‘Light’ As Characterization Tool

Need to Characterize Materials:

Say I hand you a material

Phase of the material:	Solid, liquid, gaseous or the plasma
Physical properties	Density, electrical conductivity, magnetism, optical transparency, thermal conductivity,…
Mechanical properties	Strength, elasticity, stiffness, fracture characteristics, weldability, malleability, ductility...
Structure	Constituents, phases, stoichiometry, polymorph,…

Are there correlations between the properties ?

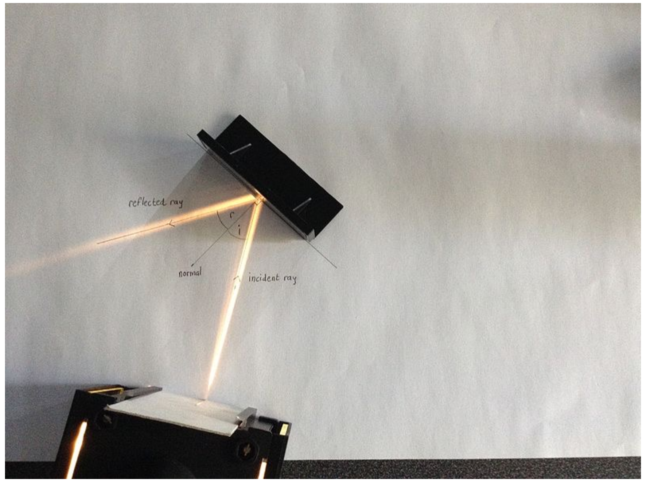
How to characterize ?

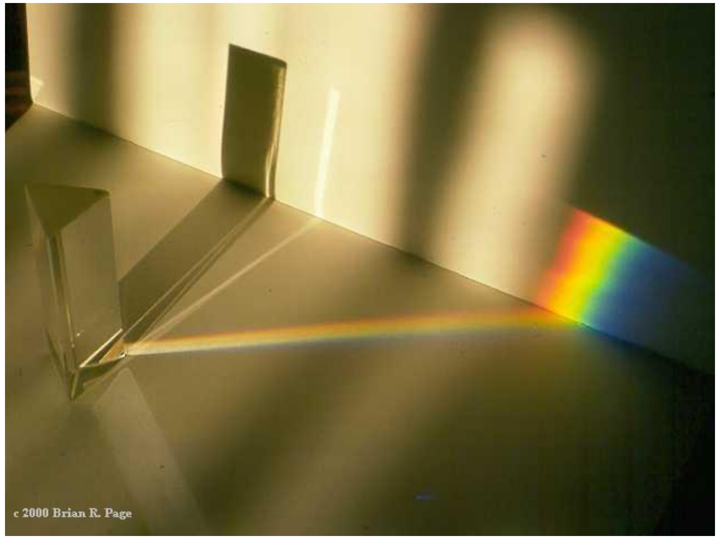
- To study/observe any property of the material, we perturb the material with an external energy source
  - Electromagnetic
  - Mechanical
  - Thermal
  - Chemical
- Measure the response of the material
- A good measure has to satisfy certain qualities mentioned before

Measurements using Electromagnetic systems

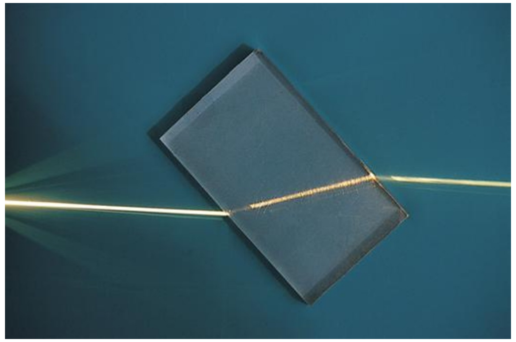
What do we know about light ?

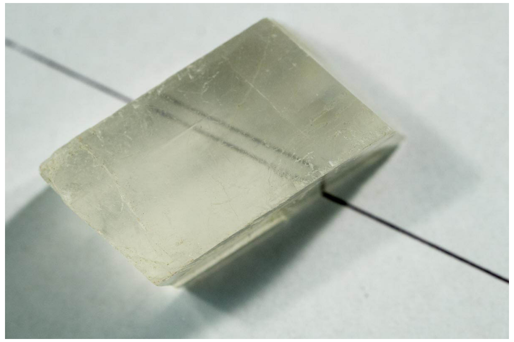
- Light (for now forget the form) has a source.
- It emanates from the source, and travels at incredible speeds.
- Certain objects can stop the transport, form shadows.
- Light beams are reflected (sent back) such that they follow a rule $\theta_{inc} = \theta_{ref}$
- Light beams at the interface of two materials bends (refract) such that $\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_1}{n_2}$
- Velocity of light in medium $v_1 = \frac{c}{n_1}$
- The 'color' of light determines the index 'n' – Reason why prism splits different colors



