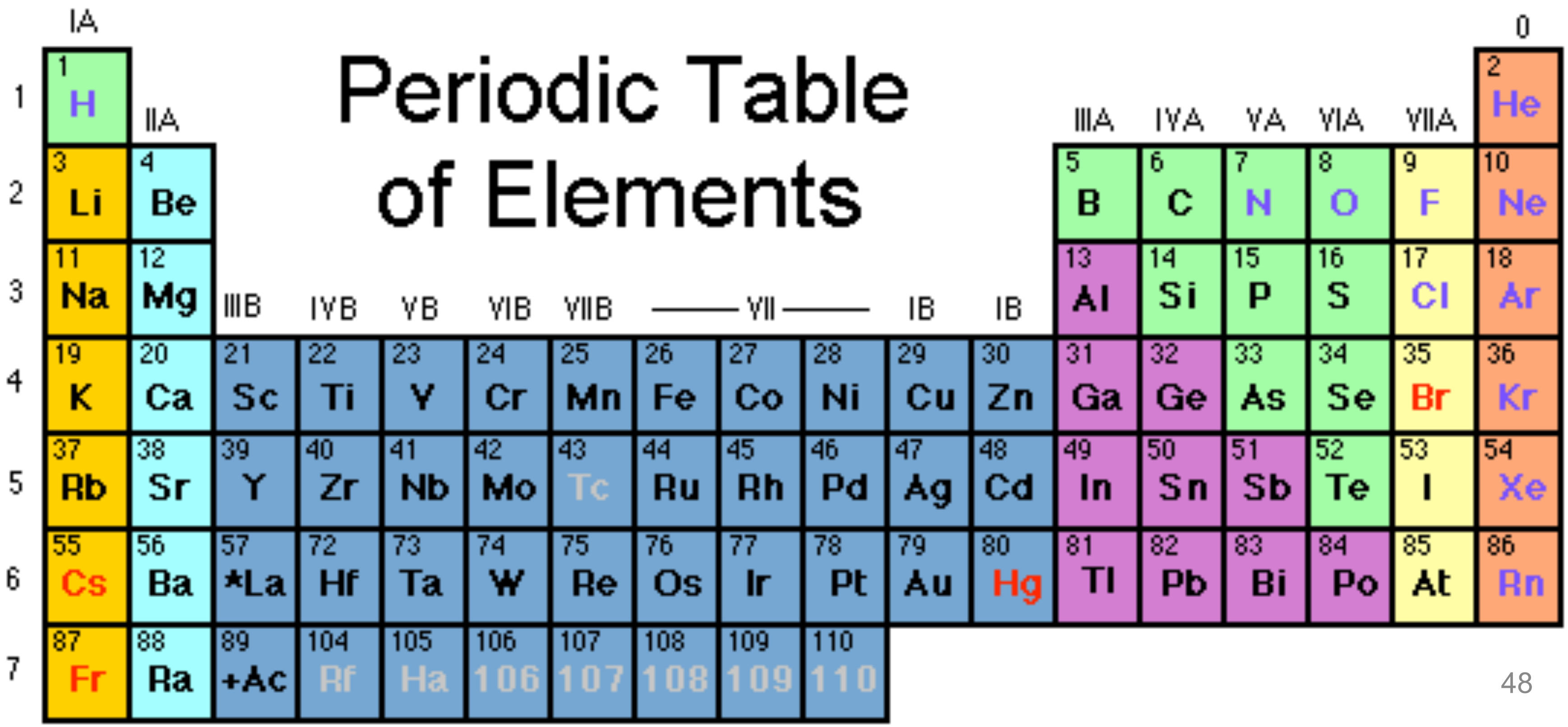
n doping: Addition of a small amount of atoms with more valence electrons



Concept Te$t

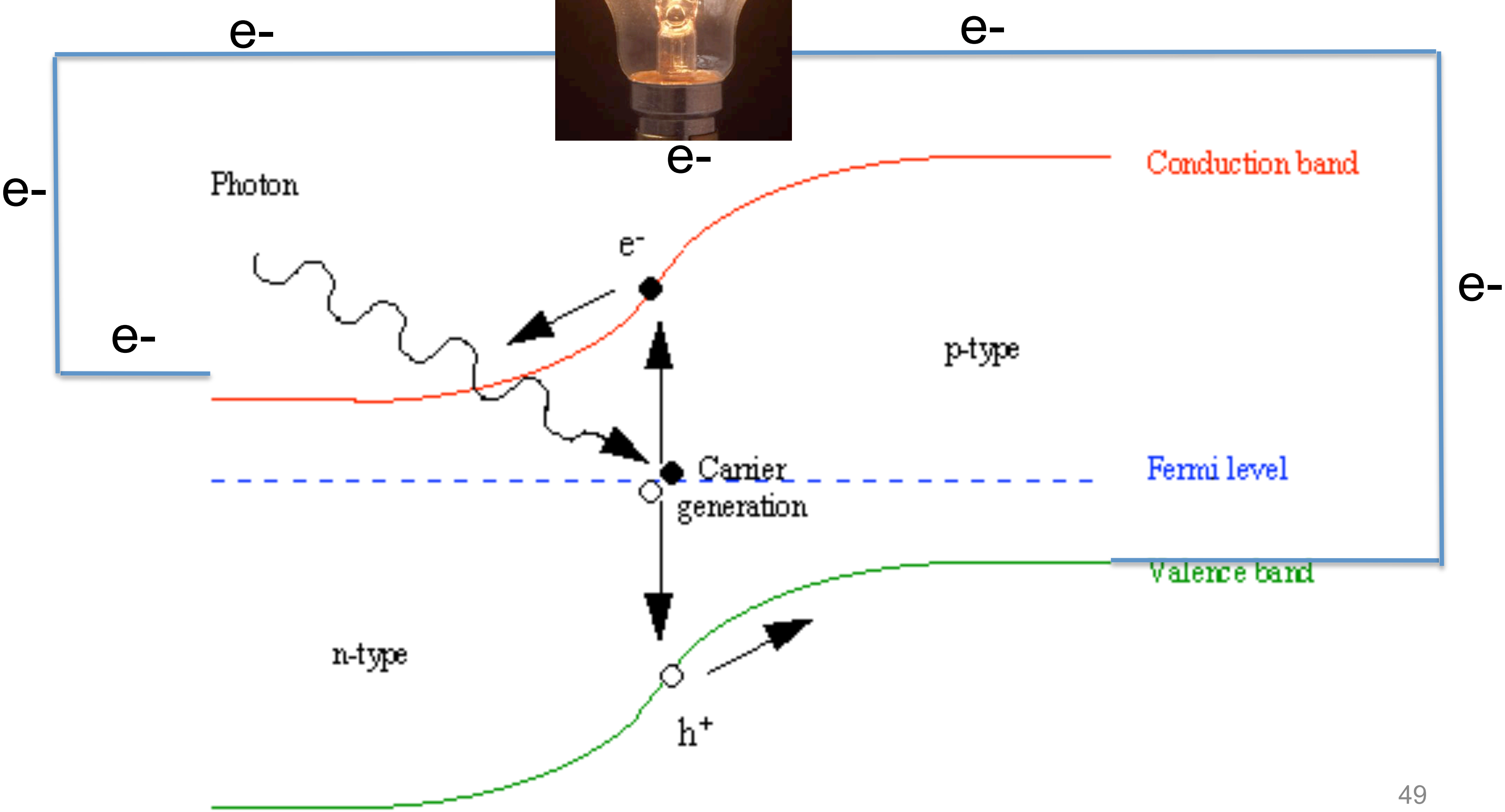
Which of the following would be a p type dopant for Si?

(A) P (B) Ge (C) Ga (D) F



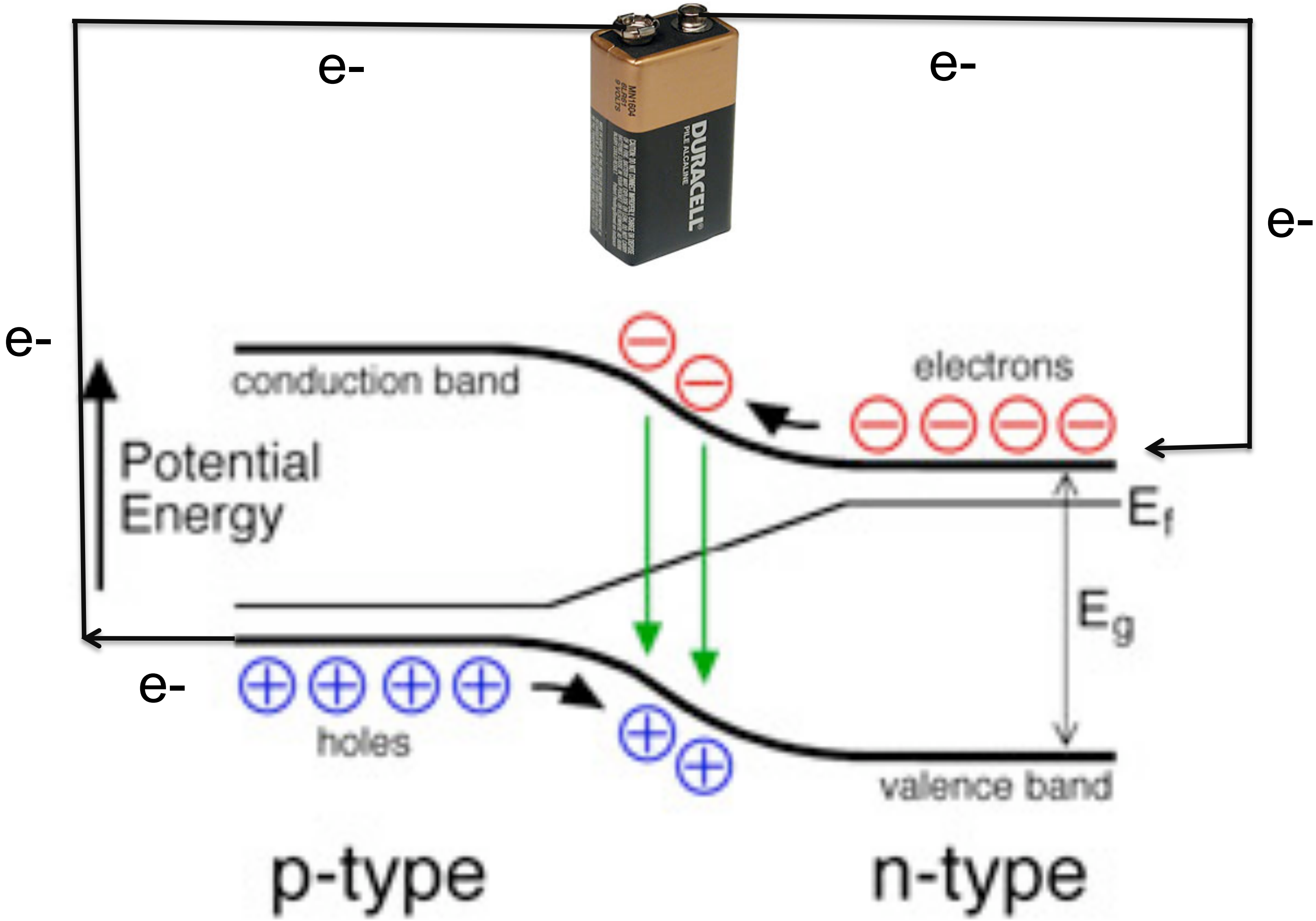
p-n Junction Solar Cells

When p and n doped materi… together, the bands at the edges bend. This results in a “gradient” of … s at the interface. A Si solar cell works because electrons excited b… ll down the energy hill and through a circuit.



p-n Junction Lasers

A diode or laser works in the opposite direction. A current is applied to inject electrons into the conduction band. When they relax back into the valence band light is emitted. This photon can cause stimulated emission and LASER light.



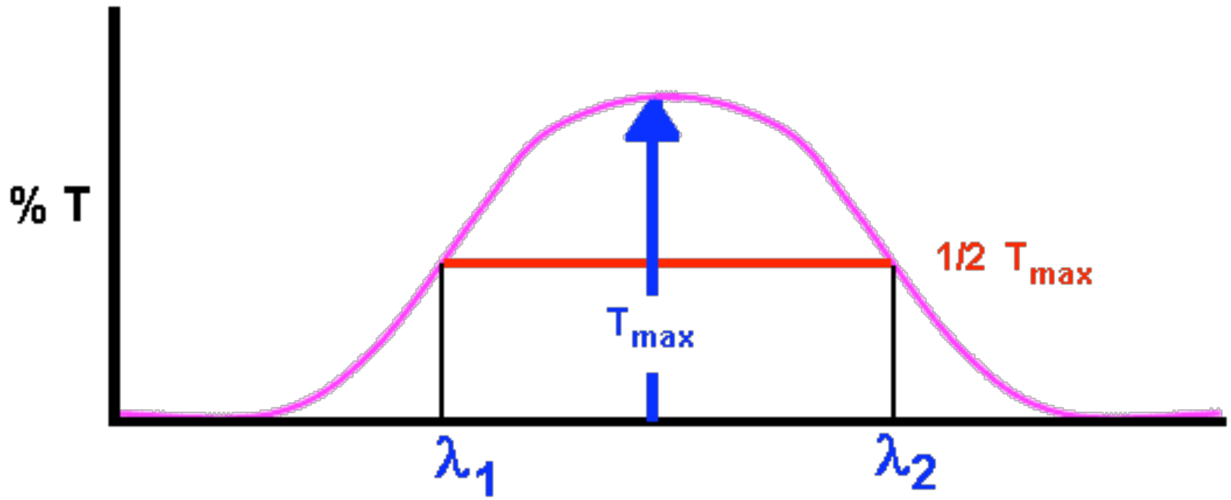
Let there be light! Now what?
Wavelength Selectors

Filters and Monochromators are used to select narrow bands of the light source for spectroscopic analysis.

