Announcements

- You should see a polling session active if you are using the REEF app. Make sure you are signed in
- I have thee iClickers to loan out. First come, first served. If you borrow one, please remember to send me an email with your name and the Clicker ID number so I can give you the credit for participation
- The reading assignment that was due Tuesday and was so confusingly displayed on Connect is due on February 11th at 5pm. Do read it before the midterm!
- Midterm in class Tuesday, 2/14

Light, Energy and Matter

- Light is energy
  - Sunlight feels warm

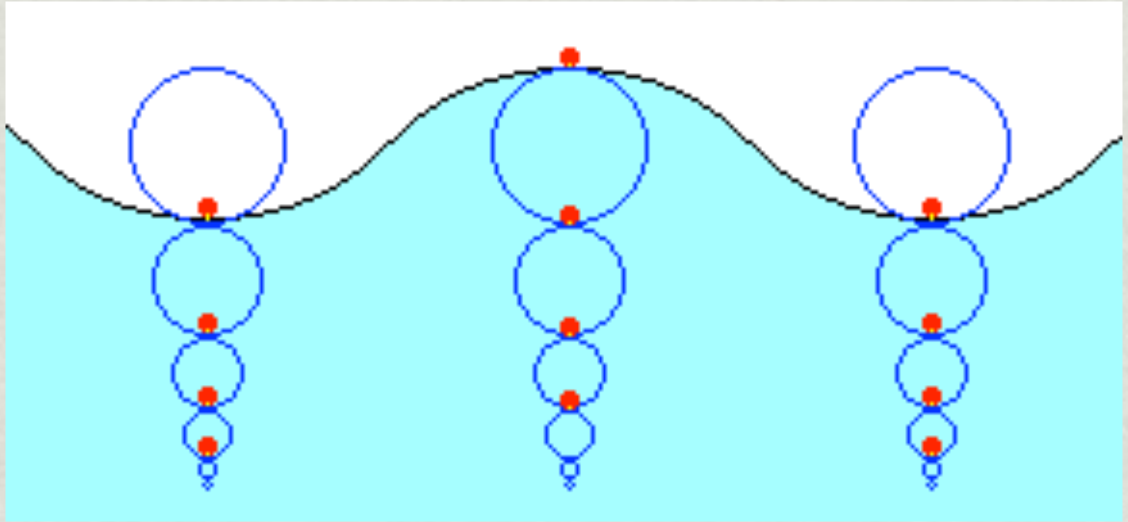
Units of energy: Joules, kg m^2/s^2
Rate of energy flow: Watt = Joule/s

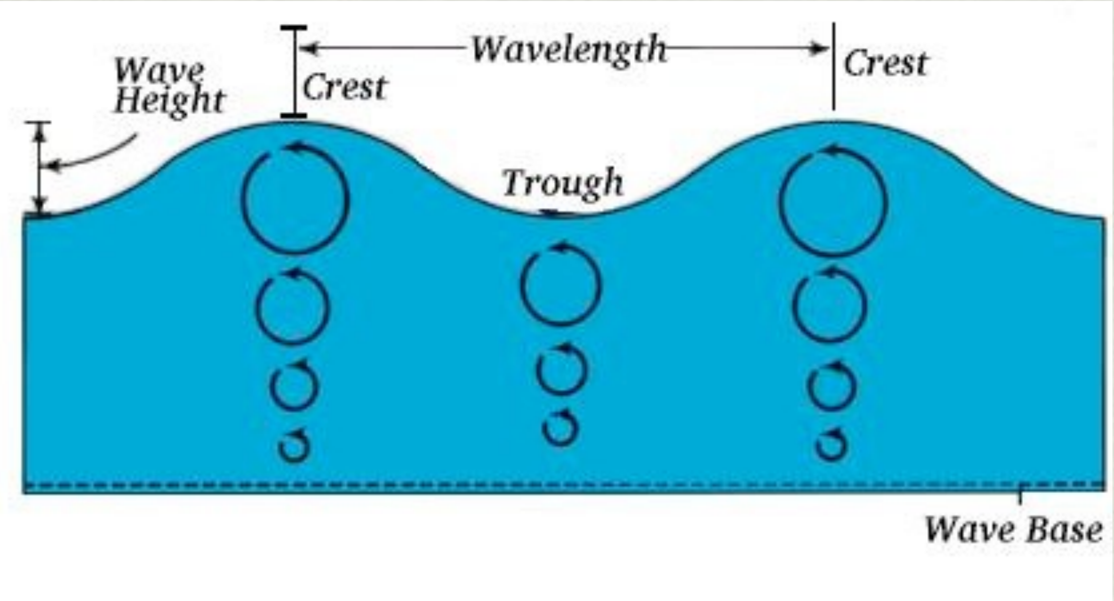
Rate at which energy comes from or goes to an object

Light and Waves

What is light? A wave

What is a wave? A pattern that can transport energy without carrying matter with it.