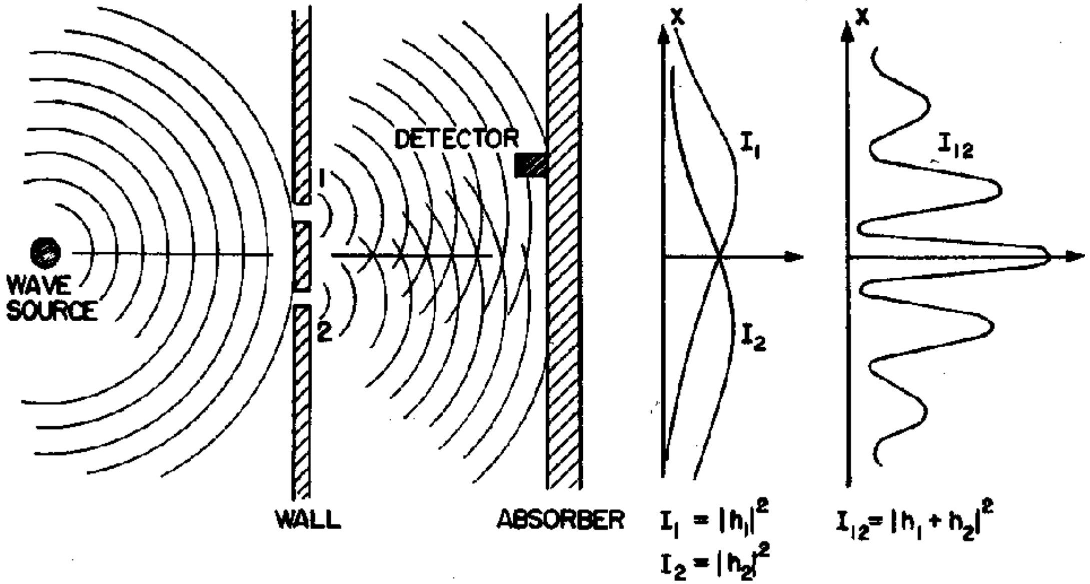


What do we know about light ?

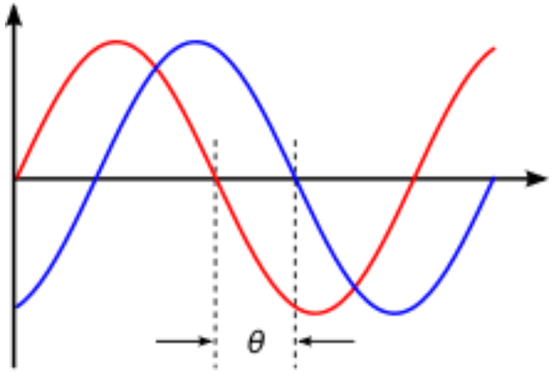




- In certain crystals, there is evidence of double refraction: evidence of at least two polarizations

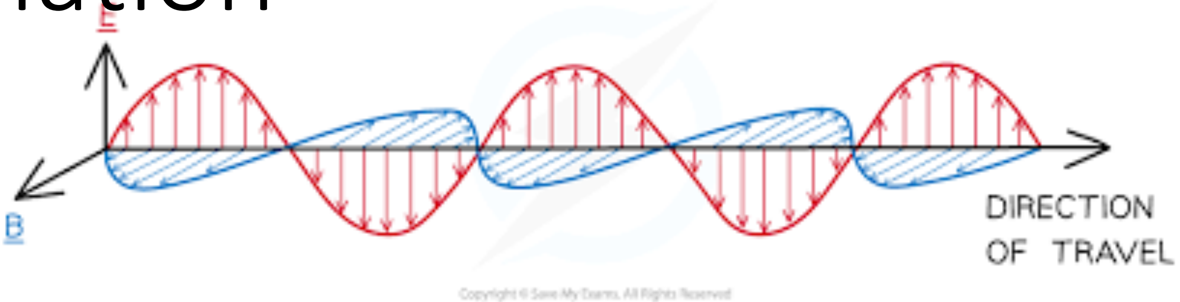


- Light radiations diffract: they seem to bend around obstacles.
- When there are two near by sources, they seem to interact – wave like.
- In addition to intensity, and polarization, light also has property: Phase



$$Ae^{i(kx-\omega t+\phi)}$$

Light as electromagnetic radiation



- All electric and magnetic fields obeys:

$\nabla . E = \frac{\rho}{\epsilon_0}$	(1)	Gauss' law
$\nabla . B = 0$	(2)	Magnetic monopoles
$\nabla \times E = -\frac{\partial B}{\partial t}$	(3)	Faraday's law
$\nabla \times H = J + \frac{\partial D}{\partial t}$	(4)	Ampere-Maxwell law

The solutions of these differential equations are sinusoidal E and M waves

- which are perpendicular to each other
- Which travel with a velocity $V = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 299792458 \frac{m}{s}$
- Energy travels perpendicular to both E and B, along the Poynting's vector $S = E \times H$