Filters

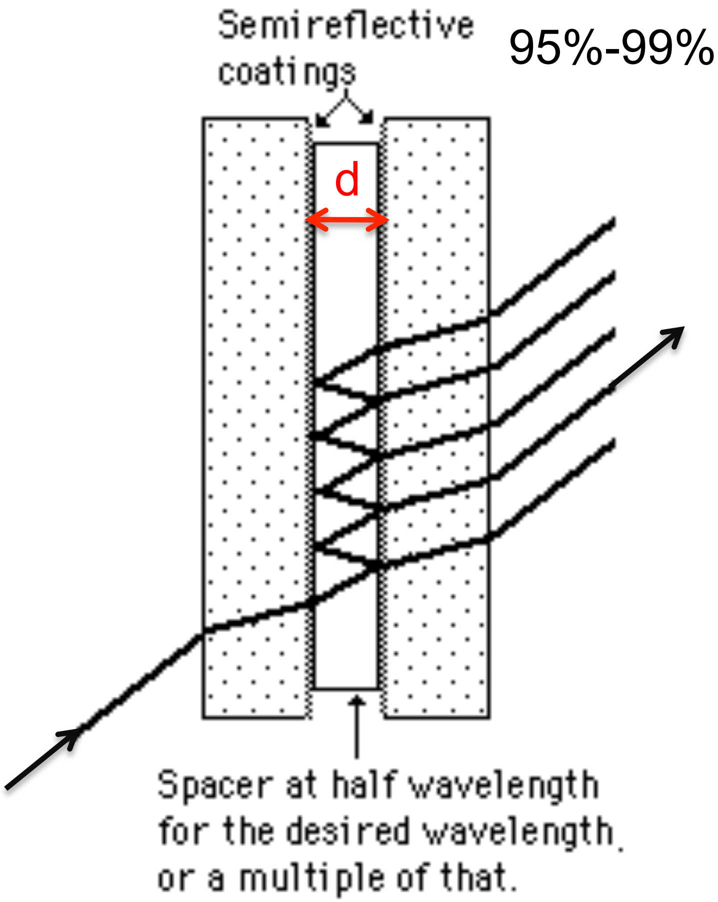
Interference-Allow narrow band widths to pass (~10 nm)

Absorption-Simple but with wider band widths (~50 nm)



effective bandwidth is between λ_1 and λ_2

Interference Filters



"Dielectric layer" (CaF_2) between two semitransparent metallic films and glass.

The light reflected off of the back metal layers interferes with light transmitted through the top metal layer. Thus, some wavelengths are destroyed while others are reinforced. The thickness and refractive index of the spacer determine the wavelengths that make it through the filter.

If the back metal layer is totally reflective, the filter is called a dichroic filter.

The wavelengths that are reinforced: $\lambda = 2d\mathit{n}/(\mathbf{n}\cos\theta)$

For light incident at 90^0: $\lambda = 2d\mathit{n}/\mathbf{n}$

n is refractive index
n is the order of interference; an integer

The glass can be selected to absorb all but one of the orders.

Interference Filters

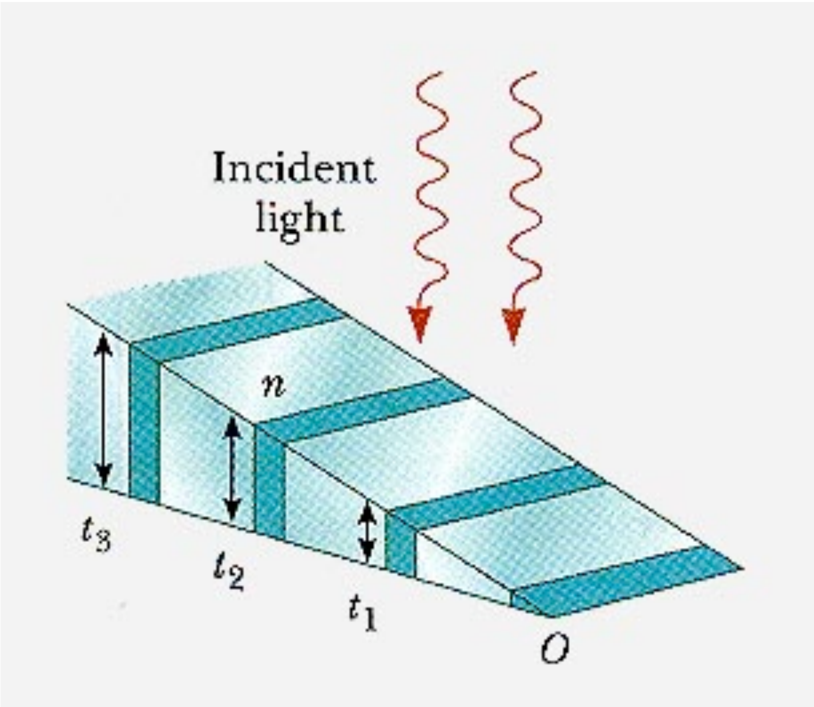
The incident angle can be adjusted to isolate different wavelengths.

http://en.wikipedia.org/wiki/Interference_filter

Interference Filters

Given $\lambda = 2dn/(\mathbf{n}\cos\theta)$

Suggest another single device capable of selecting wavelengths across the visible spectrum.



An interference wedge: Same design but with a gradient of thickness. As light is rastered across the wedge different wavelength bands emerge.

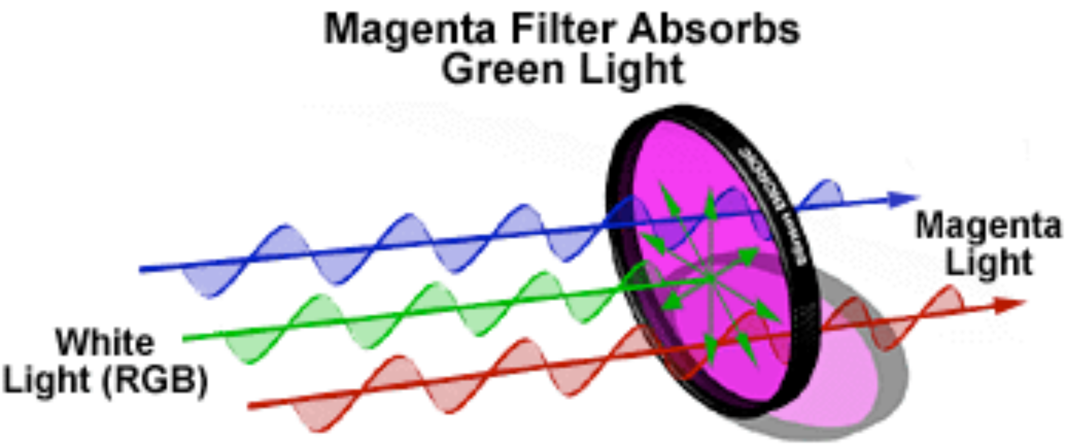
Absorption Filters

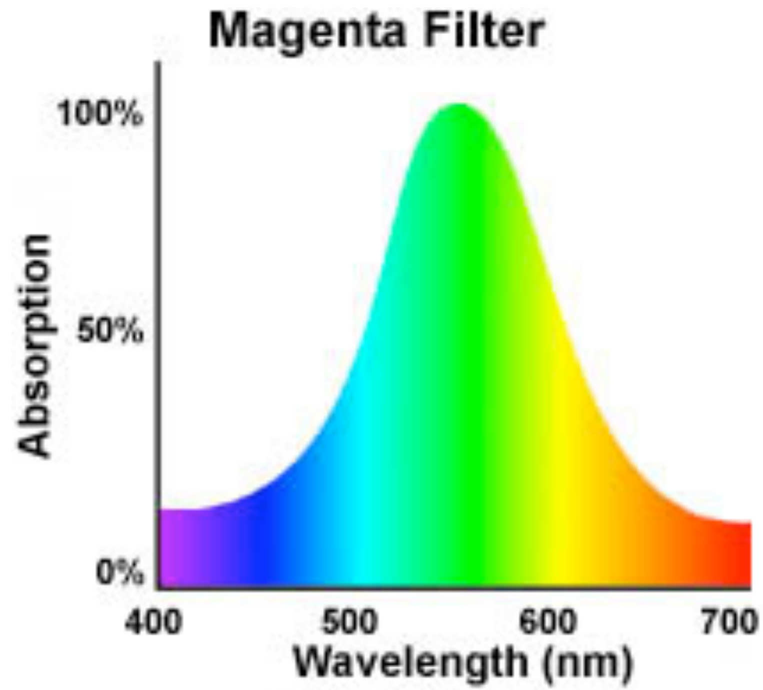
Absorption filters contain dyes that absorb light of specific wavelength ranges. They are commonly made out of glass, polycarbonate, or gelatin.

Generally less expensive than interference filters.

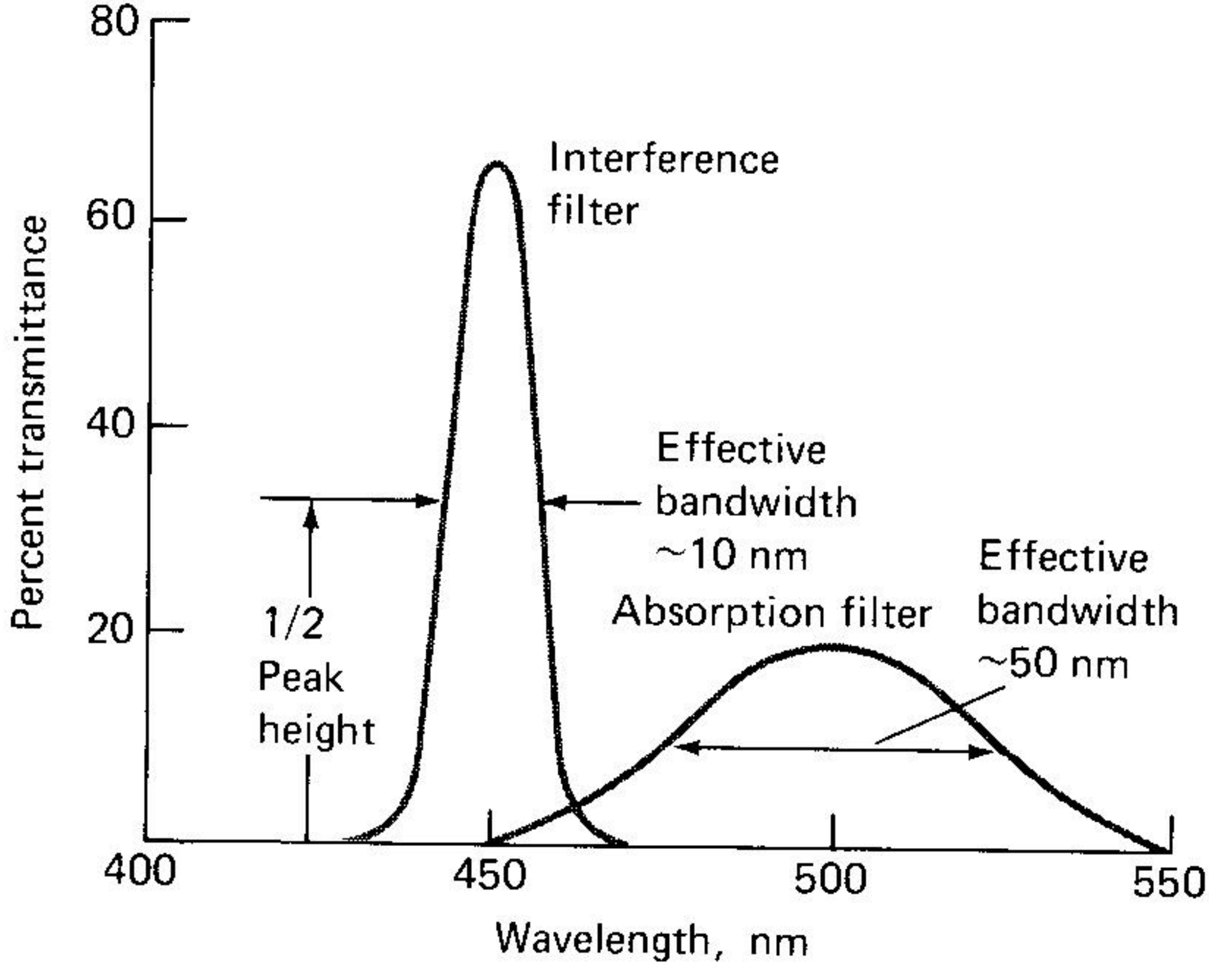
Absorption Filters

Band Filters-Absorb a band of wavelengths 50 nm – 250 nm wide.