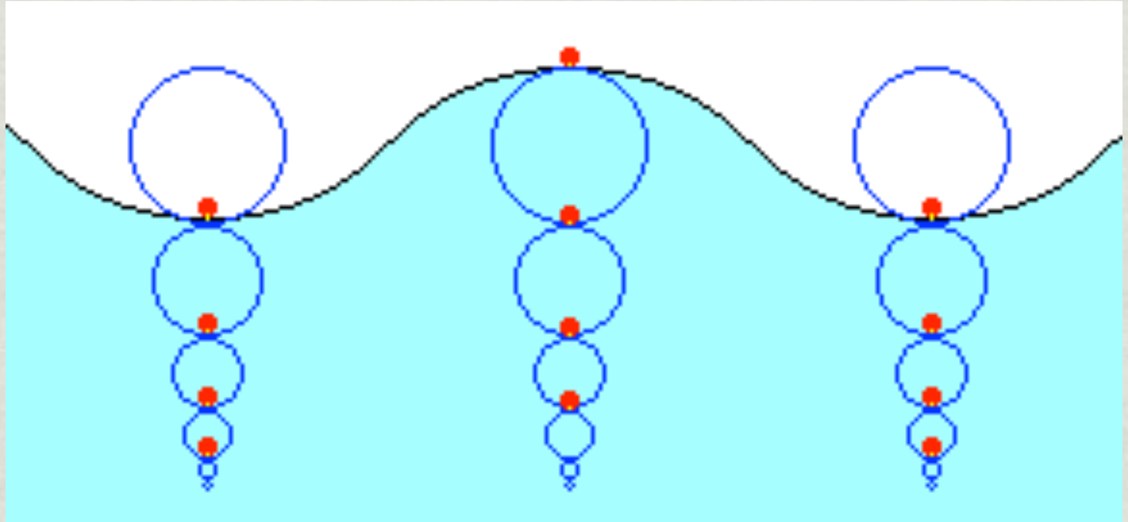


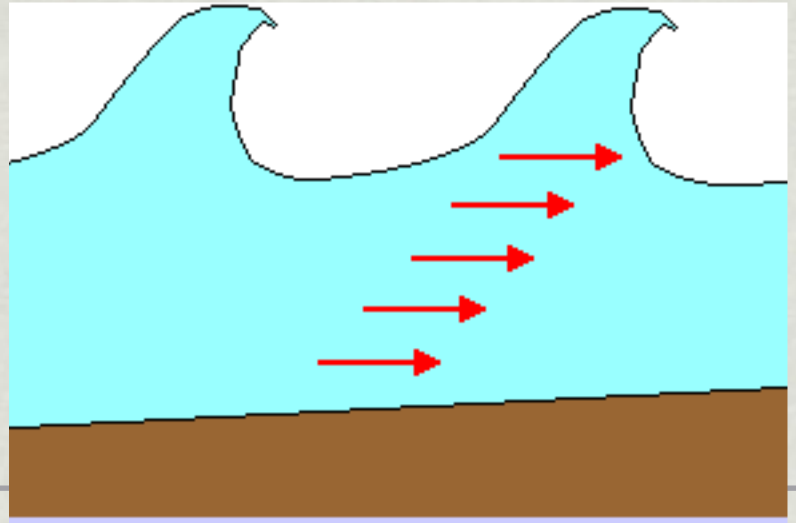


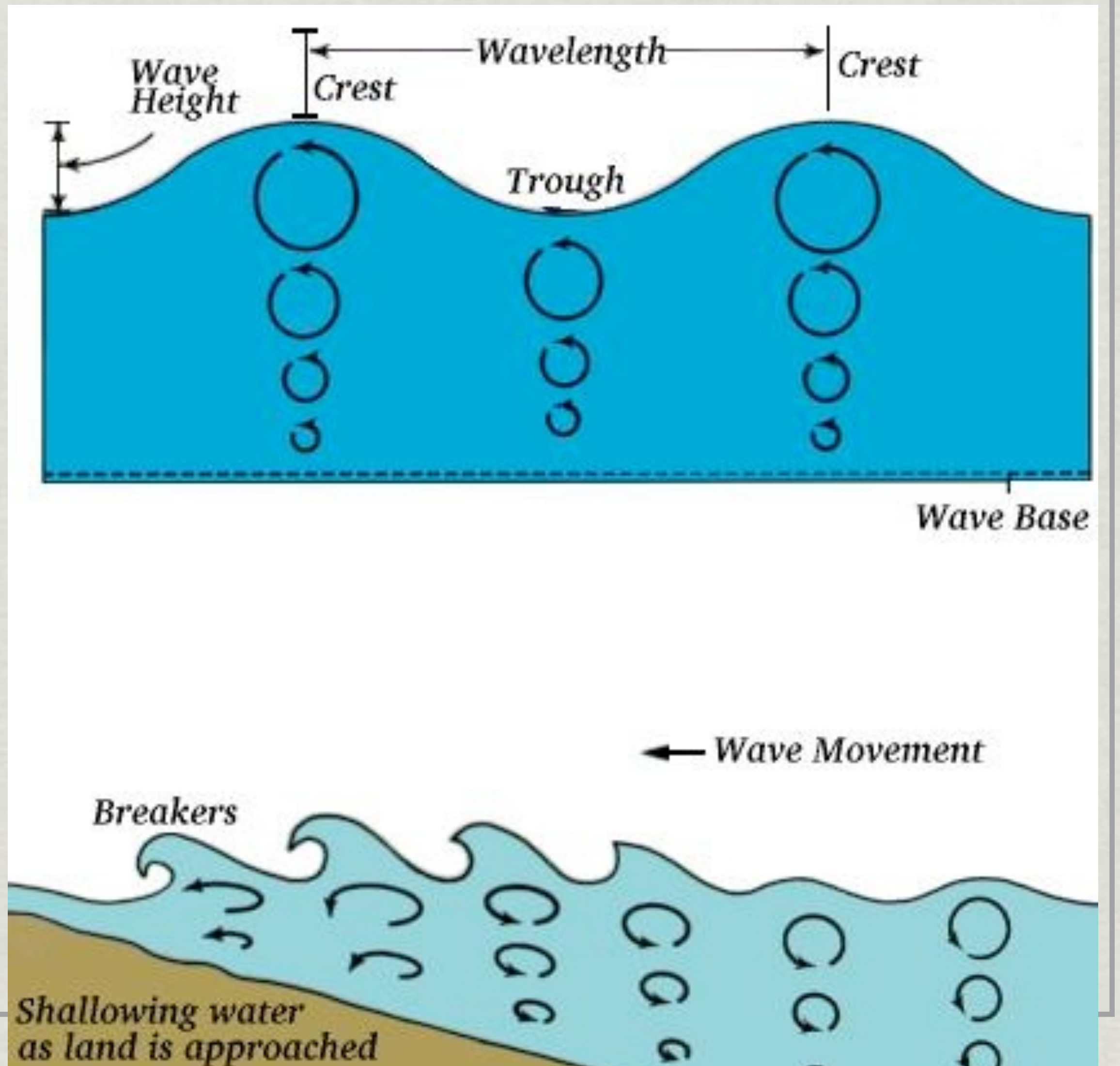
Water Waves

“What do you mean, without carrying matter?!?
When a wave breaks, water comes up on the beach and knocks me over!”

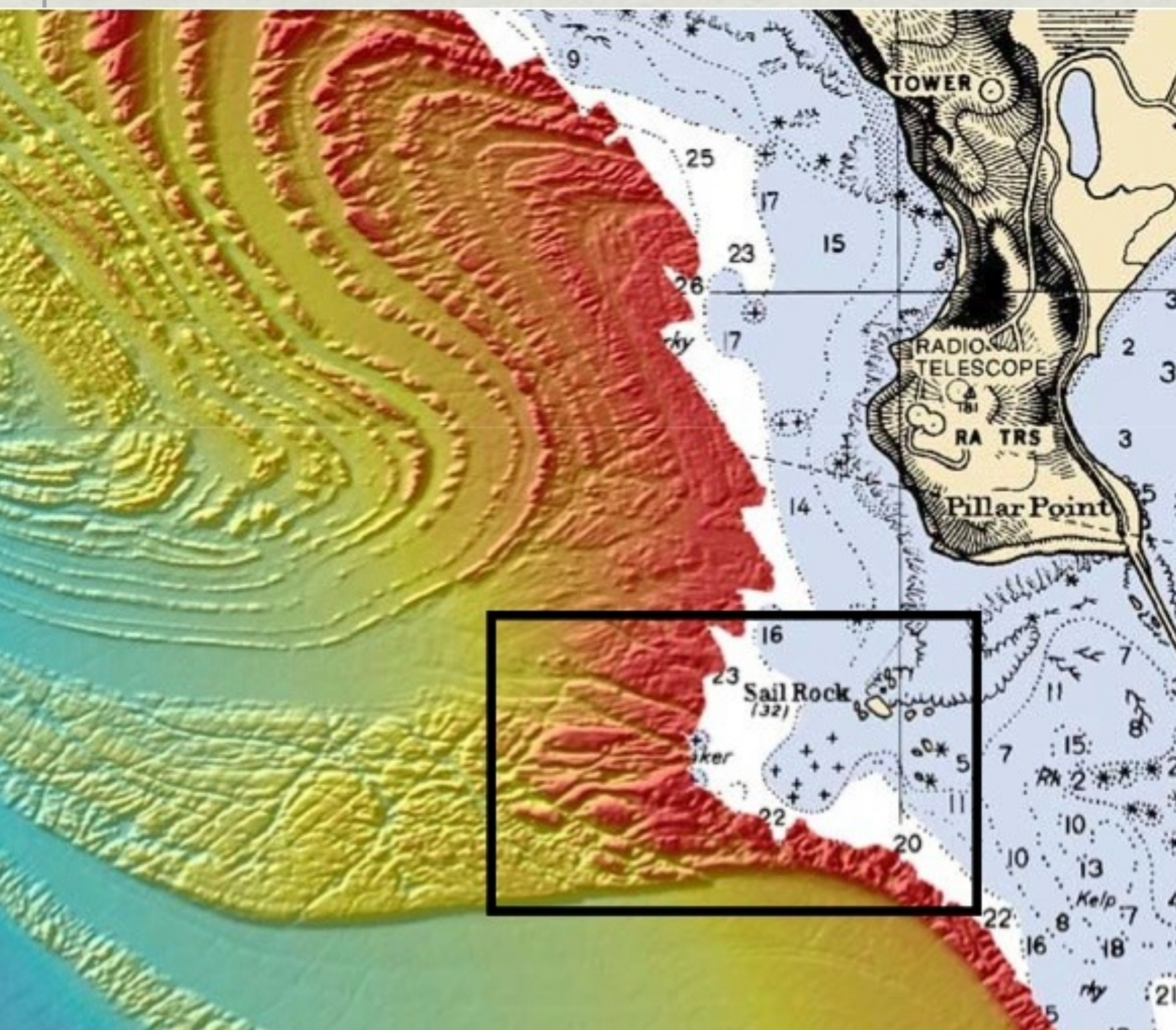
Near shore, friction slows the bottom of the wave. Water at the surface keeps moving, “piles up” and now water moves, too, as the wave “breaks”. Light doesn’t do this.