All these seems very similar to Light: -> Light must be an electromagnetic wave! With E always perpendicular to B

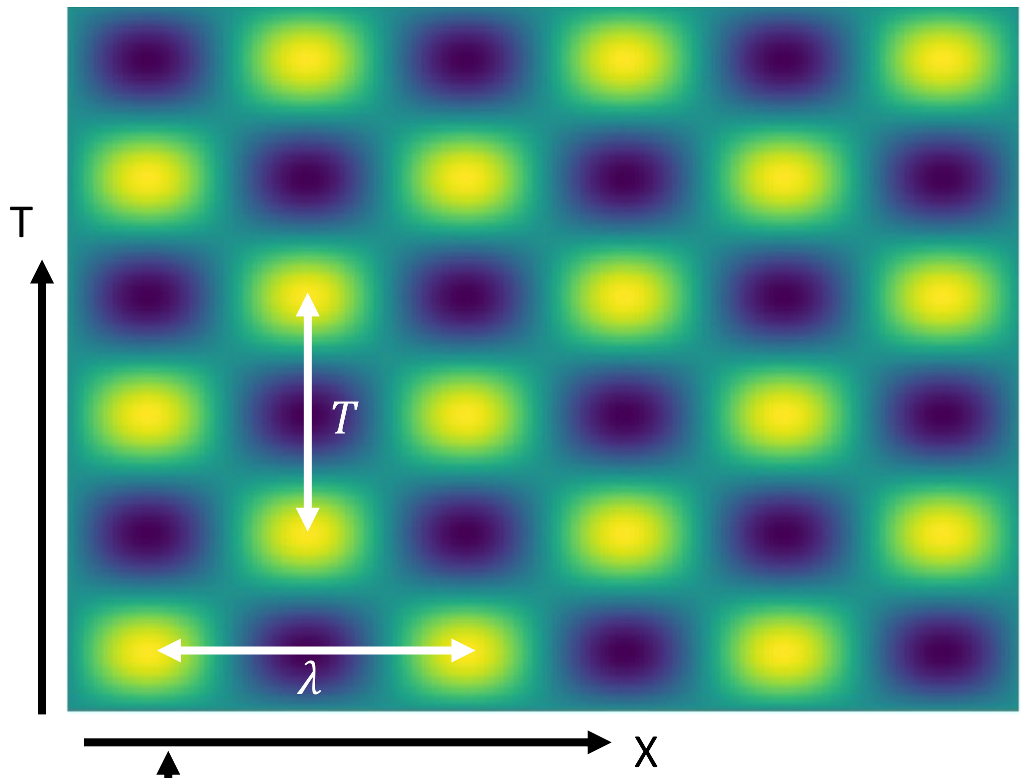
Properties of a wave

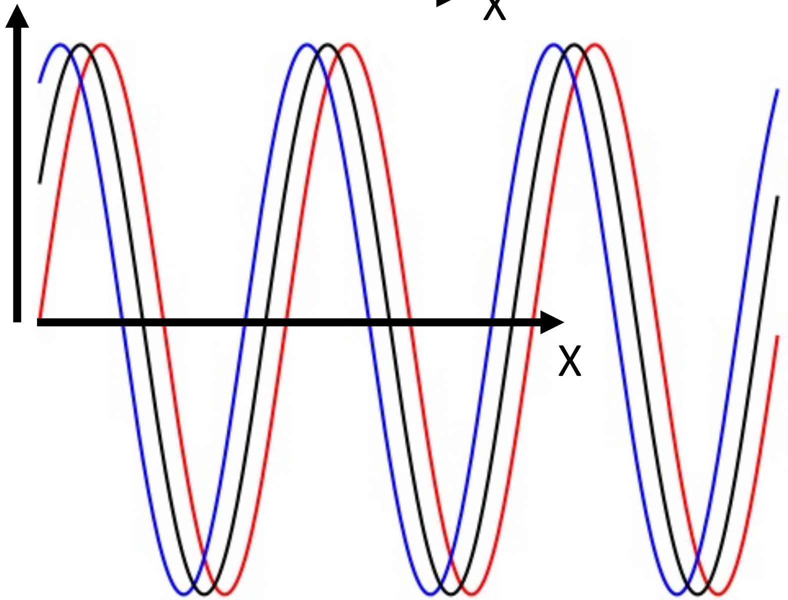
- The wave is periodic in space and in time!
  - The spatial periodicity : wave vector $k = \frac{2\pi}{\lambda}$
  - The temporal periodicity: frequency $\omega = \frac{2\pi}{T}$

  Final wave equation $\psi = A sin\,(kx\ - \omega t + \phi)$

  - Velocity of the wave: $\frac{\partial x}{\partial t} = \frac{\frac{\partial \psi}{\partial t}}{\frac{\partial \psi}{\partial x}} = \frac{\omega}{k}$
  - This velocity is also called as the phase velocity