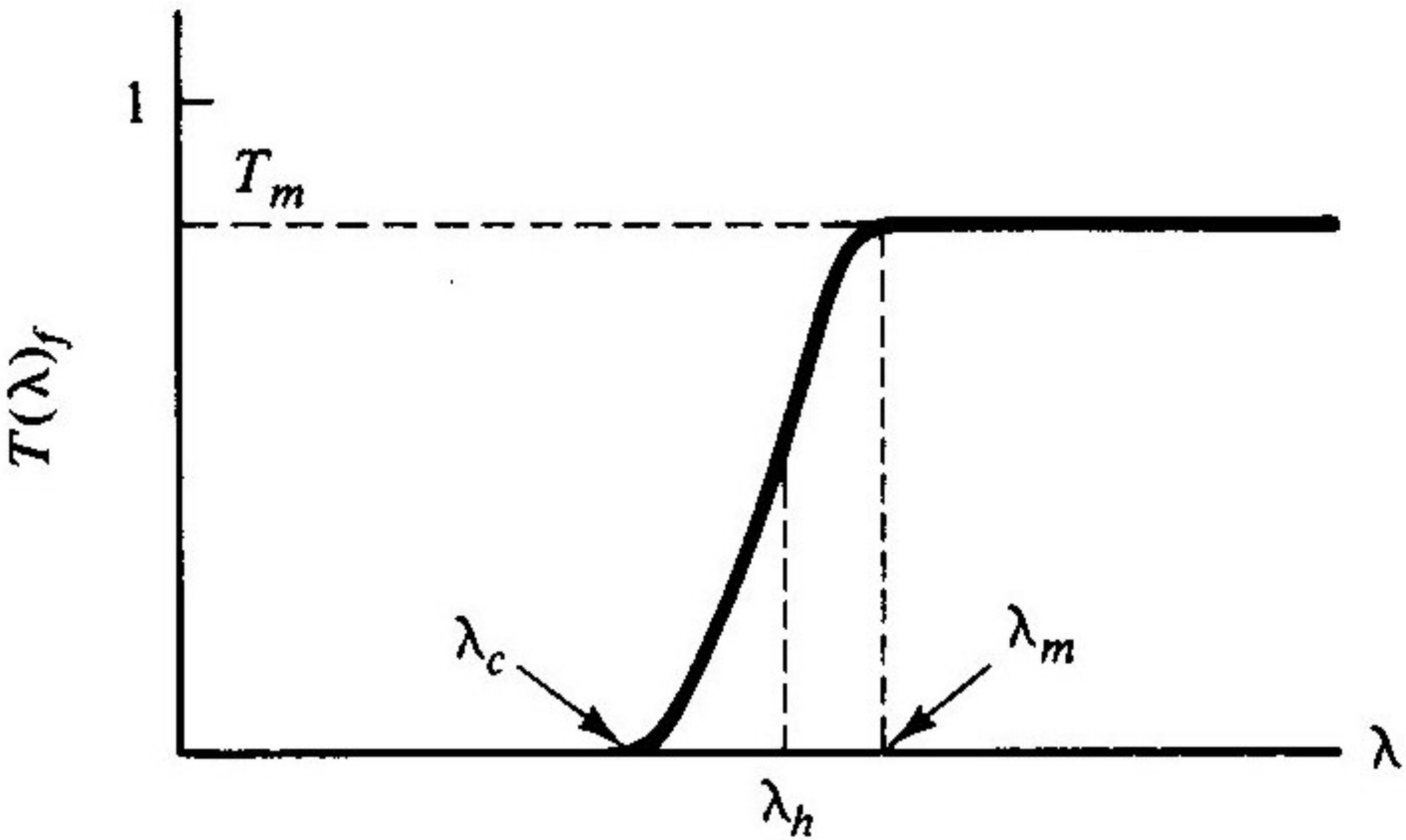




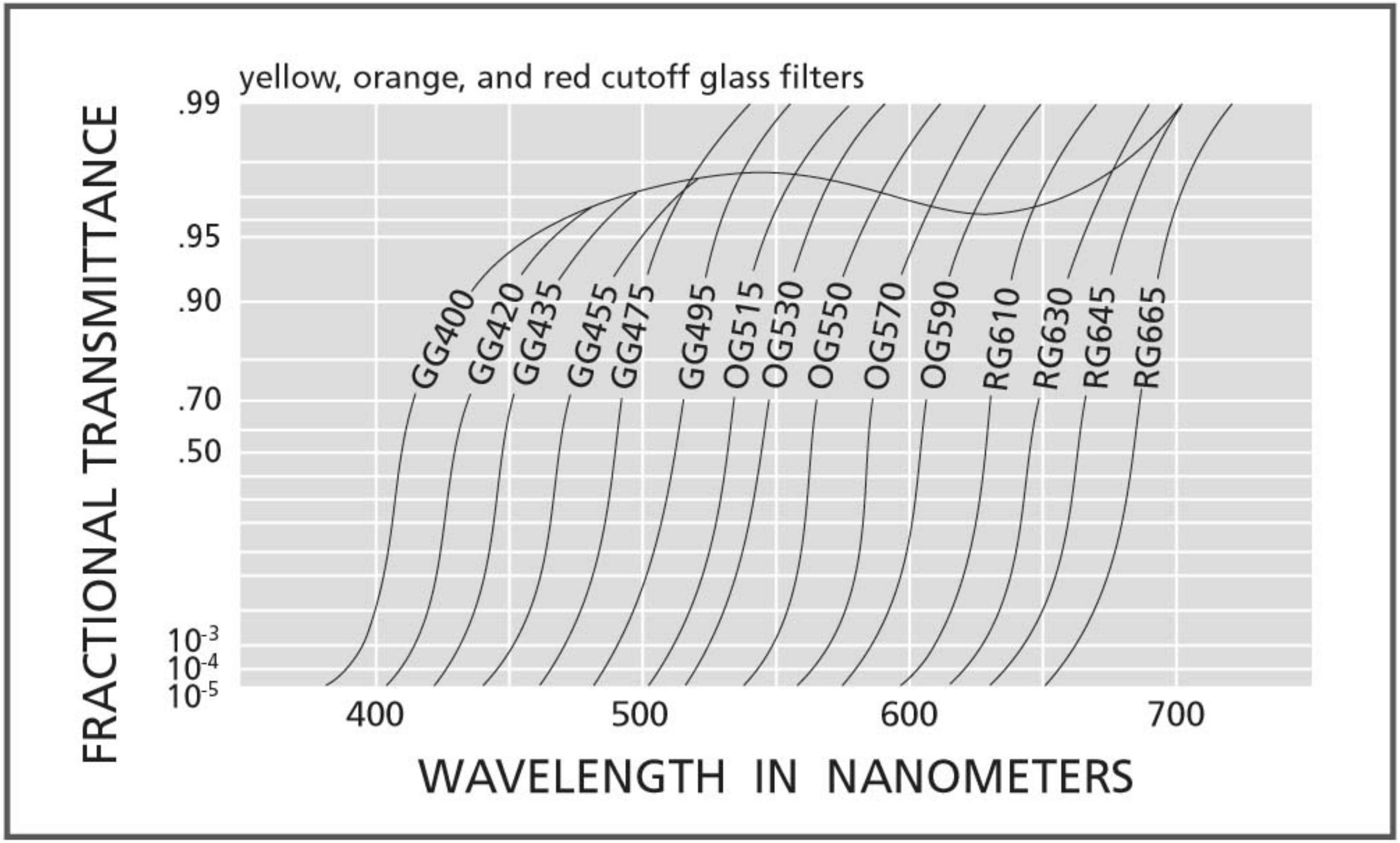
Band Widths of Interference and Absorption Filters



Cutoff Filters-Transmittances of nearly 100% over a portion of the spectrum but then rapidly decrease to zero %T over the remainder of the spectrum.



Available with cutoffs across the visible spectrum.



Typical internal transmittance curves for 3.0-mm glass thickness

Melles Griot Catalogue

Monochromators

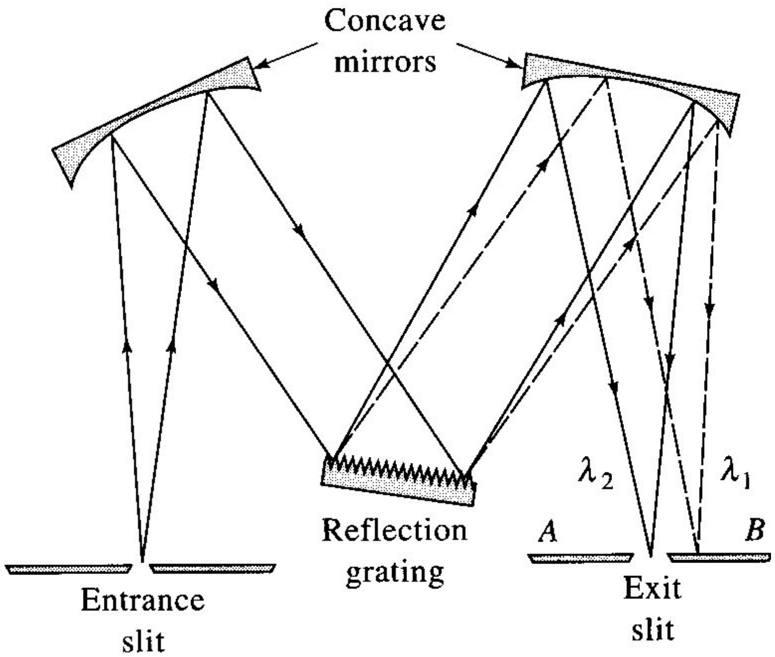
Gratings

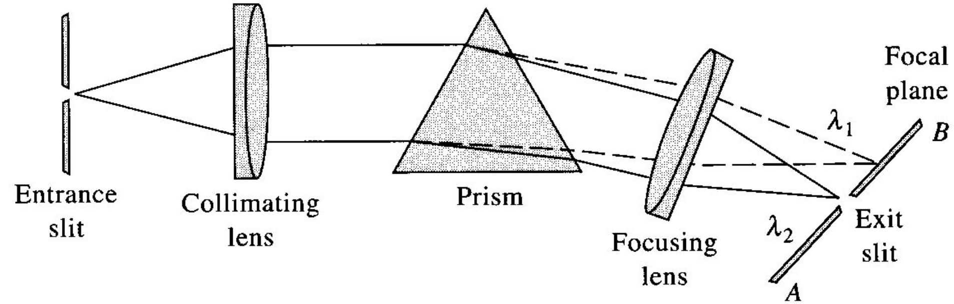
Prisms

Interferometers

Monochromators

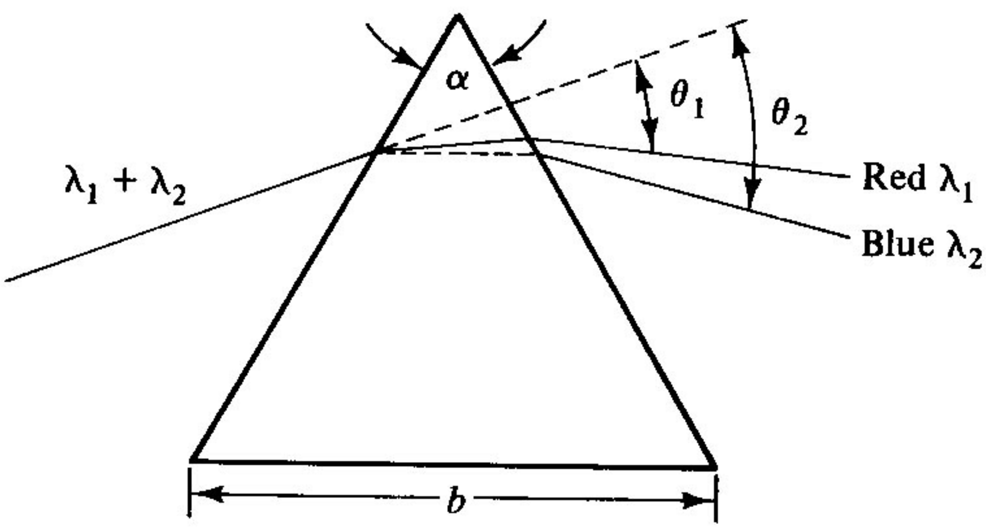
Gratings and Prisms separate wavelengths physically in space, and slits are used to select desired wavelengths.





Monochromators

- First type of widely used, "scanning" wavelength selection devices (TURN PRISM)
- Often made of salts such as sodium chloride, fluorites etc.
- VERY delicate. Often subject to damage in humidity and wide heat ranges.
- Not widely used today in spectroscopy equipment.