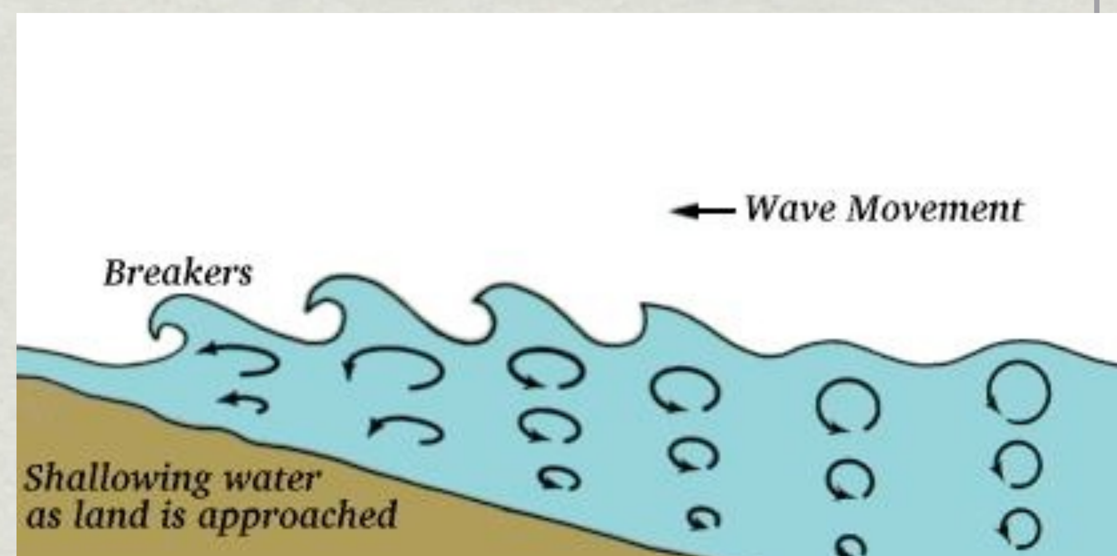






A famous “break”: Mavericks
The ocean bottom slopes up like ramp toward shore, lots of time for wave energy to cause water to pile up into huge waves





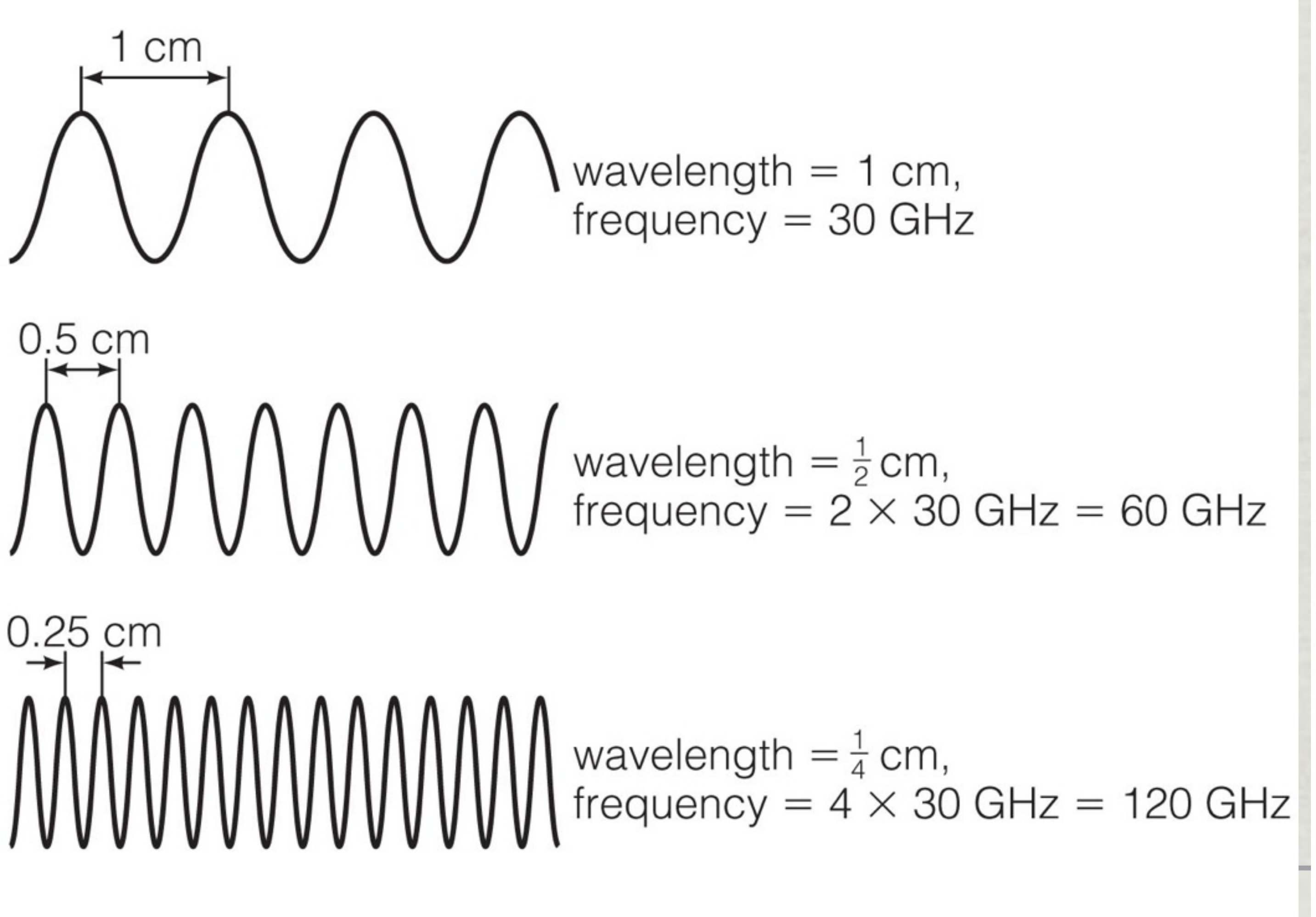
Describing Light

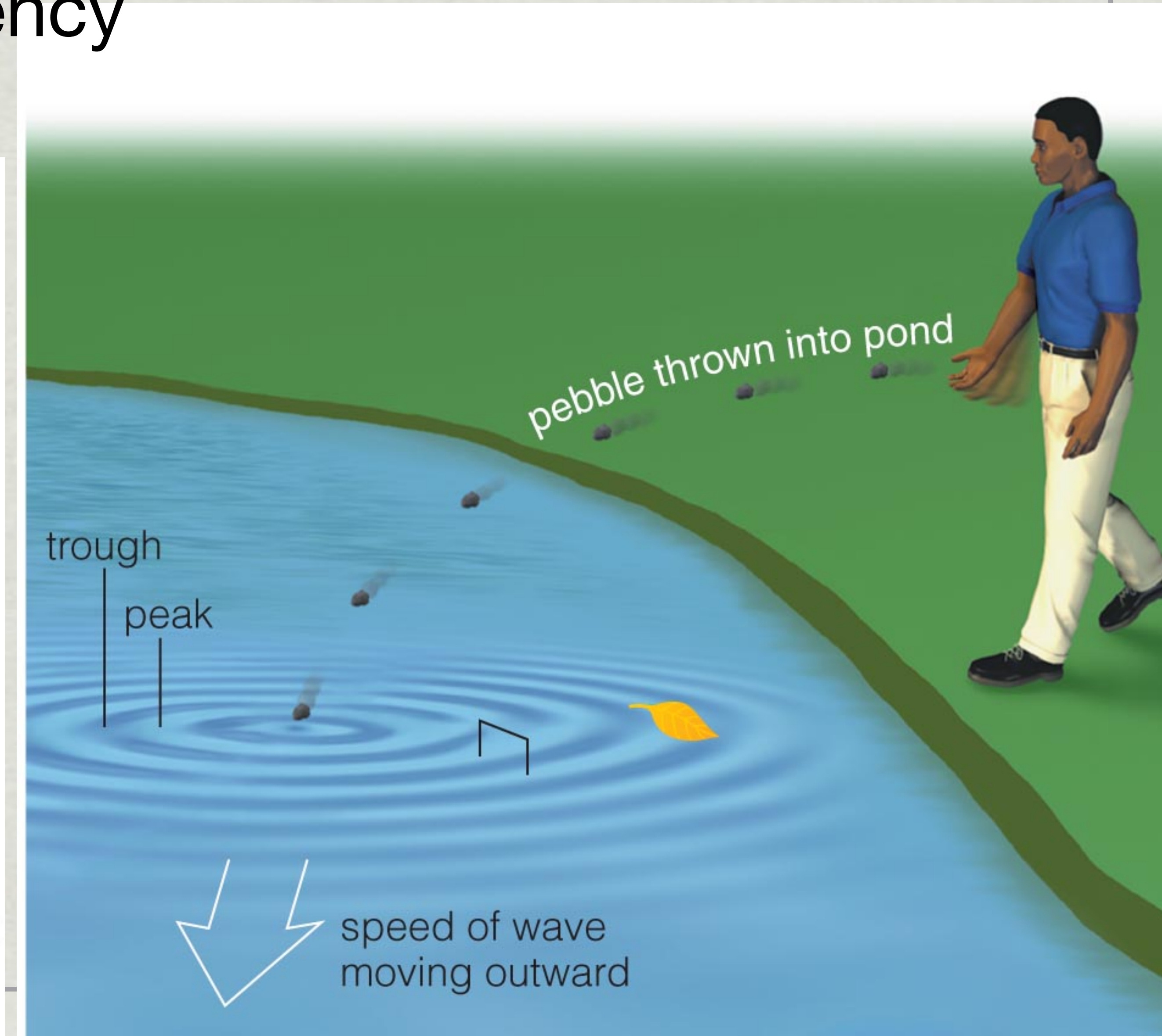
Wavelength: distance between two wave peaks
symbol: λ Units: meters