  The velocity at which the phase of the wave travel





Energy in a wave (Light)

- Many a times, we want to measure the energy in a wave
  - Typical experiments use light and one want's to measure what the object did to light

Power in electromagnetic radiation defined by ψ

$$p(x)\ \alpha \frac{\partial\psi}{\partial x}\frac{\partial\psi}{\partial t}$$

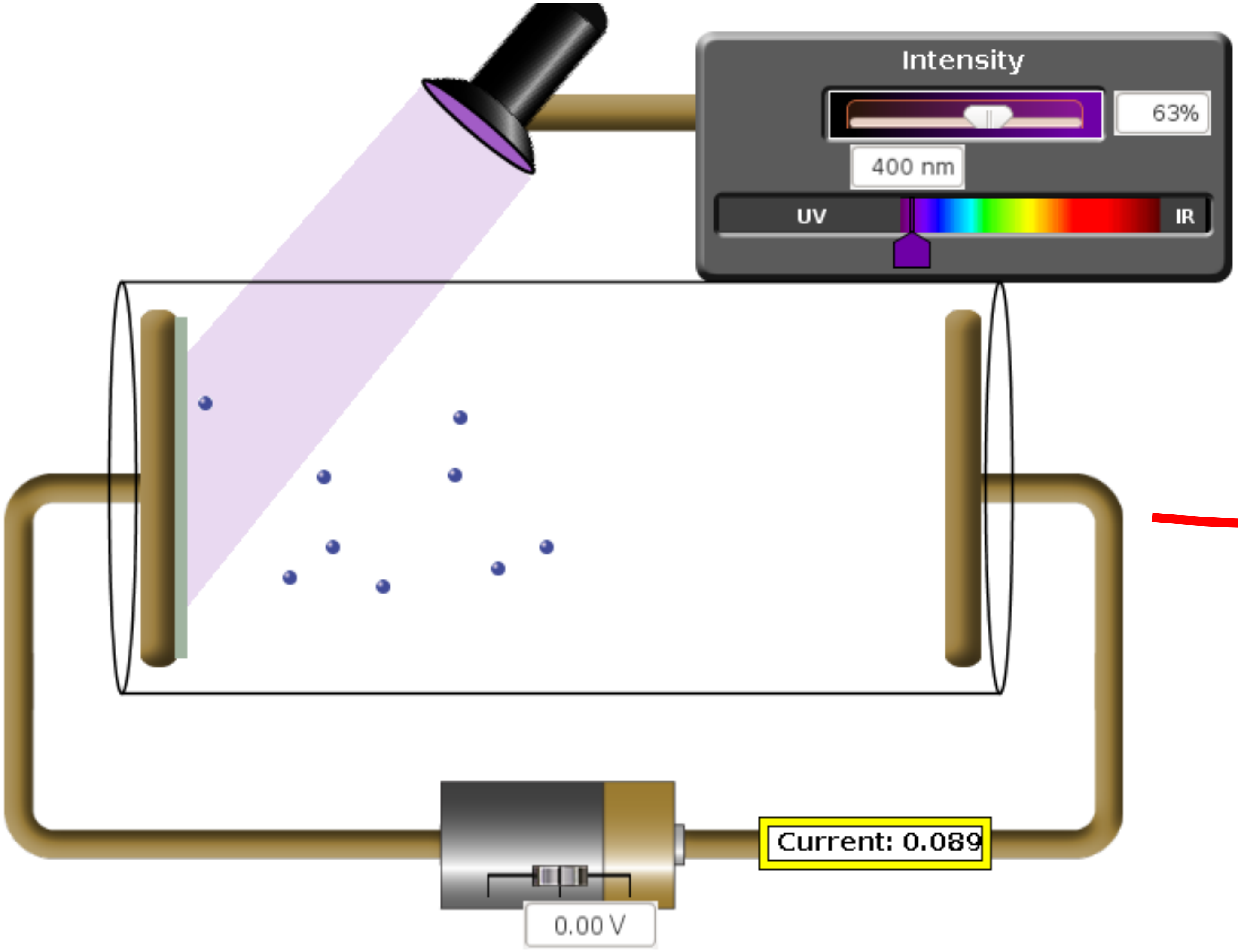
This gives the power per unit area $P(x)\ \alpha\ k\omega\ A^2 \cos^2(kx\ - \omega t)$