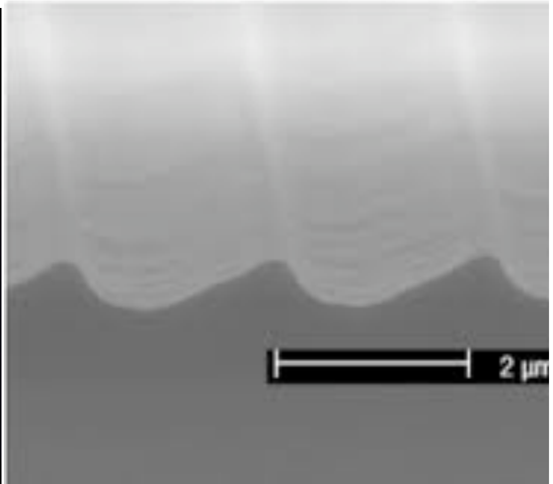


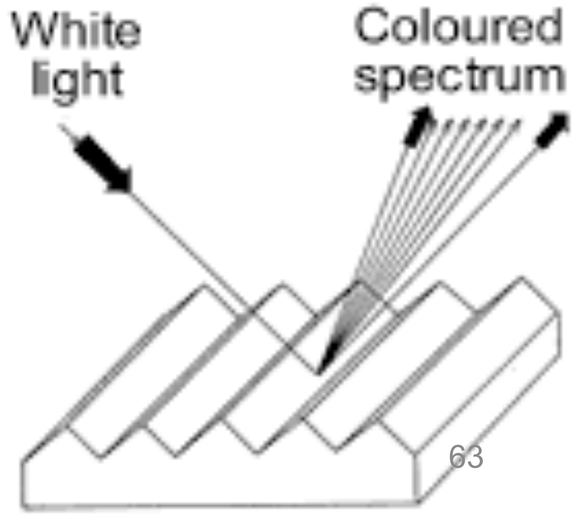
Monochromators

Gratings

Transmission: Contain large # of closely spaced slits.

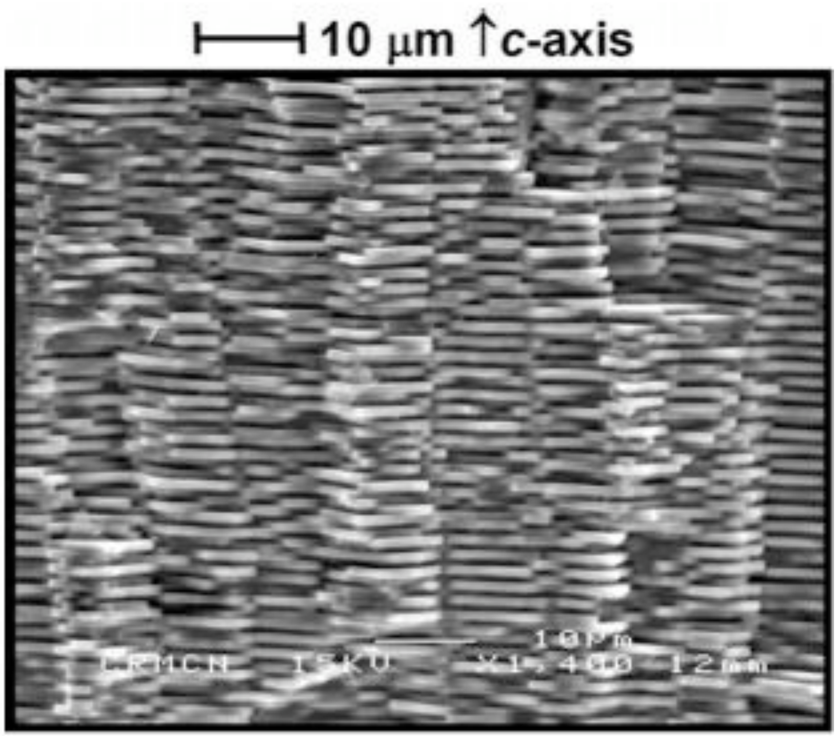
Reflection: Contain grooves (blazes) that reflect incident light. The reflected light is dispersed much like in a prism (although via a very different mechanism).





Gratings

Do you own anything that functions as a grating?



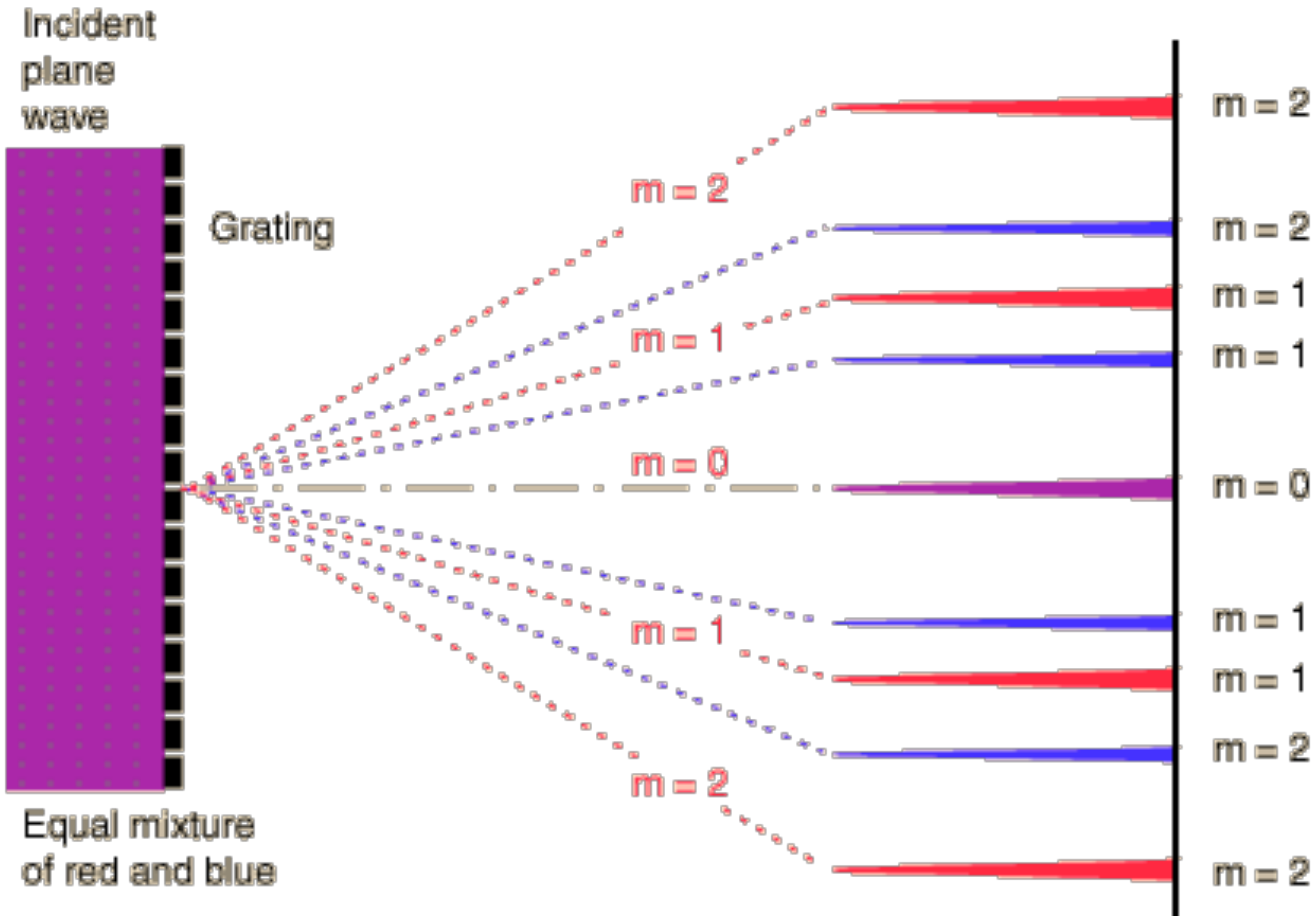
Transmission Gratings

How do they work?

Monochromatic radiation is separated on either side of incident beam because of diffraction.

Transmission Gratings

Different wavelengths are diffracted at different angles.



(Note that m and n are used interchangeably for the diffraction order.)

Transmission Gratings

Displacement y = Order m x Wavelength x focal length/Line Separation

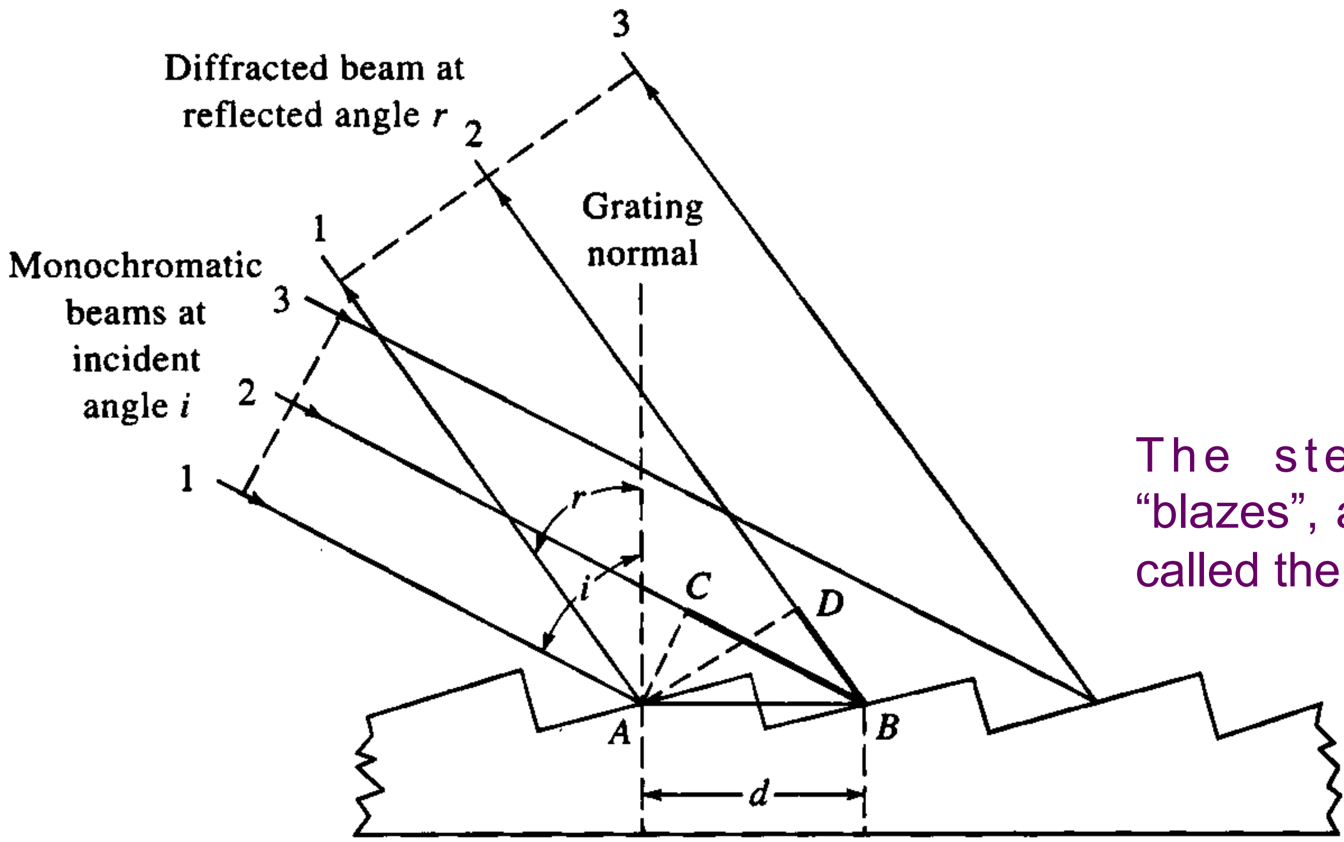
$$y = \frac{m\lambda f}{d}$$

Example: For a diffraction grating with 800 lines/mm, the line separation is 1.25 um.

Incident light of 632.8 nm projected on a screen 100 cm away will have a displacement for m=1 of 50 cm.