Frequency: number of times per second a wave vibrates
symbol: ν Units: sec^{-1}

Wave speed: wavelength x frequency

Wave speed: λ x ν





Light

What is light? Photons

What is a photon? An "energy packet"

Light

What is light? Photons
What is a photon? An “energy packet”

Energy carried by a single photon is related to its wavelength and frequency:

$$\text{Energy} = E = h\nu = \frac{hc}{\lambda}$$

λ = wavelength Units: meters
ν = frequency Units: sec^{-1}
c = speed of light
3×10^8 m/s = 300,000,000 m/s
h = Planck’s constant
6.626×10^{-24} Joule sec

Planck’s constant h:
Same everywhere in the universe (like G, a “universal constant”)
Sets how wave size relates to the amount of energy in a photon packet

Light

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$$E = h\nu = \frac{hc}{\lambda}$$

Energy increases if ν increases: wave vibrates faster

Energy decreases if λ increases: wave size gets larger

Light

Intensity: total number of photons emitted by a source (like the sun, a lamp, etc.)

Can have low intensity (dim) or high intensity (bright) light of any wavelength (color)

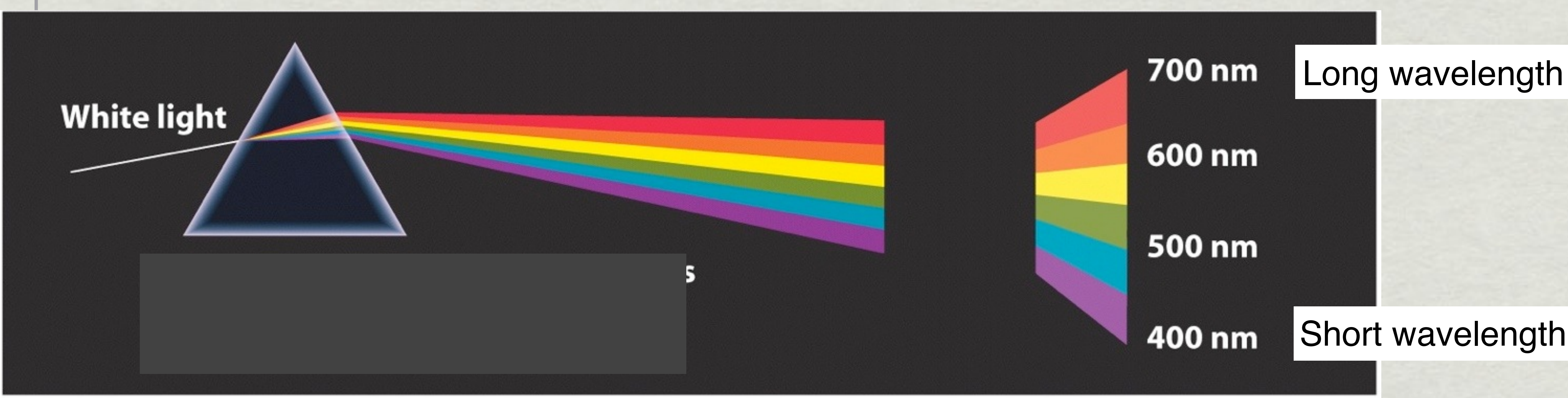
Energy of a photon = $E = h\nu = \frac{hc}{\lambda}$

Light

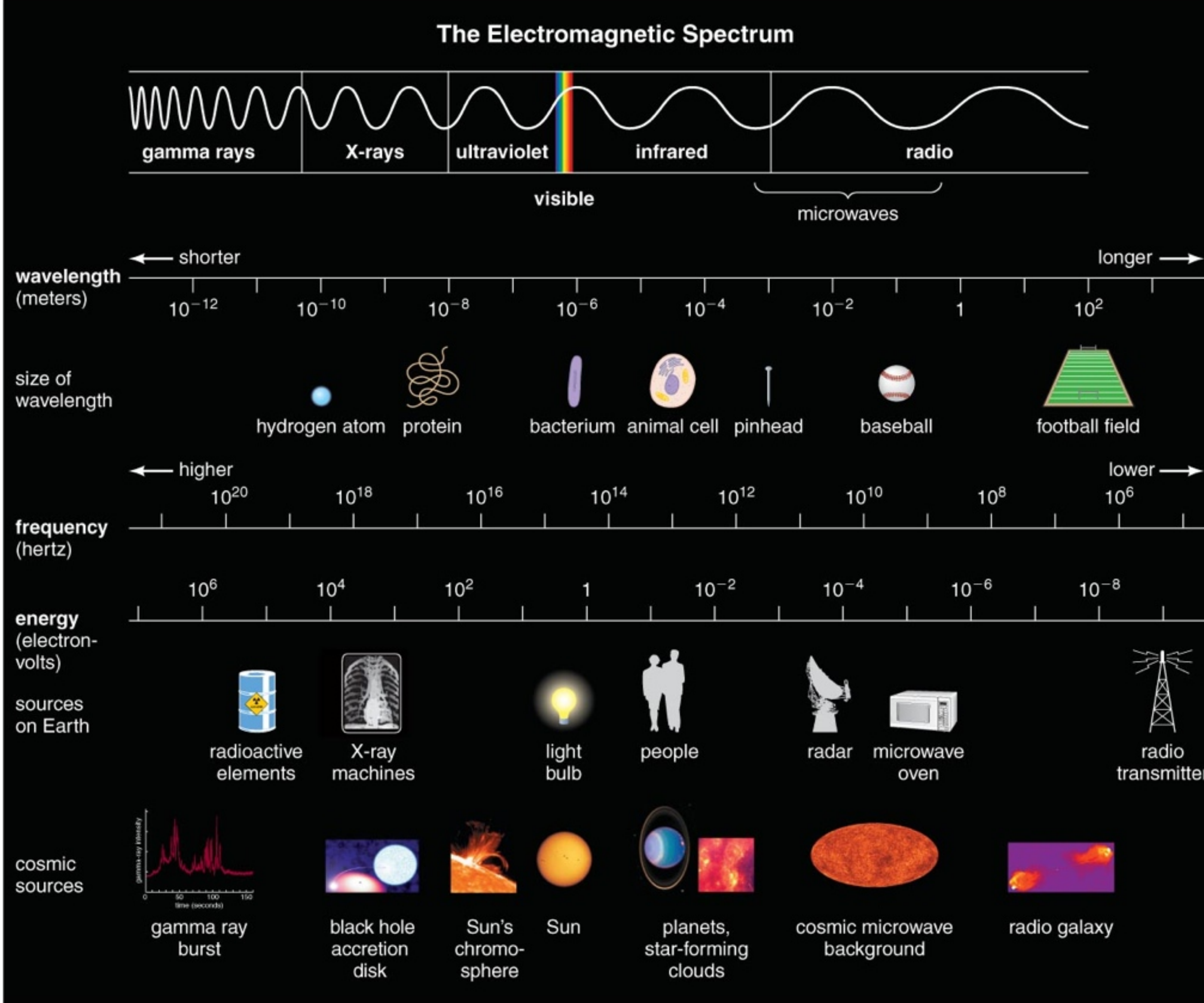
Prisms bend the path of photons according to their energy
White light contains a ***continuum*** of energies (wavelengths)

Our eyes are photon detectors!