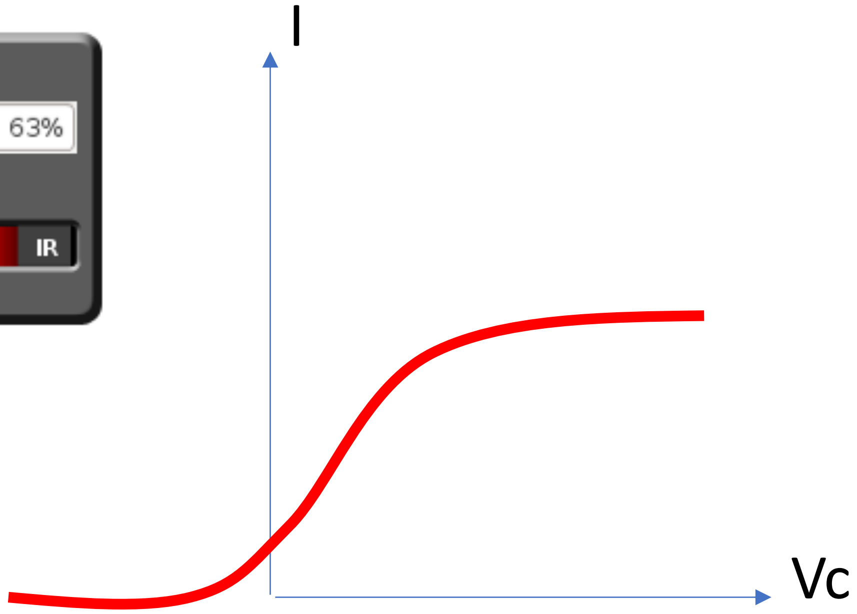
Finally a time averaged power in an EM wave is given by $I\alpha\ k\omega \frac{1}{T}\int_0^T \cos^2(kx\ - \omega t)$

Intensity of an EM wave $I\ = \alpha A^2$

Where $\alpha = \frac{1}{2}k\omega\tau$

Surprise Googly – Photo electric effect





- Increasing the intensity of light didn't change the threshold for conduction !! - Why ?

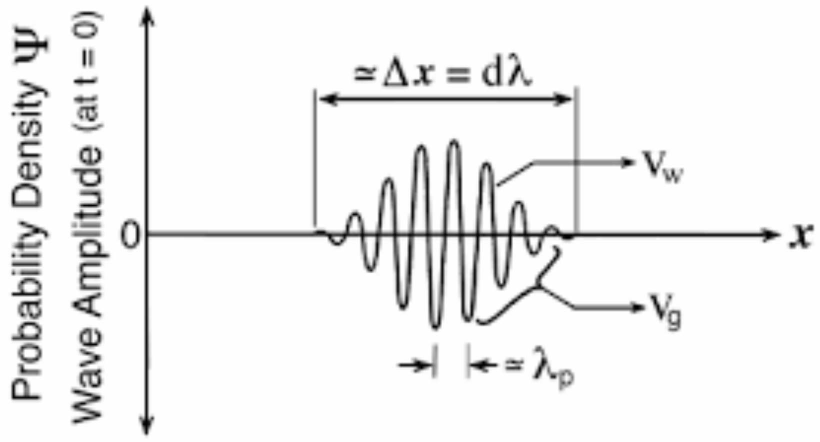
Duality conundrum

- Photons, which were once wave like with intensity decided only by the amplitude, also behaves like a particle!
- Each particle interacts with other particles in a collision kind-of-behavior, which can kick electrons out of the electrode!
- No particle can diffract, cause interference! So how do we reconcile ?

Wave-Particle Duality

- A Plane wave: $A = A_0 e^{i(kx - \omega t)}$ oscillates in space and time.
  - Is present everywhere in space !
- A particle on the other hand, has precise position in space and has a definite velocity
  - Much like a ball whose forces are known.
- So now, what is light ? What's the confusion all about?

The idea of a wave packet



Properties of such waves

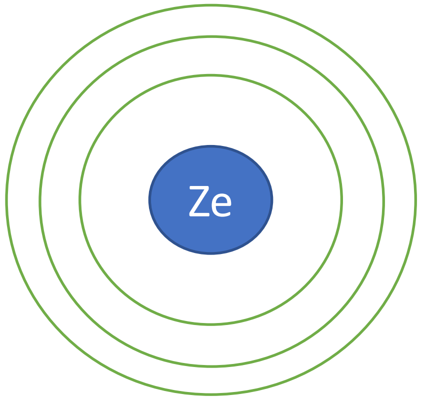
- We can define a wavelength λ, frequency ν and a velocity v such that
- Velocity = distance /time $V = \lambda v$
- The energy of the particle moving at velocity is give by $E \ = h\nu$
  - Where h is called as the Planck's constant
- The packet of light which propagates is called as the 'quanta' – minimum measurable physical quantity
  - Though thought to be used in atomic/low energy physics, quantum and quanta has been in usage by Physicians long before!

How does light interact with Matter ?