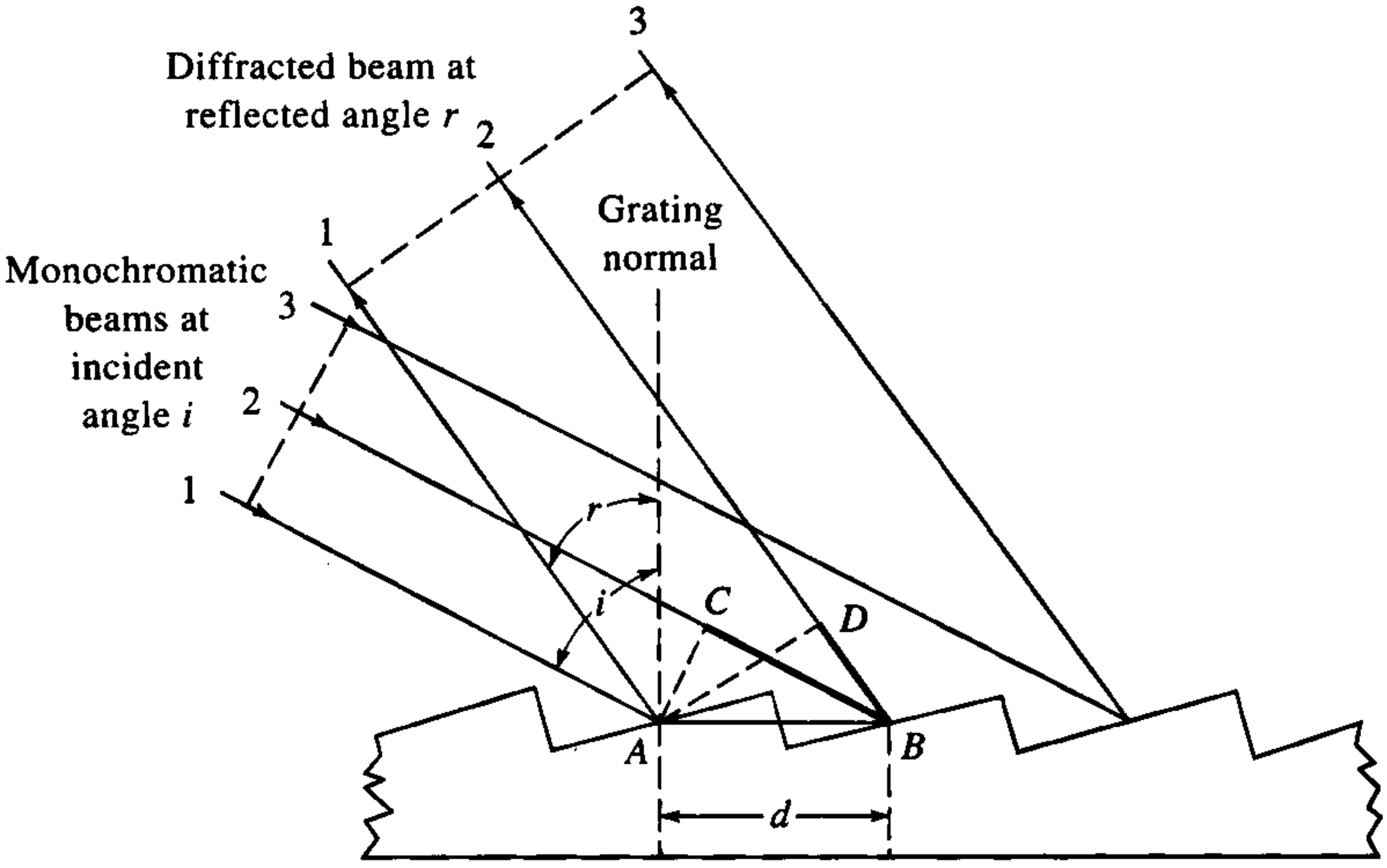
Reflection Gratings

The distances that parallel waves travel differs, causing diffraction in the reflected beam.



The steps are called "blazes", and have an angle called the "blaze angle".

Reflection Gratings



$$n\lambda = d(\sin i + \sin r)$$

$n = 0, \pm 1, \pm 2, \pm 3, \ldots$

Reflection Gratings

Consider a grating with 1450 blazes/mm and incident polychromatic light at *i* = 48 deg

What is λ of the monochromatic reflected light at R = +20, +10 and 0 deg?

$$d(\sin i + \sin r) = n\lambda$$

d = 1 mm/1450 blazes = 689.7 nm per groove

Calculate λ for n = 1 at i = 48 deg and r = +20 deg

$$\lambda = 689.7 \text{ nm } (\sin 48 + \sin 20)/1$$
$$= 748.4 \text{ nm}$$

This grating will disperse a polychromatic beam of light into monochromatic beams of 748.4 nm at 20 deg, 632 nm at 10 deg and 513 nm at 0 deg.

Quantitative Parameters of Gratings

The resolvance or chromatic resolving power is defined using the Rayleigh criterion as:

$$R = \lambda/\Delta\lambda = mN$$

where $\Delta\lambda$ is the smallest resolvable wavelength difference, λ is the average wavelength, m is the order, and N is the # of lines illuminated.

Other related parameters:

Linear Dispersion (mm/nm): *How far over is one wavelength from another?*

$D = dy/d\lambda = mf/(d \cos r)$

f is the focal length of the monochromator

Reciprocal Linear Dispersion 1/D (nm/mm)

Example: If a 10 nm spectral region is spread over 1 mm D = 1 mm/10 nm and D^{-1} = 10 nm/mm

“10 nm are spread out over a distance of 1 mm”

Concept Te$t

Which of the following would increase the resolution of a grating?

(A) Increasing the number of blazes illuminated

(B) Increasing the diffraction order

(C) Increasing the focal length

(D) All will improve the resolution

Gratings

$$R = \lambda/\Delta\lambda = mN$$

Concept Test

A standard benchmark for the resolvance of a grating is the resolution of the sodium “doublet” (two emission lines of Na). If this doublet appears at wavelengths of 589.00 nm and 589.59 nm, could the m = 1 diffraction spots be resolved by a grating with a resolvance of 900?

(A) Yes (B) No

A resolvance of at least 999 is required.

Gratings

$$R = \lambda/\Delta\lambda = mN$$

$$R = 589.30/0.59 = 998.8$$

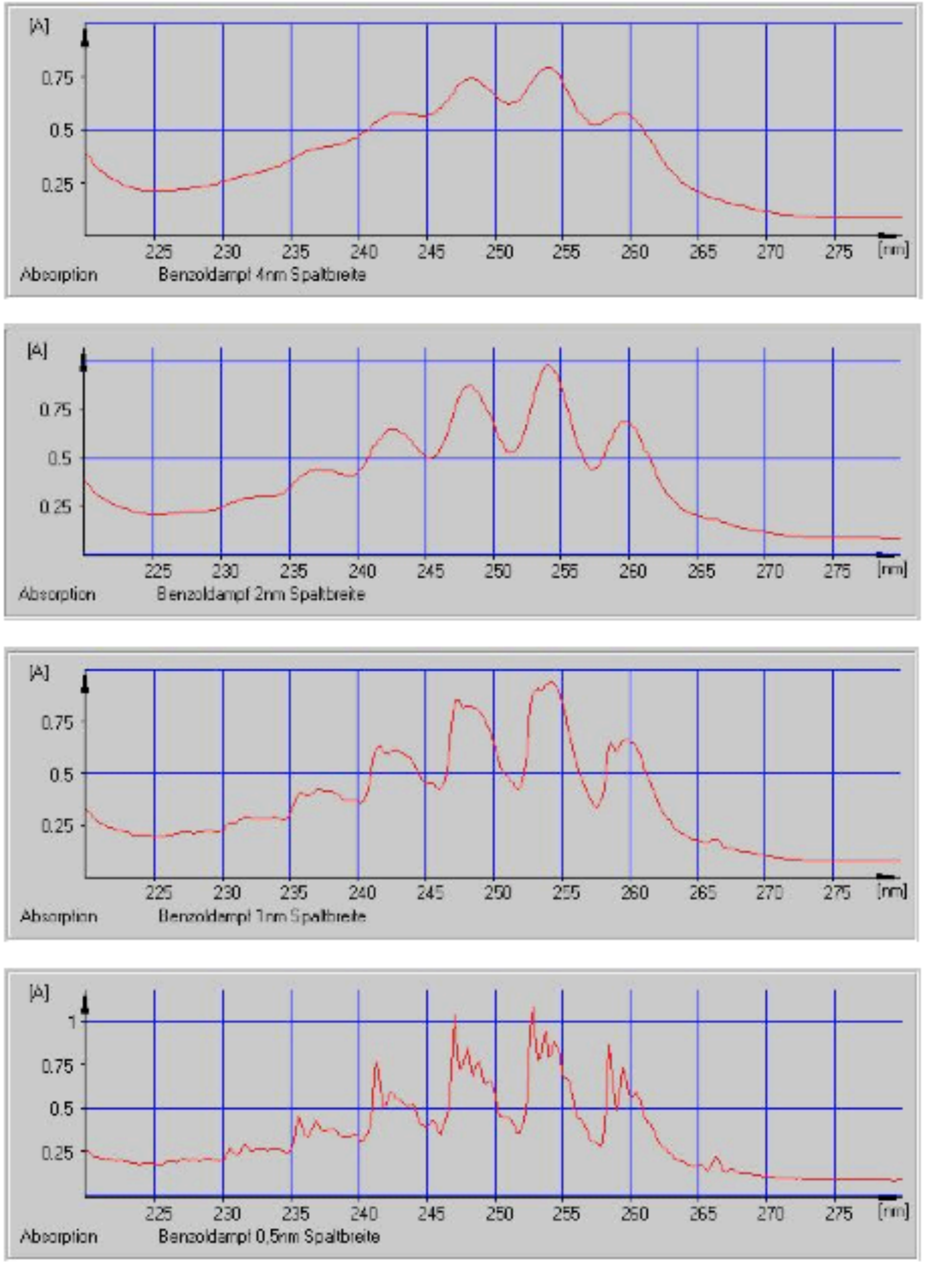
Monochromator Slits

The entrance slit selects a defined beam of (polychromatic) light from the source (helps collimate the beam) and controls the intensity of light that enters the monochromator. The incoming beam needs to be collimated for the dispersive device to work properly.

The dispersion device causes the different wavelengths of light in the source beam to be dispersed (separated) at different angles.

The exit slit enables selection of a particular wavelength to produce the required monochromatic light.

Monochromator Slits

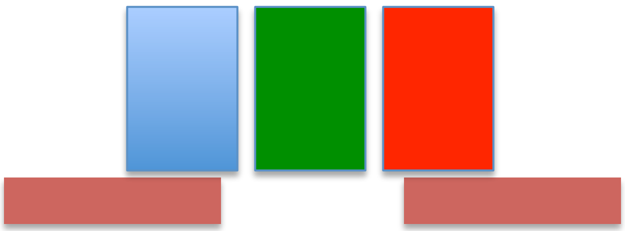


Benzoldampf – benzene vapor; Spaltbreite – slit width

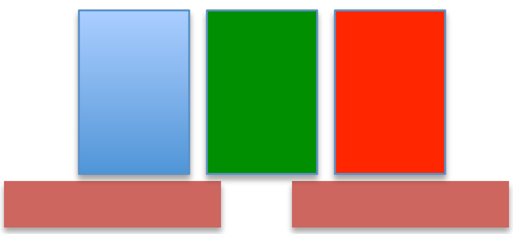
The slit width also determines the resolution. The smaller the slit width, the better the wavelength resolution, but the lower the intensity of light that reaches the detector.

Typically, the entrance and exit slits have the same width, so that the width of the light beam entering the monochromator matches the width that hits the exit slit.

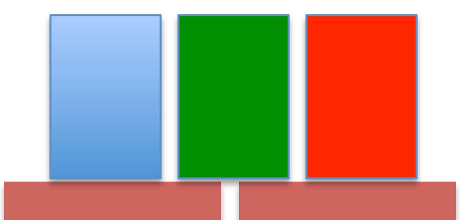
Scenario: A grating focuses three wavelengths onto the exit slit.



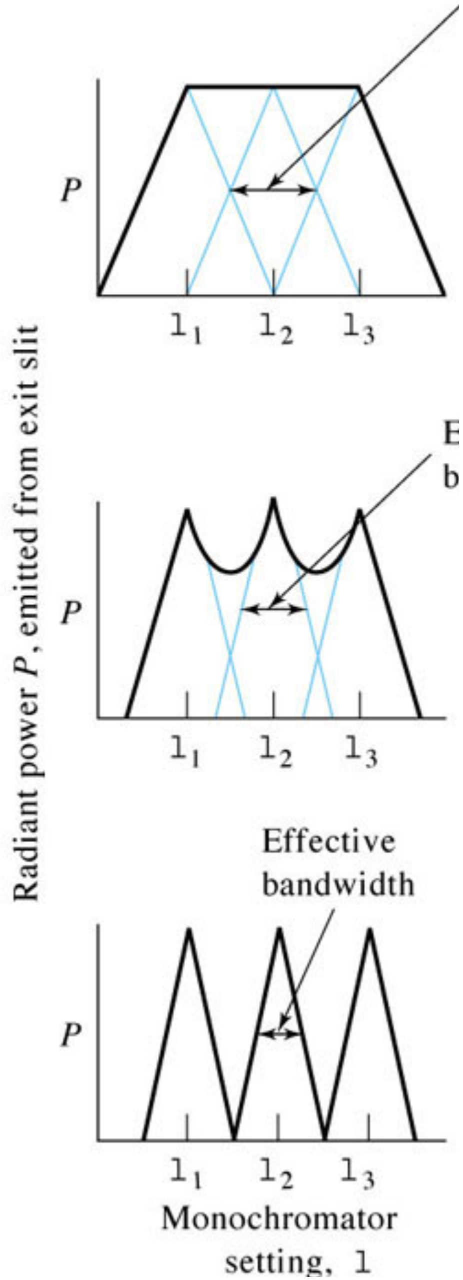
Green, Red, and Blue come through.



Less overlap



Even better resolution, but the power coming through drops.