We see the energy of photons as the color of light
Different colors = different wavelengths of light,
photons of different energies



$1\ \text{nm} = 1\text{x}10^{-9}\ \text{m} = 1\text{x}10^{-6}\ \text{mm}$


The Electromagnetic Spectrum
gamma rays
X-rays
ultraviolet
visible
infrared
radio
microwaves
shorter
longer
wavelength (meters)
10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}
size of wavelength
hydrogen atom
protein
bacterium
animal cell
pinhead
baseball
football field
higher
lower
frequency (hertz)
10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6}
energy (electron-volts)
10^{6} 10^{4} 10^{2} 1 10^{-2} 10^{-4} 10^{-6} 10^{-8}
sources on Earth
radioactive elements
X-ray machines
light bulb
people
radar
microwave oven
radio transmitter
cosmic sources
gamma ray burst
black hole accretion disk
Sun's chromo-sphere
Sun
planets, star-forming clouds
cosmic microwave background
radio galaxy

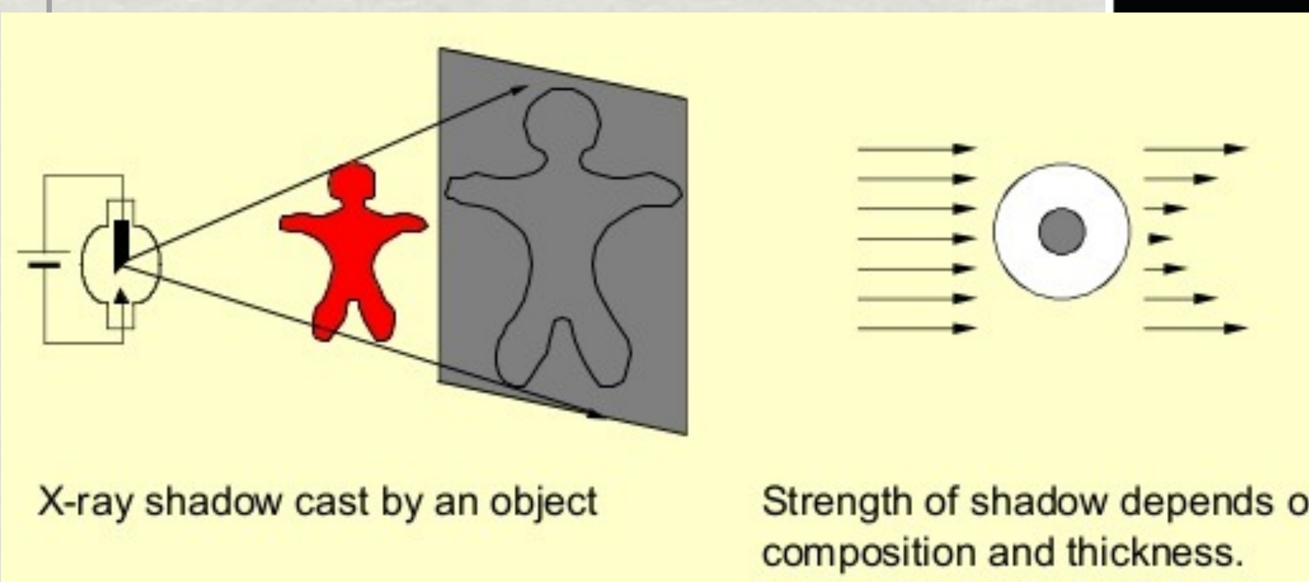
X-rays: high energy photons

- Difficult to interact with matter.
- X-ray photons zoom right through low density things.

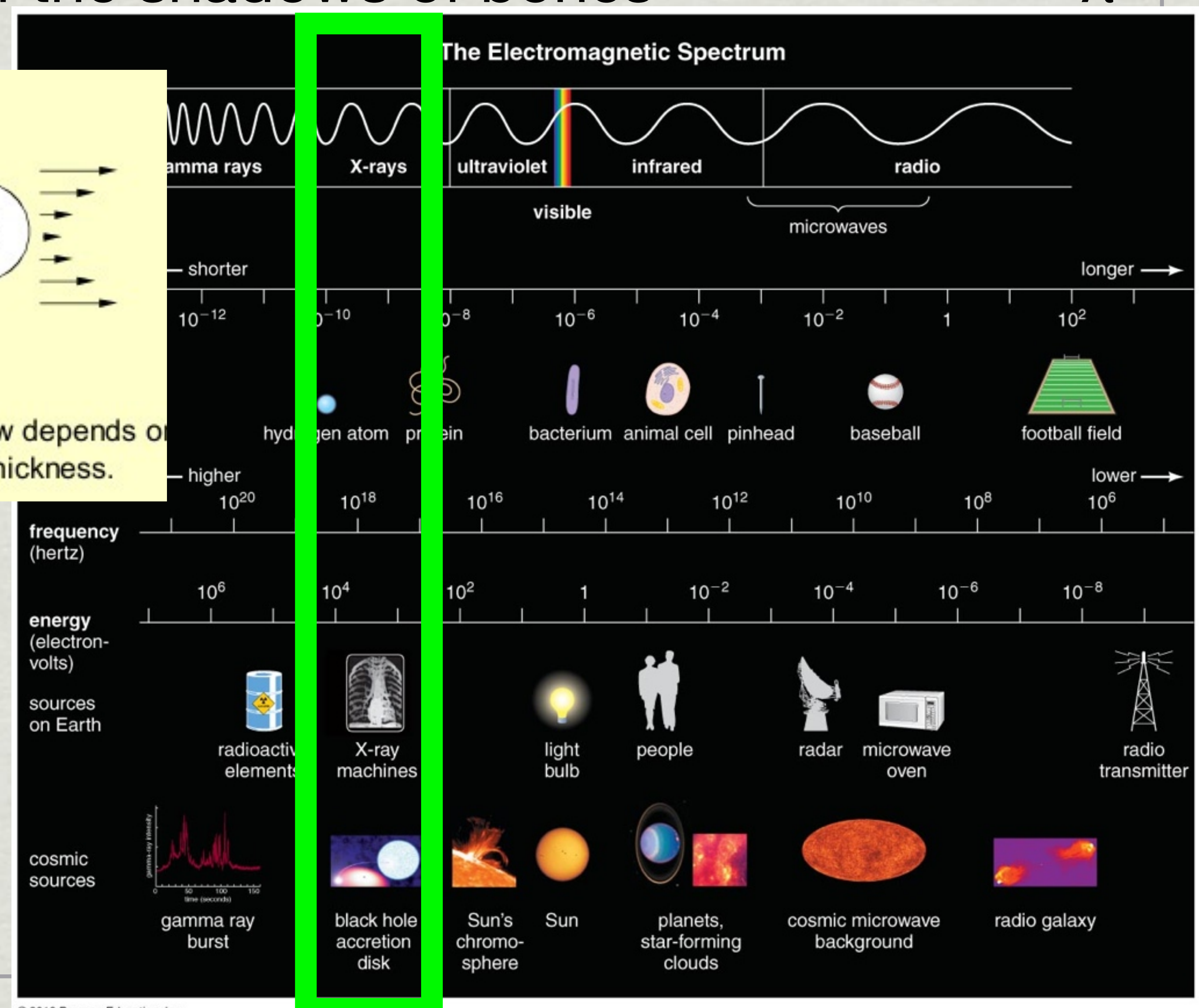
Get absorbed/blocked by higher-density things (like bone)

More x-rays are absorbed by bone than soft tissue $E = h\nu = \frac{hc}{\lambda}$