Interaction of EM waves with Matter

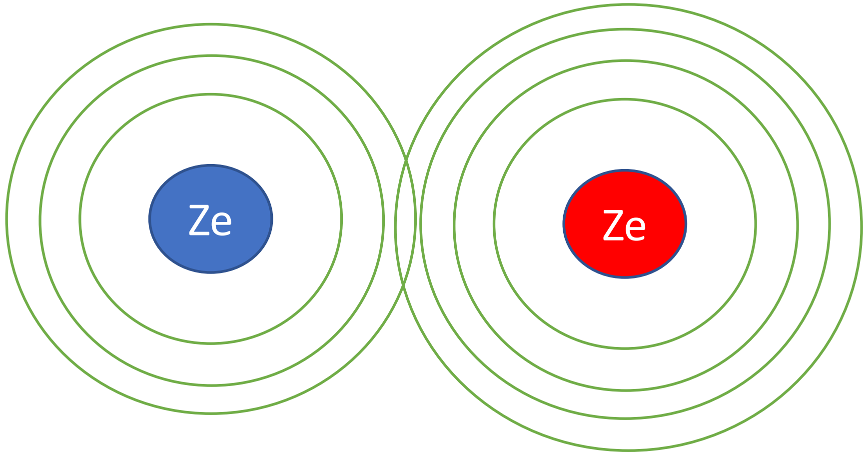
- For simplicity, we consider matter as either atom/molecule or a solid.
- What is the difference between them ? What similarities they share ?
- For that we need to understand energy levels:

Sodium Atom

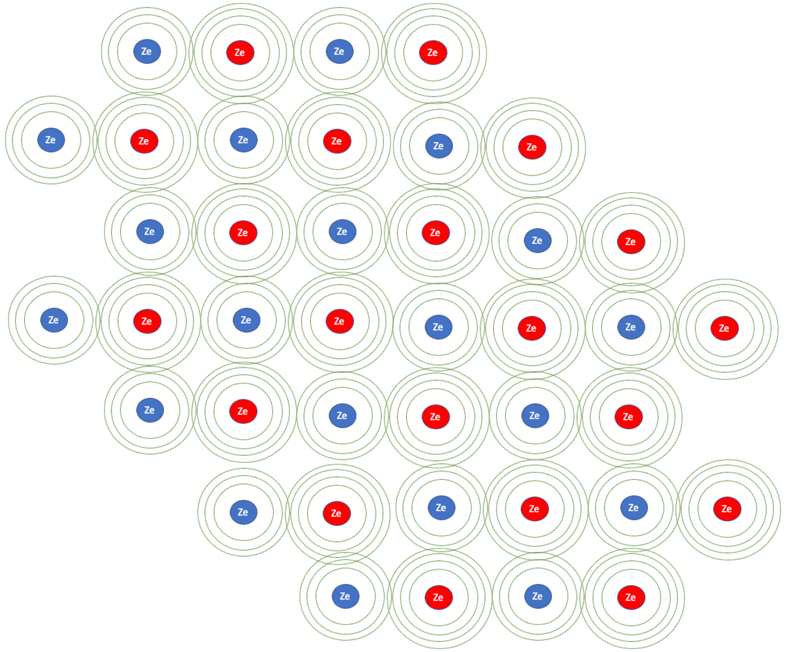


Atomic number Z- 11

Chlorine Atom



Atomic number – Z=17

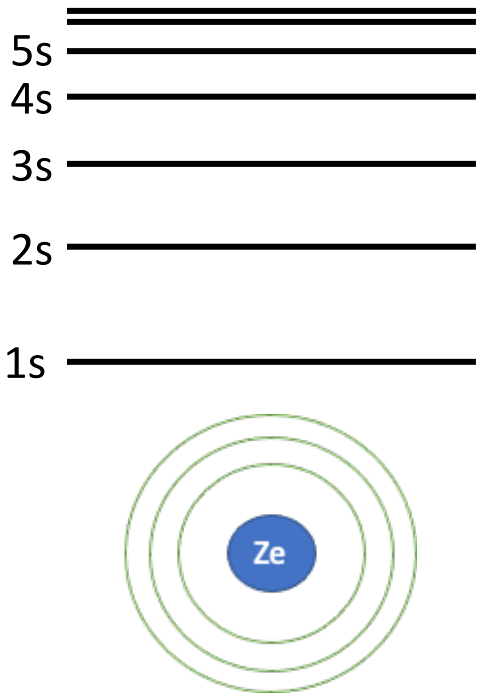


Energies and Energy levels in matter

Atom

Energy levels in an atom

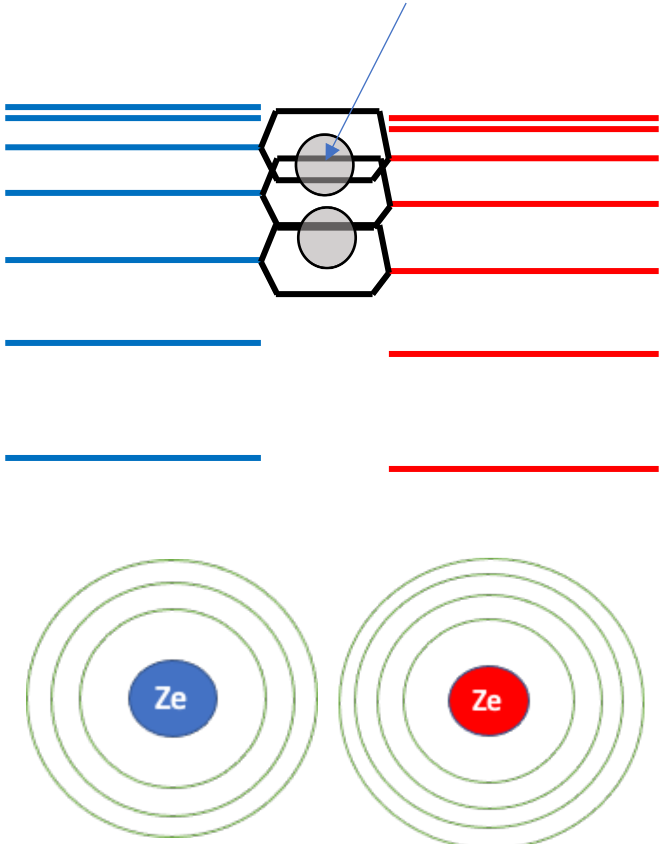
$$E_n = -\frac{hcR_yZ^2}{n^2}$$



Molecule

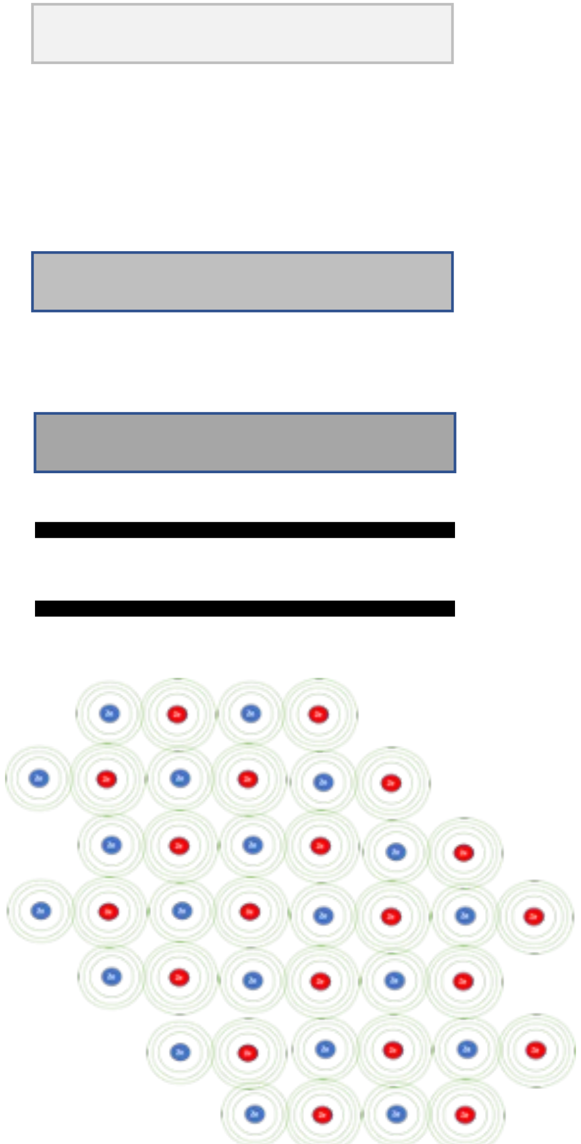
Discrete energy levels separated from each other