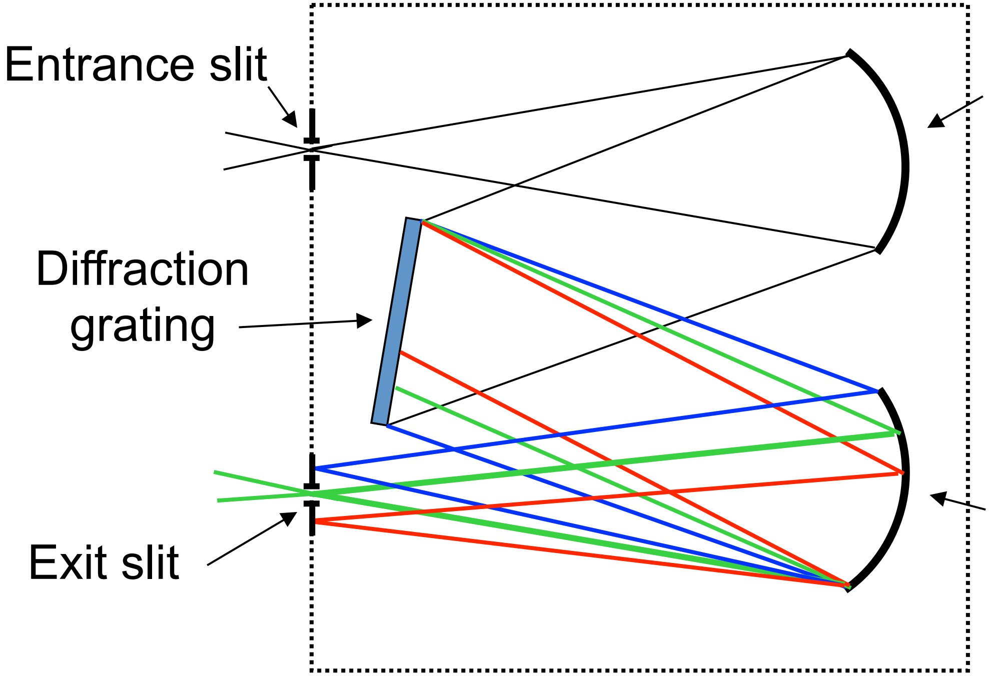
If the slit is too wide, intensity of light reaching the detector will be high, but the wavelength resolution will be low.

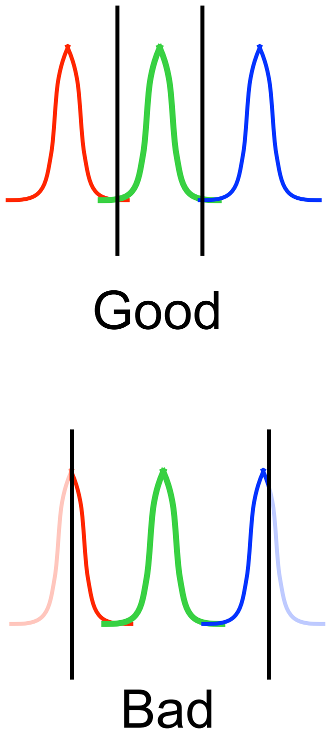
When the slit is narrowed, the ability to resolve adjacent wavelengths improves, but the light intensity that reaches the detector will be lower.

Complete resolution of two spectral lines:

$\Delta\lambda_{eff}$ = "Effective Bandwidth" = 1/2 the difference of the lines being resolved.

Monochromators





If the dispersion is poor and the slit wide open, then the resolution will decrease.

Monochromator Slits

These ideas may be quantified using the reciprocal linear dispersion and effective bandwidth, which is the wavelength range that passes through the slit:

$$\Delta\lambda_{eff} = wD^{-1}$$

w is slit width
D^{-1} is reciprocal linear dispersion

In practice you would normally adjust the slit width until you achieve the right balance of signal intensity and peak resolution.

Effect of Slit Width On Resolution

A grating monochromator with a reciprocal linear dispersion of 1.2 nm/mm is to be used to separate the sodium lines at 588.9950 nm and 589.5924 nm. In theory, what slit width would be required?

Complete resolution of the two lines requires that

$$\Delta\lambda_{eff} = \tfrac{1}{2}(589.5924 \text{ nm} - 588.9950 \text{ nm}) = 0.2987 \text{ nm}$$

$$\Delta\lambda_{eff} = wD^{-1}$$

$$w = 0.2987 \text{ nm}/1.2 \text{ nm/mm} = 0.25 \text{ mm}$$

Monochromator Slits

Concept Test

You work for the environmental protection agency and you have been given a water sample to analyze. It is suspected that the sample contains trace levels of a compound that absorbs visible light. To improve your detection limits you would set the spectrometer's slits to be:

(A) Narrow

(B) Wide

(C) Would not matter for this analysis

Monochromator Slits

Concept Test

You work for the environmental protection agency and you have been given a water sample to analyze. It is suspected that the sample contains trace levels of two compounds that absorb visible light of very similar wavelengths. To improve your ability to determine if both compounds are present you would set the spectrometer's slits to be:

(A) Narrow (B) Wide (C) Would not matter for this analysis

Detectors-Photon Transducers

- **Respond to the intensity of EMR striking them by changing a voltage or current emitted**

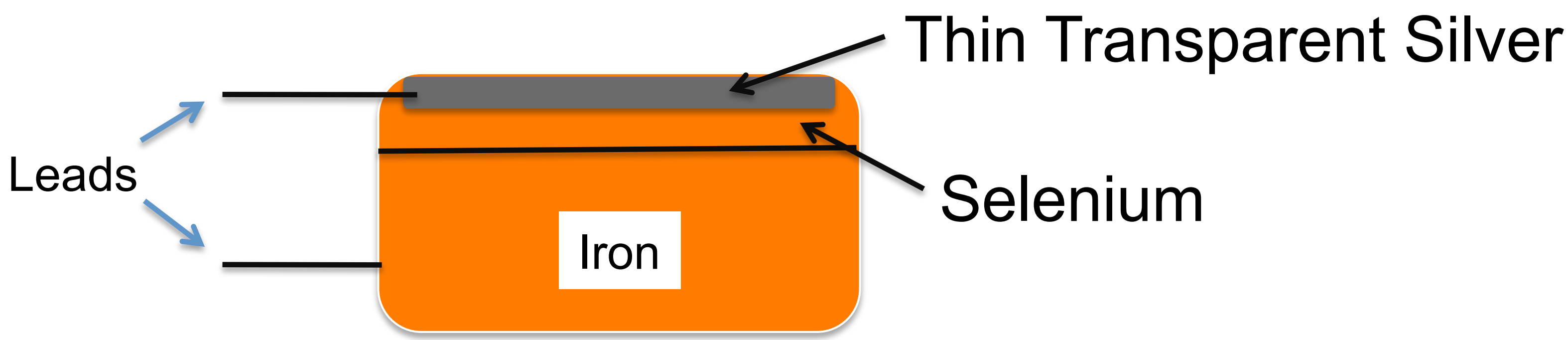
- **Do NOT respond selectively to specific wavelengths (that is what the wavelength selector is for) but work over a range of wavelengths (DUMB COUNTERS OF PHOTONS!)**

- **Ideally respond linearly to power: $S = kP$**
  In practice there is always a dark current: $S = kP + k_d$

- **Various types**
  - **Photographic films (not widely in use any more)**
  - **Phototubes (used in simpler instruments)**
  - **Photomultiplier tubes (used in more complex instruments)**
  - **Multichannel transducers**
    - **Diode arrays**
    - **Charged coupled devices (CCD's, like in many camcorders)**

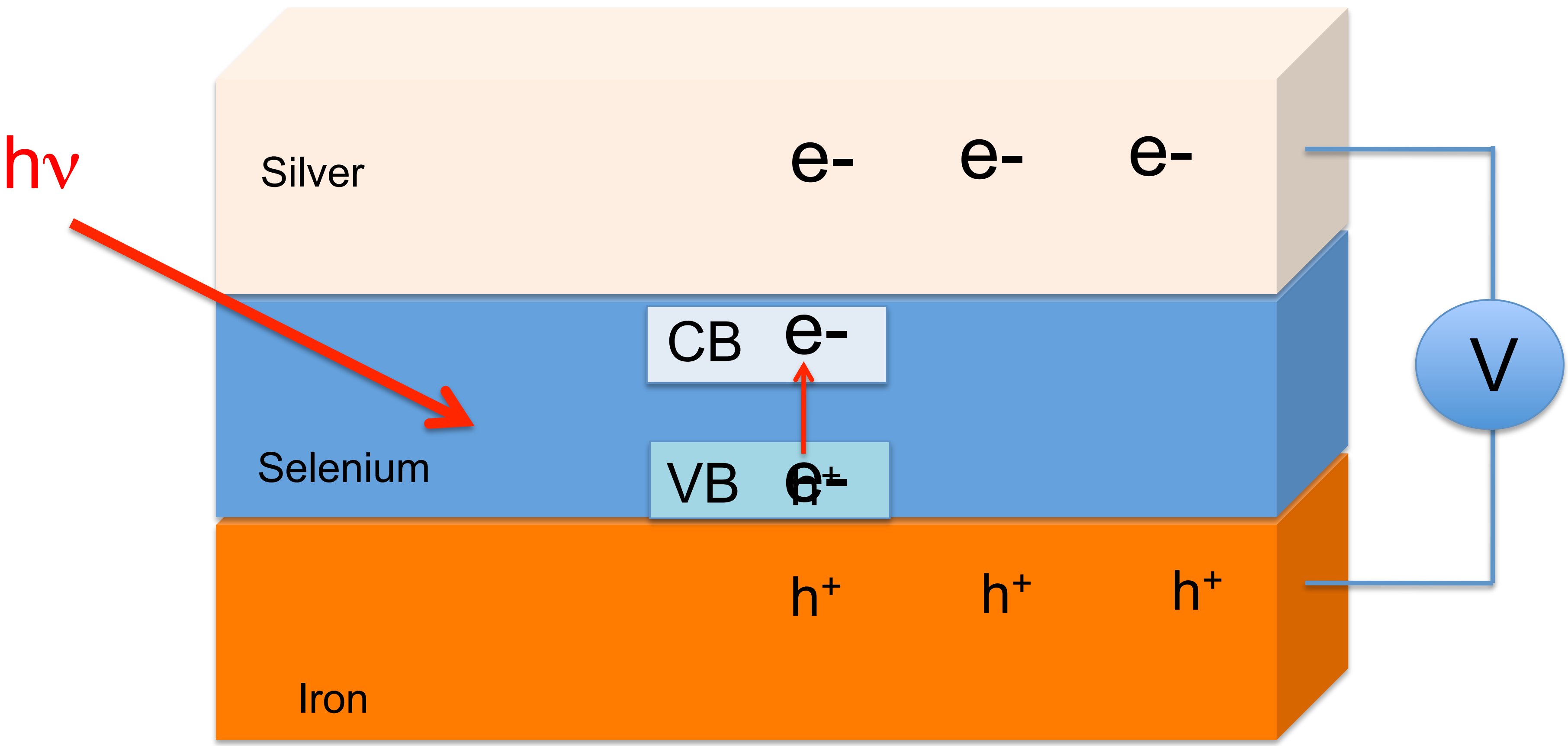
Detectors-Photon Transducers

Semiconductor Photovoltaic cells: Visible light detectors



Detectors-Photon Transducers

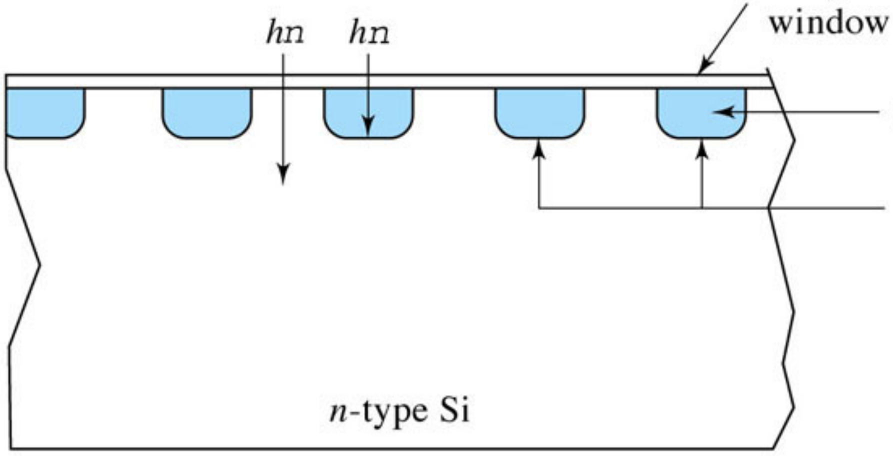
Semiconductor Photovoltaic cells: Visible light detectors