X-ray images are images of the shadows of bones



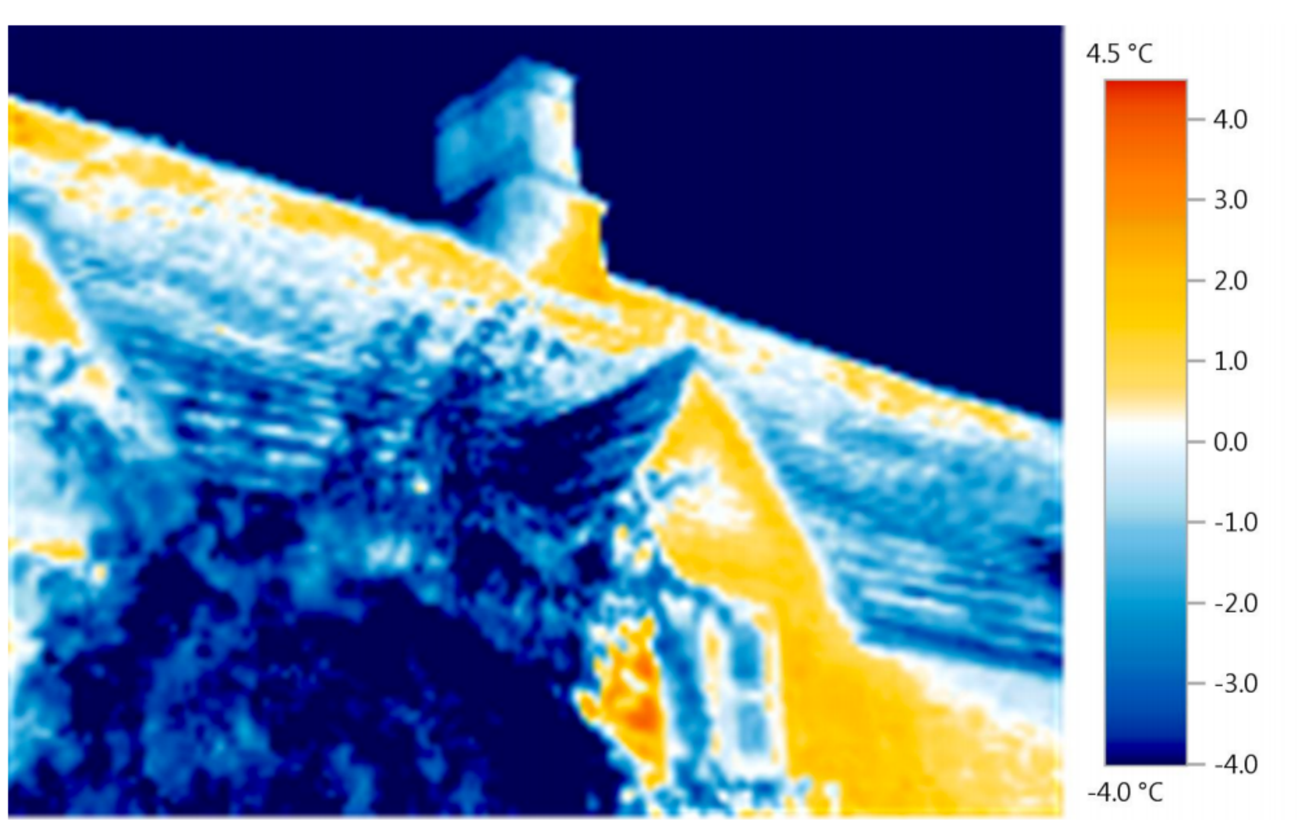
first medical use: ~1896

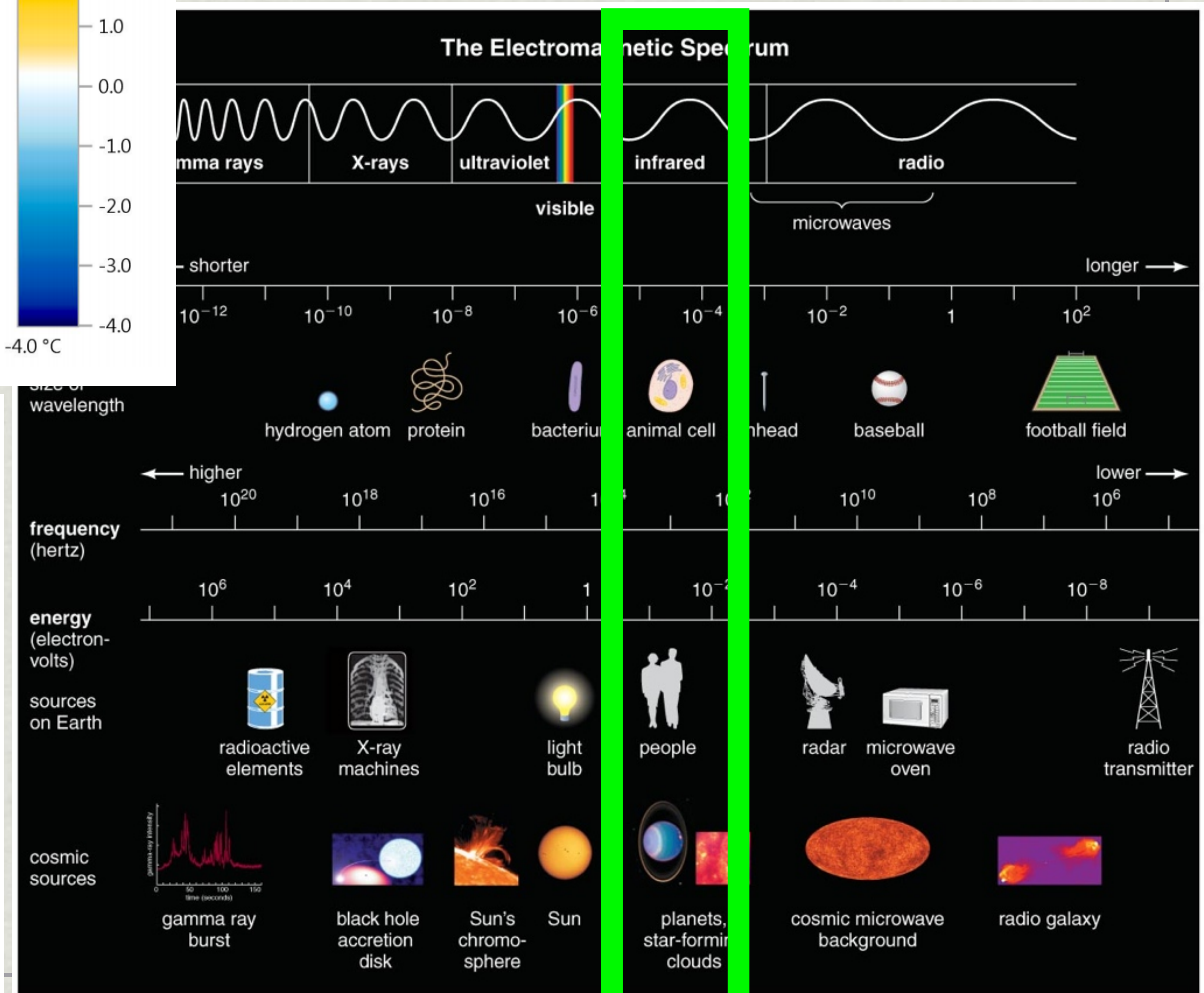


Infra-red (thermal) radiation

$\lambda \sim 1000 - 10000$ nm

$$E = h\nu = \frac{hc}{\lambda}$$

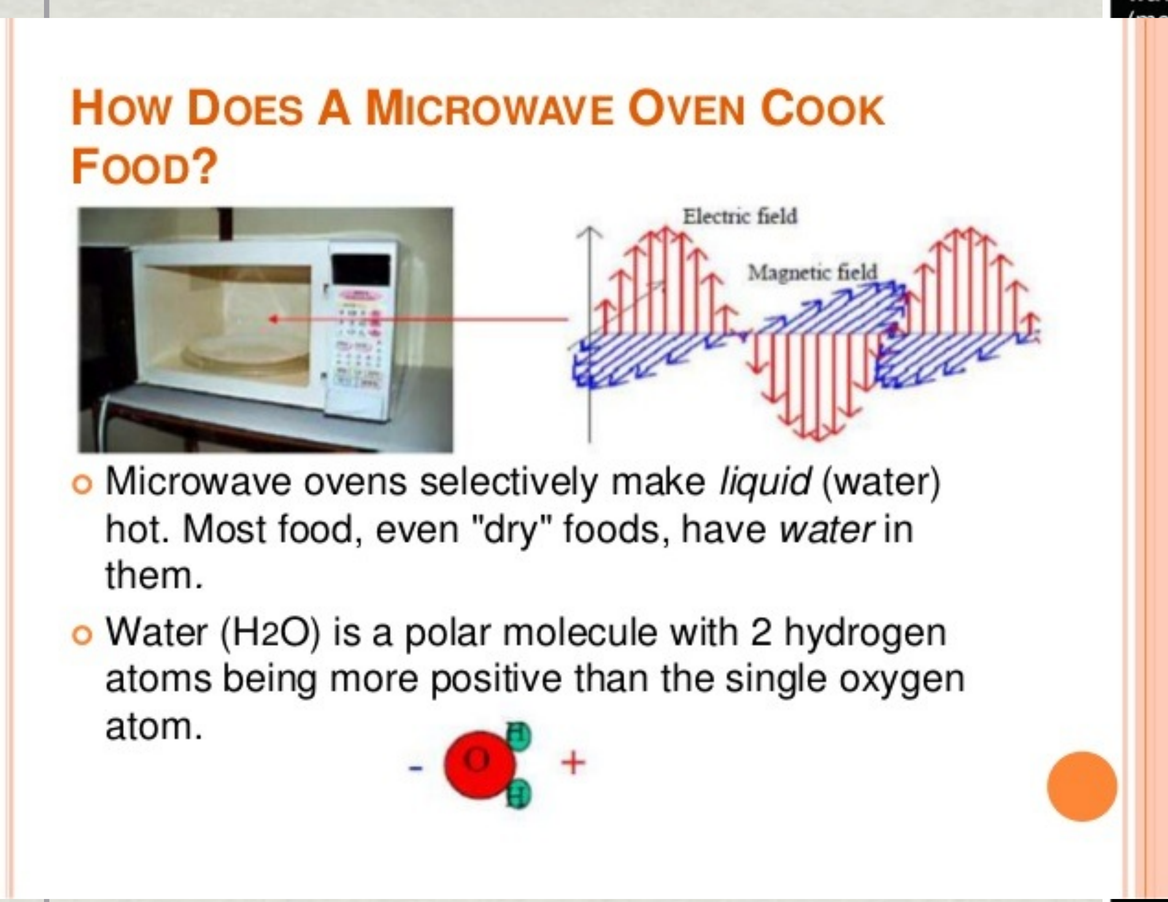


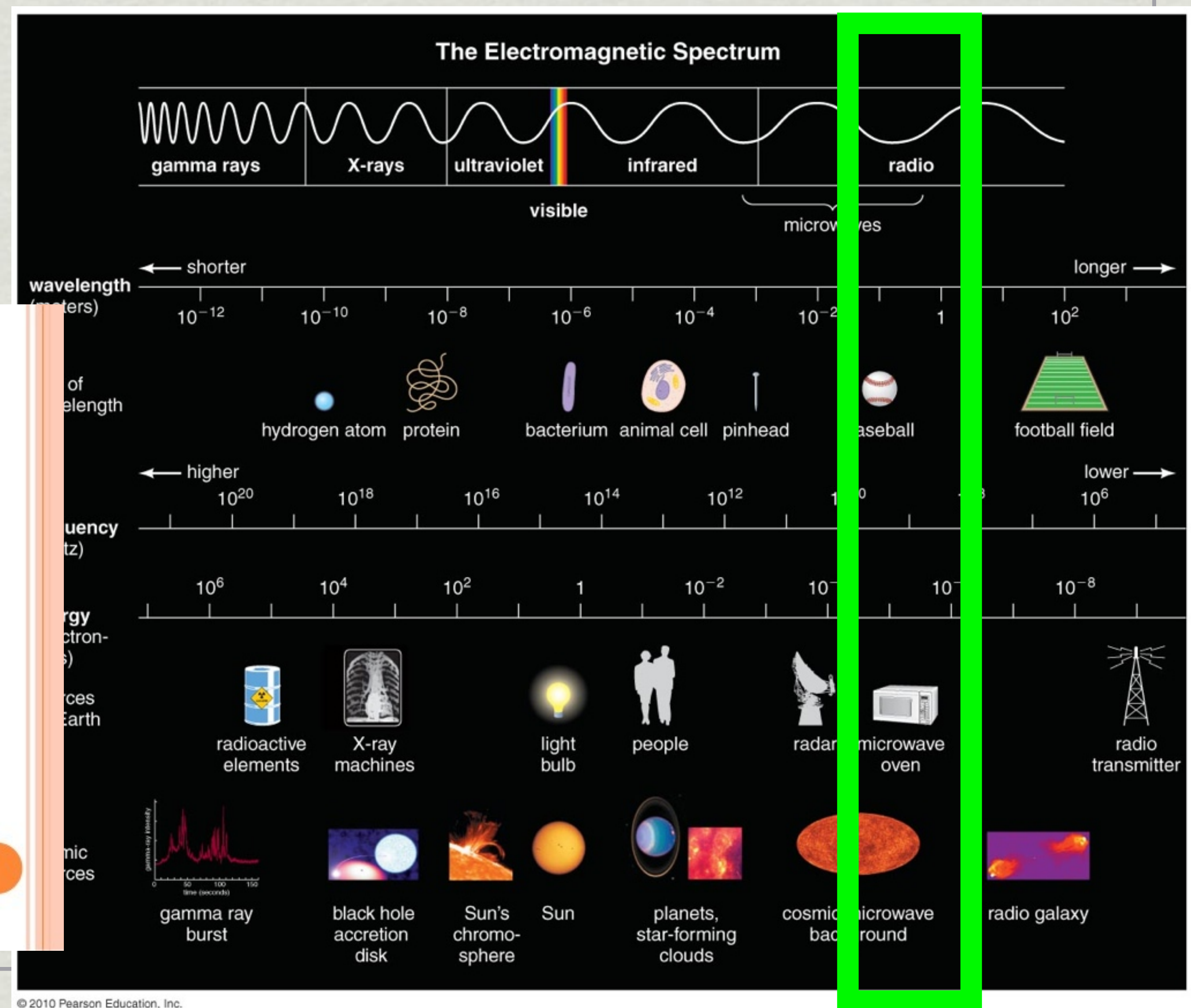


microwave oven: 2.45 GHz
(wireless 801.11b = 2.4 GHz!)

$\lambda \sim 12$ cm

$$E = h\nu = \frac{hc}{\lambda}$$





Light

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What is a photon? An “energy packet”