Interacting energy levels/orbitals



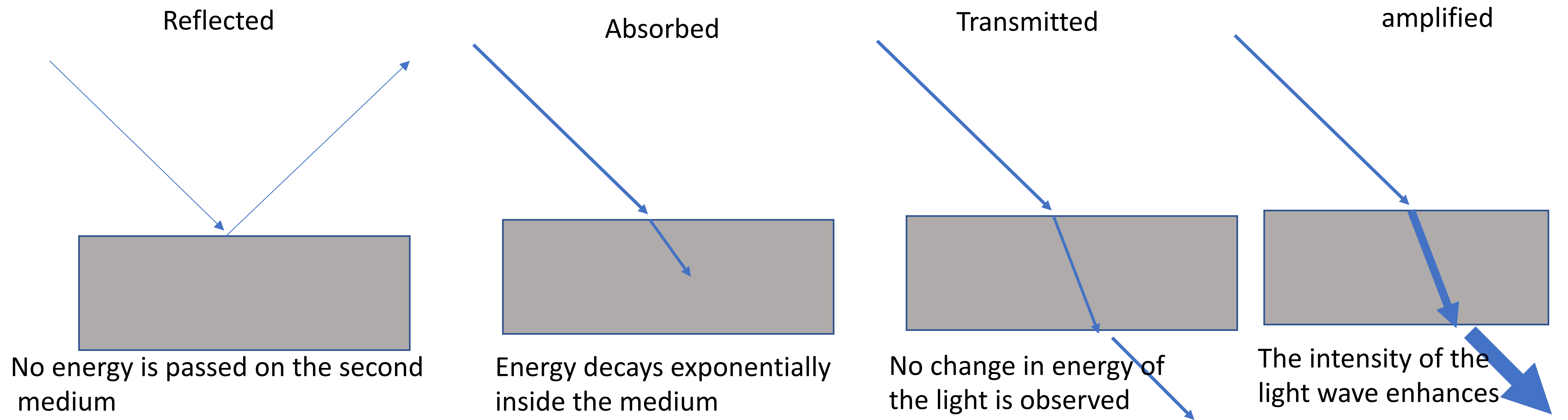
Solid

Continuum of energy levels called bands, separated from each other



Light – Matter Interaction

- Consider a light of energy of frequency ν, energy $\mathrm{E} = h\nu$
  - Wavelengths are not used here as it is material dependent.
- Different modes of interaction with matter:



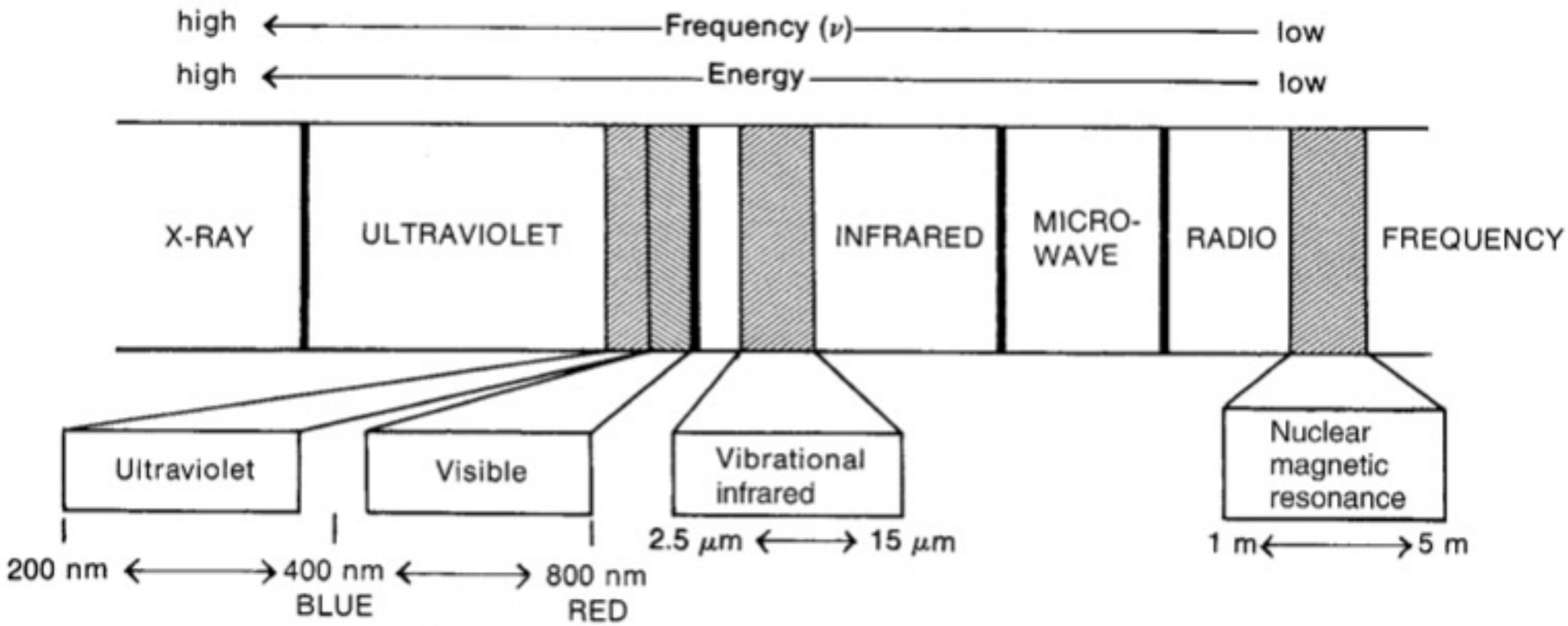
Selection Criteria for Interaction

- A material has a finite probability to absorb an electromagnetic radiation with energy E, iff

1. $\Delta E = E_f - E_i = h\nu$
2. E_f has empty electronic levels
3. E_i has filled electronic levels

Now can you explain, why $CuSO_4$ solution appears blue ? What color of light does it absorb ?

Choice of Light



Type of radiation	Energy	Frequency	Type of transitions
X-Rays	>1 keV	$>10^{18}$	Bond breaking
Ultraviolet	10 – 100 eV	$>10^{16}$	Electronic transitions
Infra-red light	10^{-2} - 1	$>10^{12}$	Vibrations
Microwave	10^{-4} – 10^{-2}	$>10^{8}$	Rotational transitions
Radio frequencies	10^{-8} – 10^{-4}	$>10^{4}$	Nuclear spin resonances and Electron spin resonances