Metal-Semiconductor Junctions

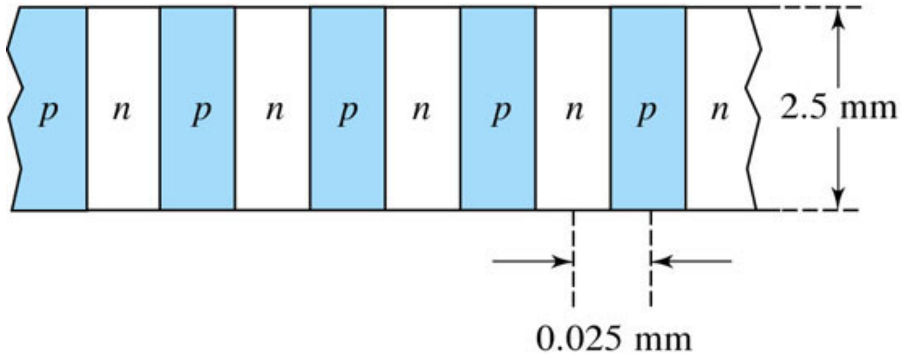
Detectors-Photodiode Arrays

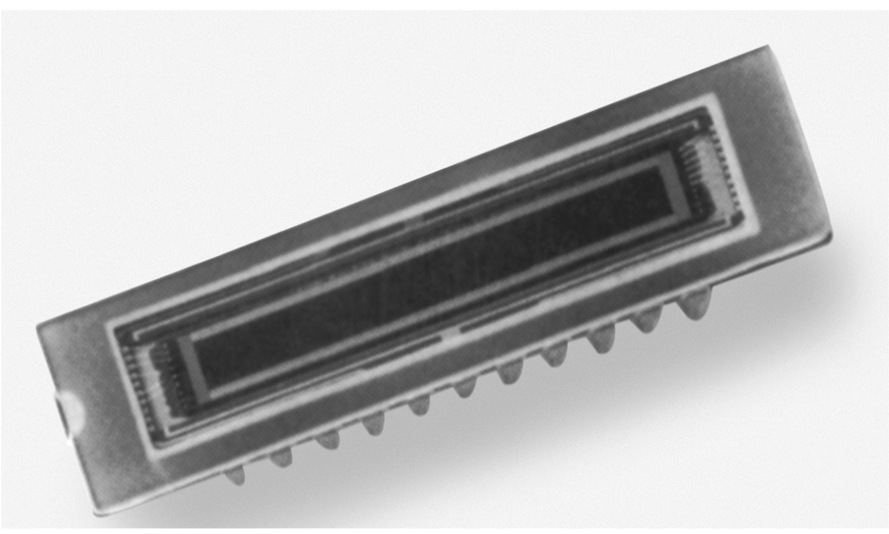
Cross Section



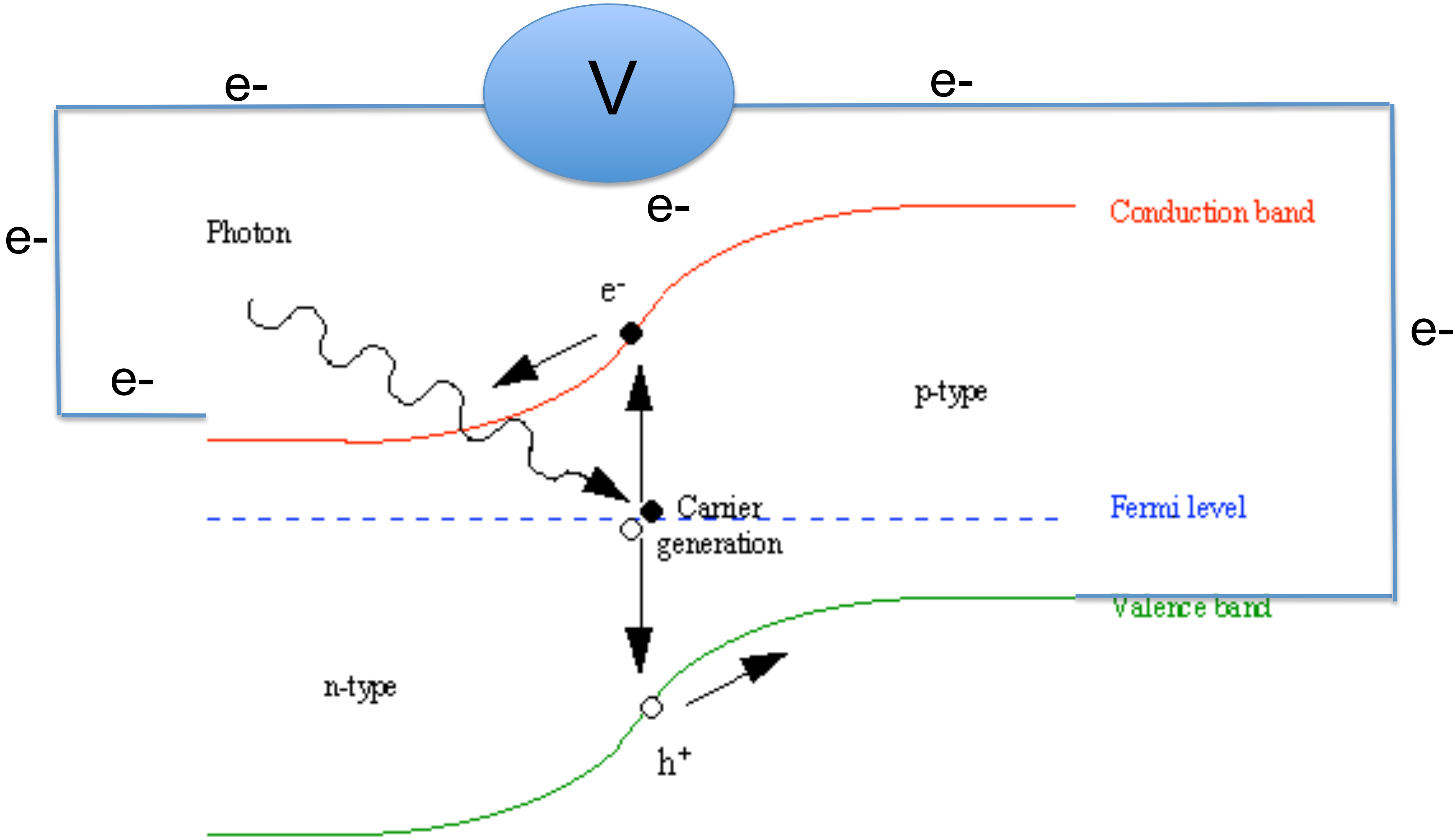
p-n Junctions

Top View



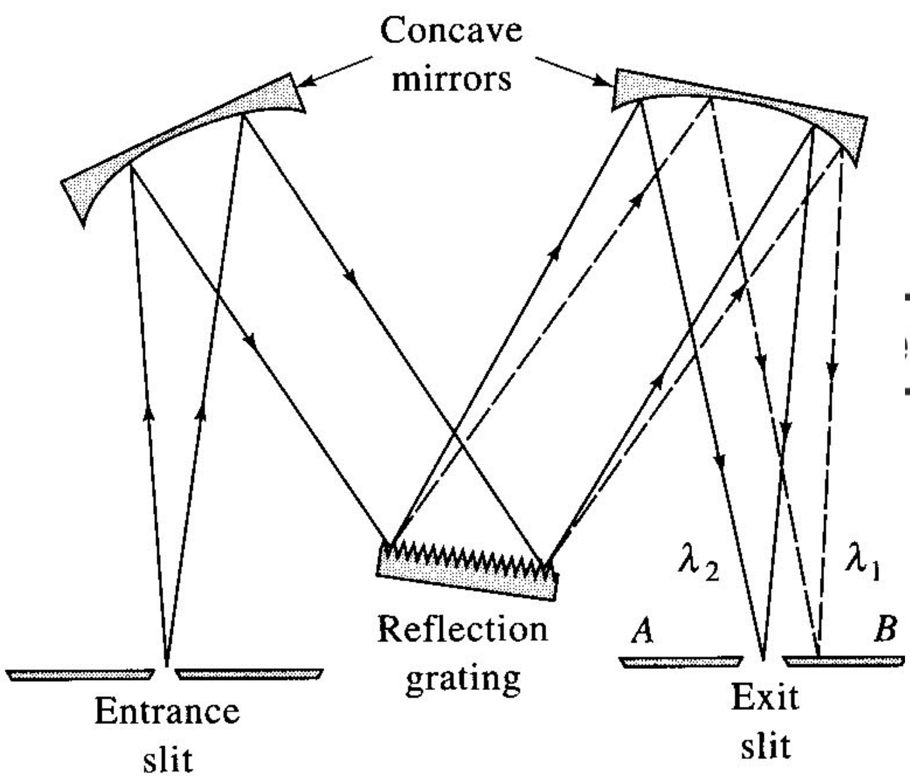


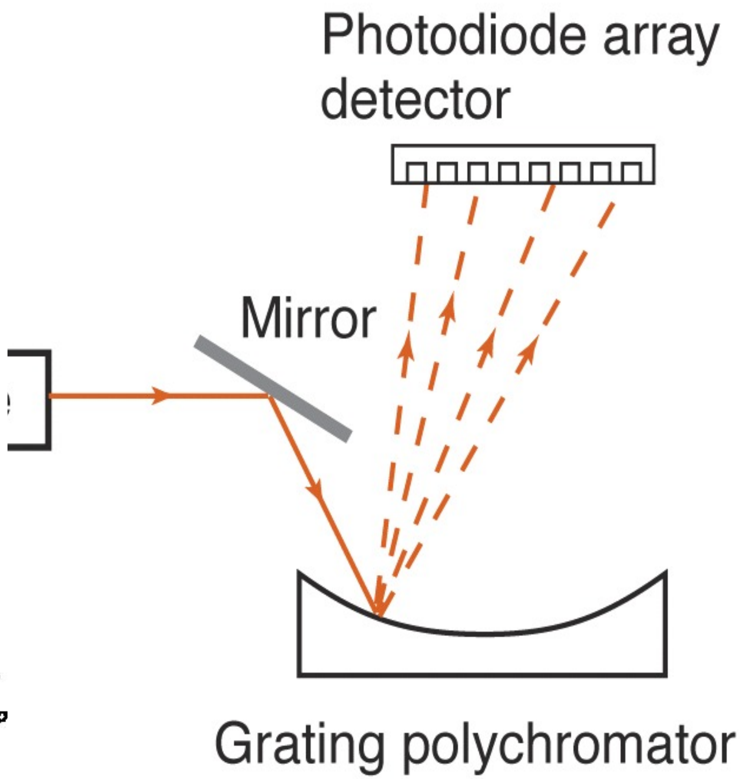
Detectors-Photodiode Arrays



Detectors-Photodiode Arrays

With 1024 individually addressable diodes, there is no need to scan the grating. The dispersed lines of different wavelengths each fall on separate diodes and are detected simultaneously.