Energy carried by a photon is related to its wavelength and frequency:

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wave vibrates faster

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wave size gets larger

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iClicker question:
Which part of the sign emits light at higher frequency ν?

A OPEN
B square frame

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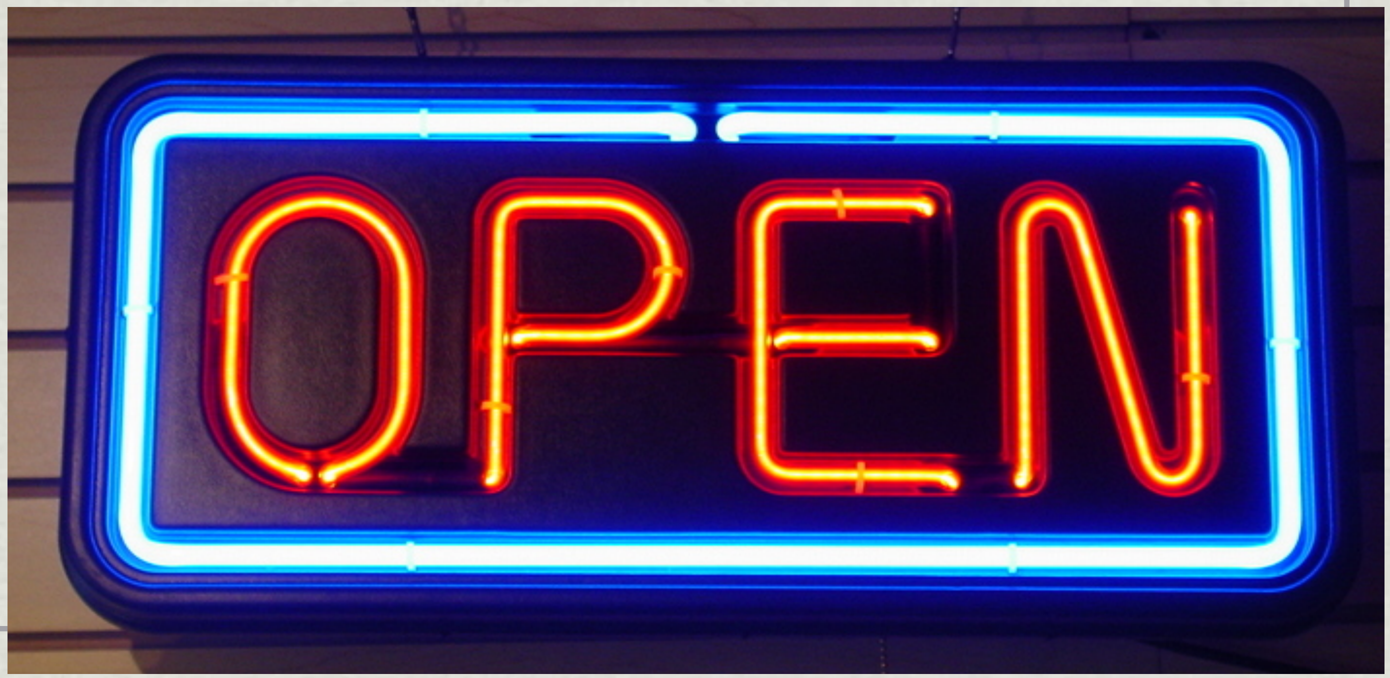