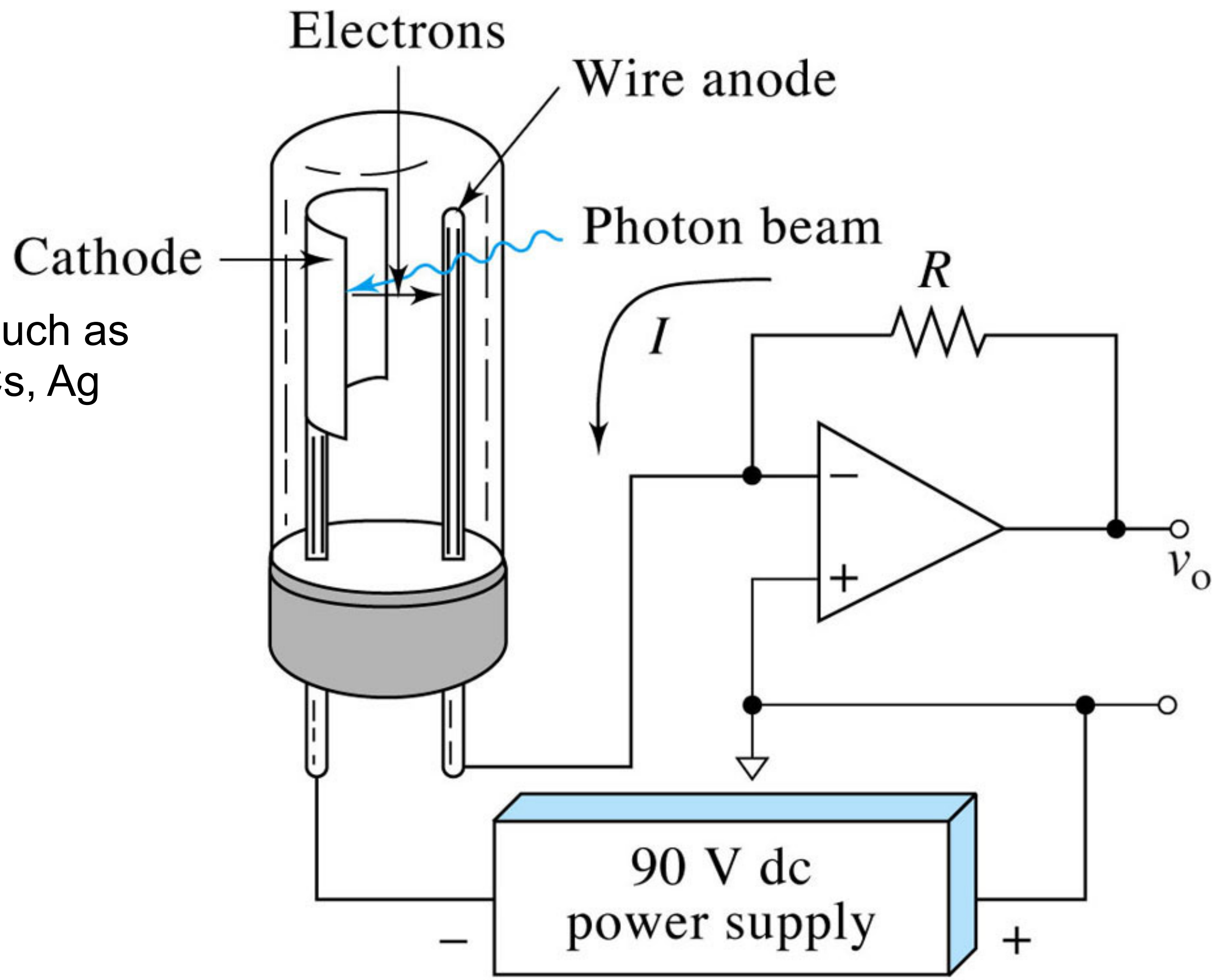




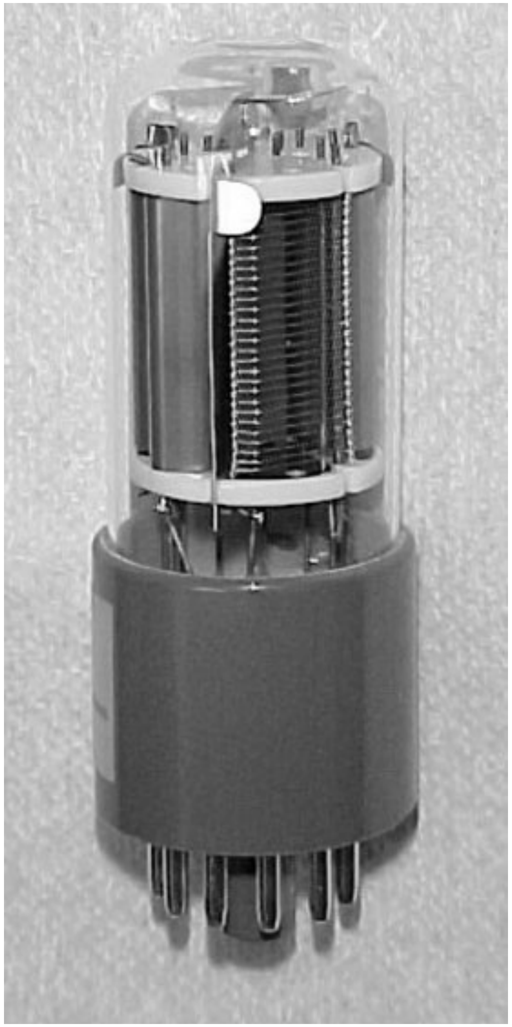
Detectors-Phototube

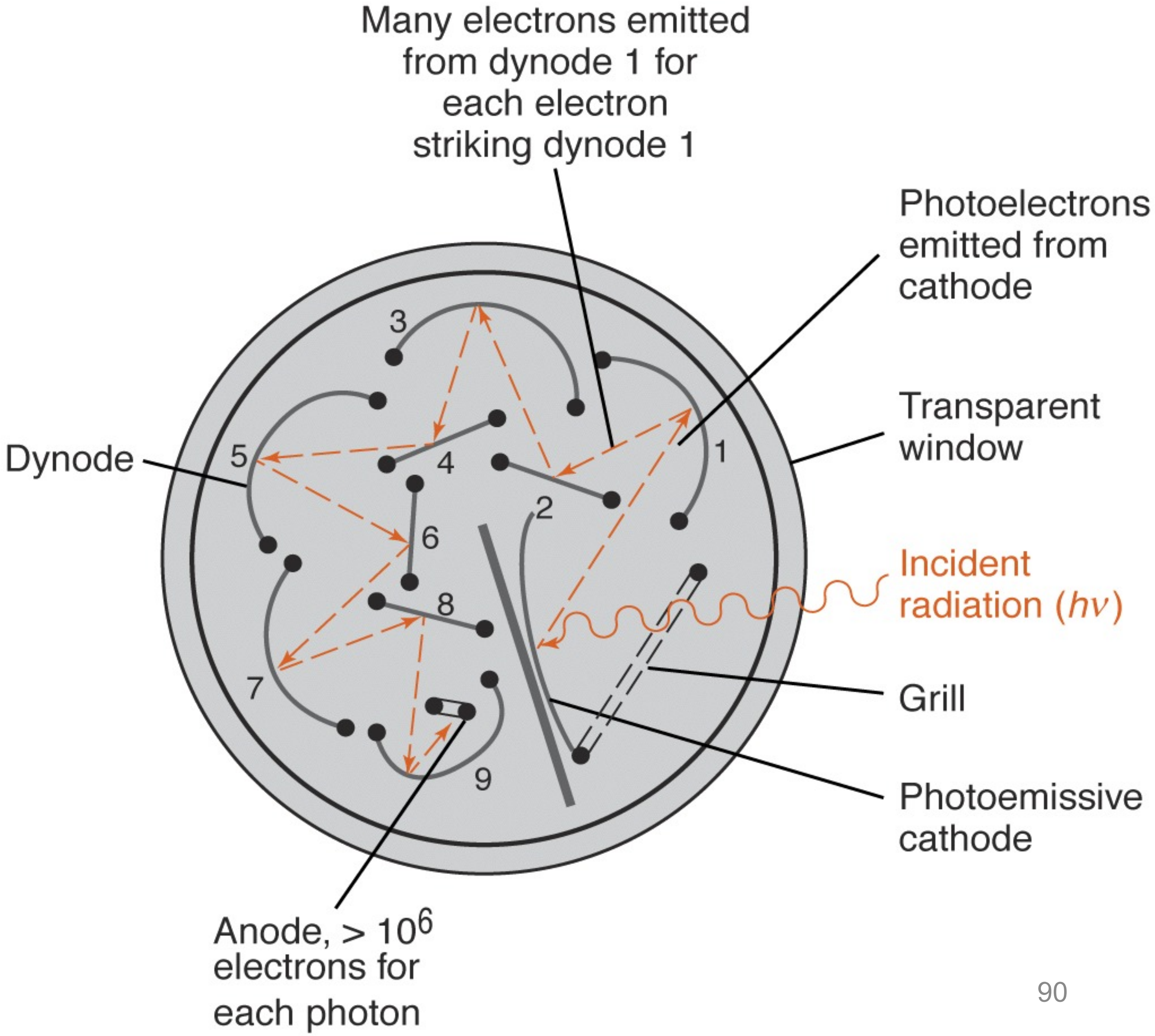
Based upon the photoelectric effect. Higher light intensity, more electrons.

Metals such as
Na, K, Cs, Ag



Detectors-Photomultiplier tube





UV-Visible Detectors

Arrays: Not as sensitive, but collect an entire spectrum at once and use simpler instrumentation. (No slits or moving gratings.)

PMTs: More sensitive, but require good monochromators.

Detectors for Measuring Heat (IR Radiation)

Bolometer

Invented in 1878 by the astronomer and aviation pioneer Samuel Langley.

A bolometer is a device which detects incoming radiation by producing a change in electrical resistance proportional to the amount of radiation received. Incoming radiation is absorbed by the bolometer which causes an increase in its temperature, which in turn causes a change in its electrical resistance.

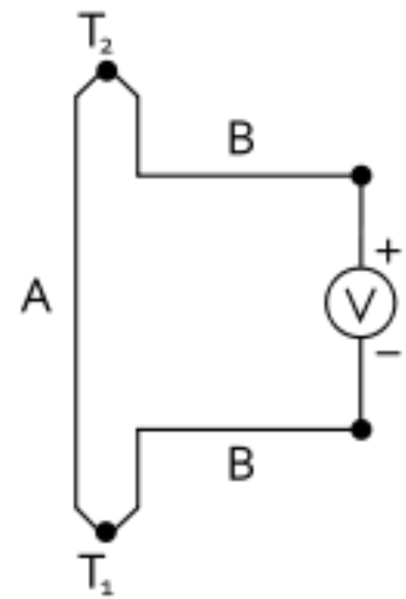
Originally made of Pt but now made from semiconductors such as Ge and even superconductors.

Sensitivities of <0.0001 of a °C.

Detectors for Measuring Heat (IR Radiation)

Thermocouple

Based upon the Seebeck effect: Two junctions of dissimilar metals or semiconductors (A and B) at two temperatures will produce a current.



(Converse is also true: An applied V will cause a T difference (Peltier Effect).

Sensitivities of 10^{-6} K.

$V = (S_B - S_A)(T_2 - T_1)$

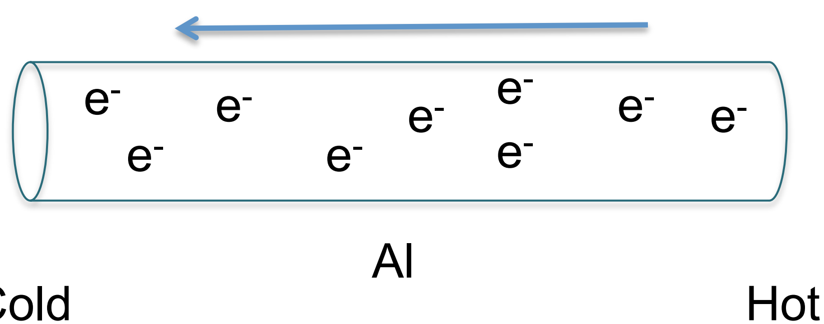
S is the Seebeck coefficient (V/K)

Detectors for Measuring Heat (IR Radiation)

Material	Seebeck Coeff. μV/°C
Aluminum	3.5
Gold	6.5
Rhodium	6.0
Antimony	47
Iron	19
Selenium	900
Bismuth	-72
Lead	4.0
Silicon	440

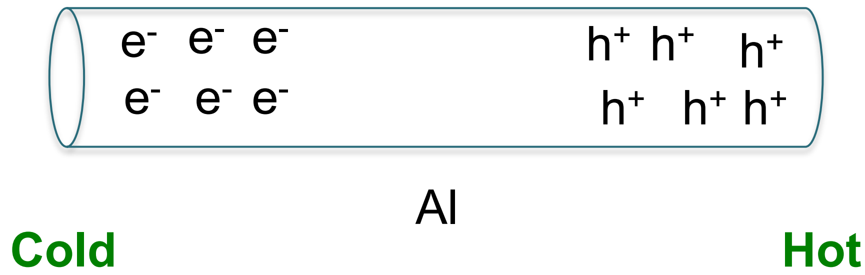
$$V = (S_B - S_A)(T_2 - T_1)$$

Electrons will move from the hot side to the cold side

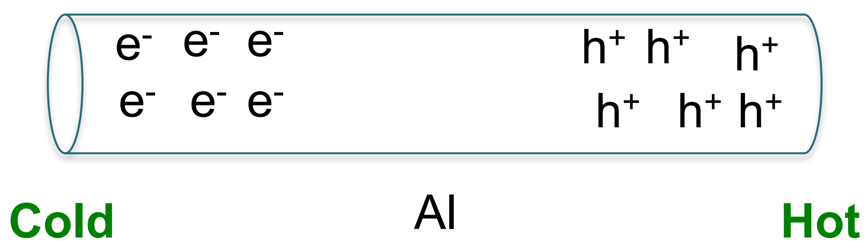


Detectors for Measuring Heat (IR Radiation)

Voltage develops across the rod



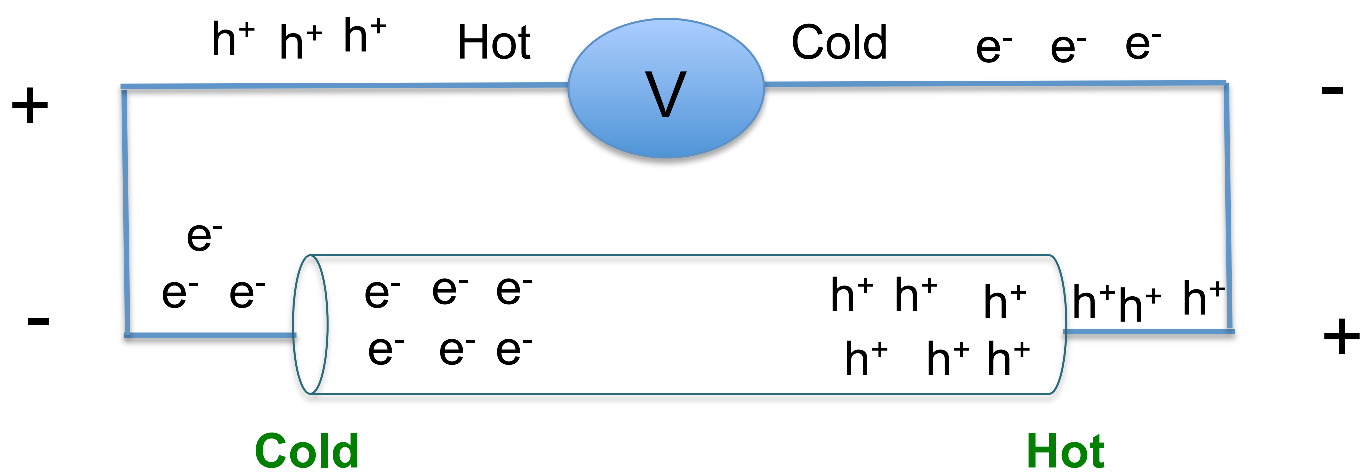
In some materials the holes move to the cold side (-S)



Why do we need two materials with different S values?

Detectors for Measuring Heat (IR Radiation)

Imagine what would happen if I measure the voltage by attaching Al leads to the Al rod.



If the wires are the same material as the “rod” the voltages would cancel!

The two materials must have different S values.