Light

Light can interact with matter because light delivers energy

- Atoms can absorb and emit photons
- Light can transfer its energy and heat matter
- Matter can transmit, reflect or scatter light

Scattering vs. Transmission

- Opaque objects: reflect and scatter light, don't let it pass through (don't transmit)
  - opaque = dense
  - chairs, you, me, planets, dust particles
  - A mirror: very smooth, scatters in only one direction: reflection
  - Most things (chairs, screens, ...) are rough, scatter in all directions
  - Color: things that have color scatter light at one wavelength more than others

Scattering vs. Transmission

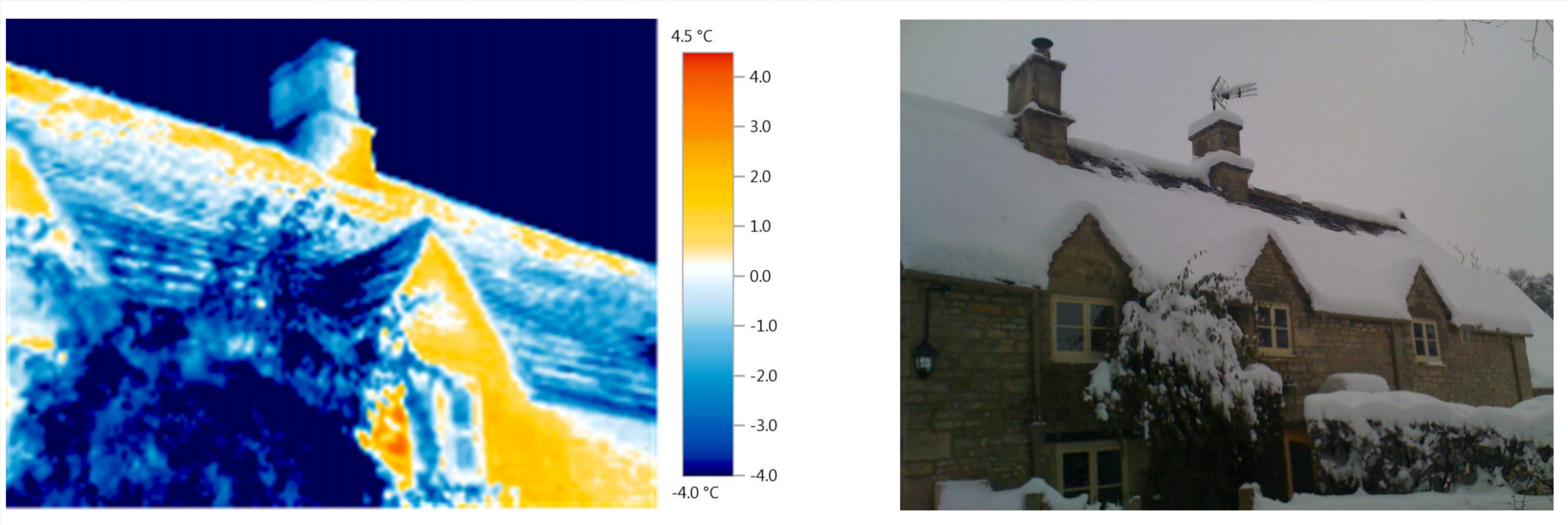
- Transparent objects do not scatter or reflect light
  - Transparent = not dense
  - Clouds of hydrogen and other gas
    - like our atmosphere, in space usually less dense
  - Strange cases you’ll think of later:
    - water: yes, it does reflect and scatter
      - think about how different things look underwater
    - glass: special material, atoms let light through

Scattering vs. Transmission

- Atoms always interact with light if they can.
- In astronomy, everything we look at is very far away. What we can figure out about matter is pretty simple: Dense or not dense, opaque or transparent.
- What matters for what we see out in the universe: how densely spaced the atoms are

Thermal Emission

- All dense, opaque objects emit thermal radiation
  - you, me, chairs, plants, dust particles...stars, planets...



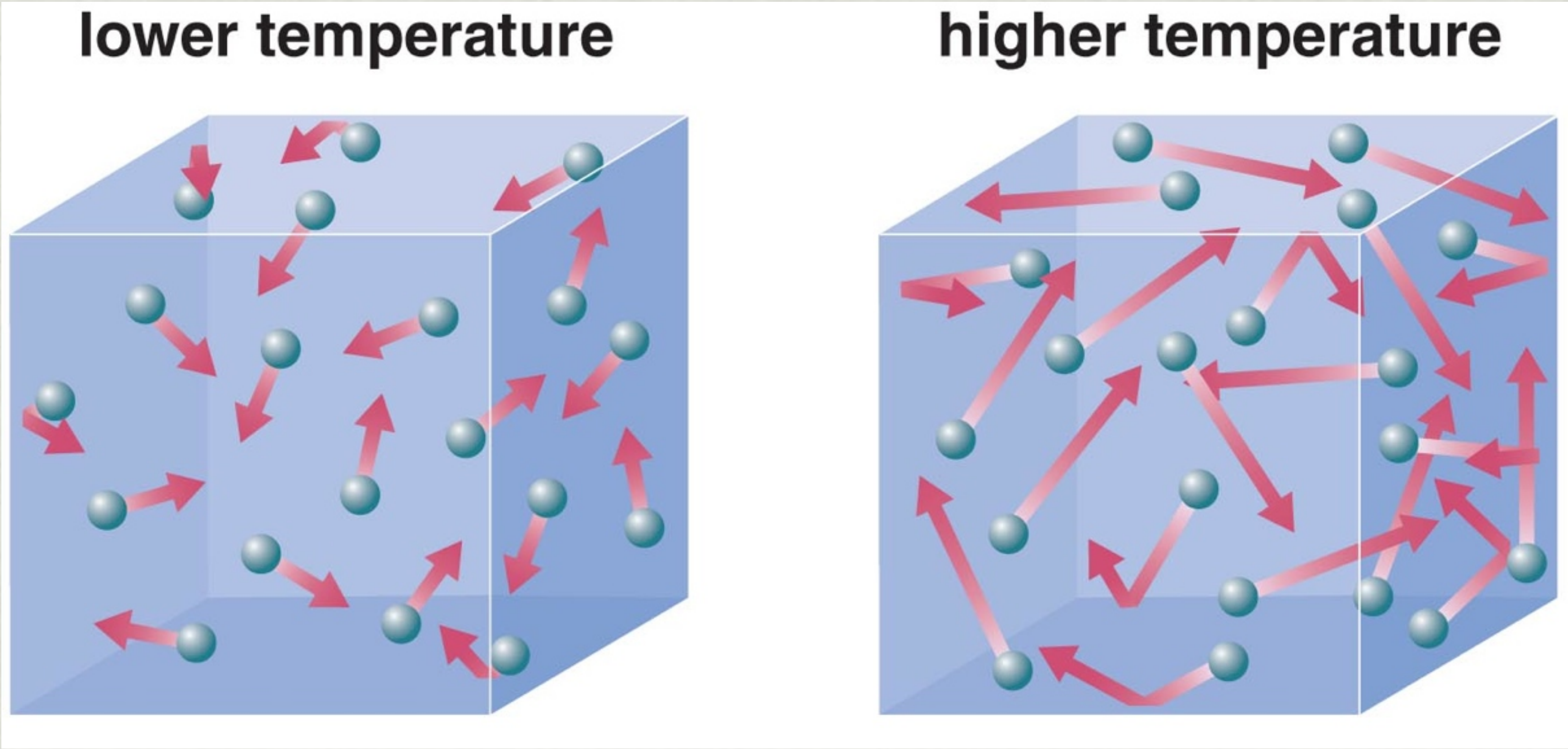
An object's thermal radiation spectrum depends on only one thing: its temperature

Thermal Emission

Some definitions:

Thermal energy: sum of kinetic energy of many particles
- all the atoms in an object

For one particle: $E_{kinetic} = \frac{m\,v^2}{2}$ For many particles: sum $E_{kinetic}$



More thermal energy

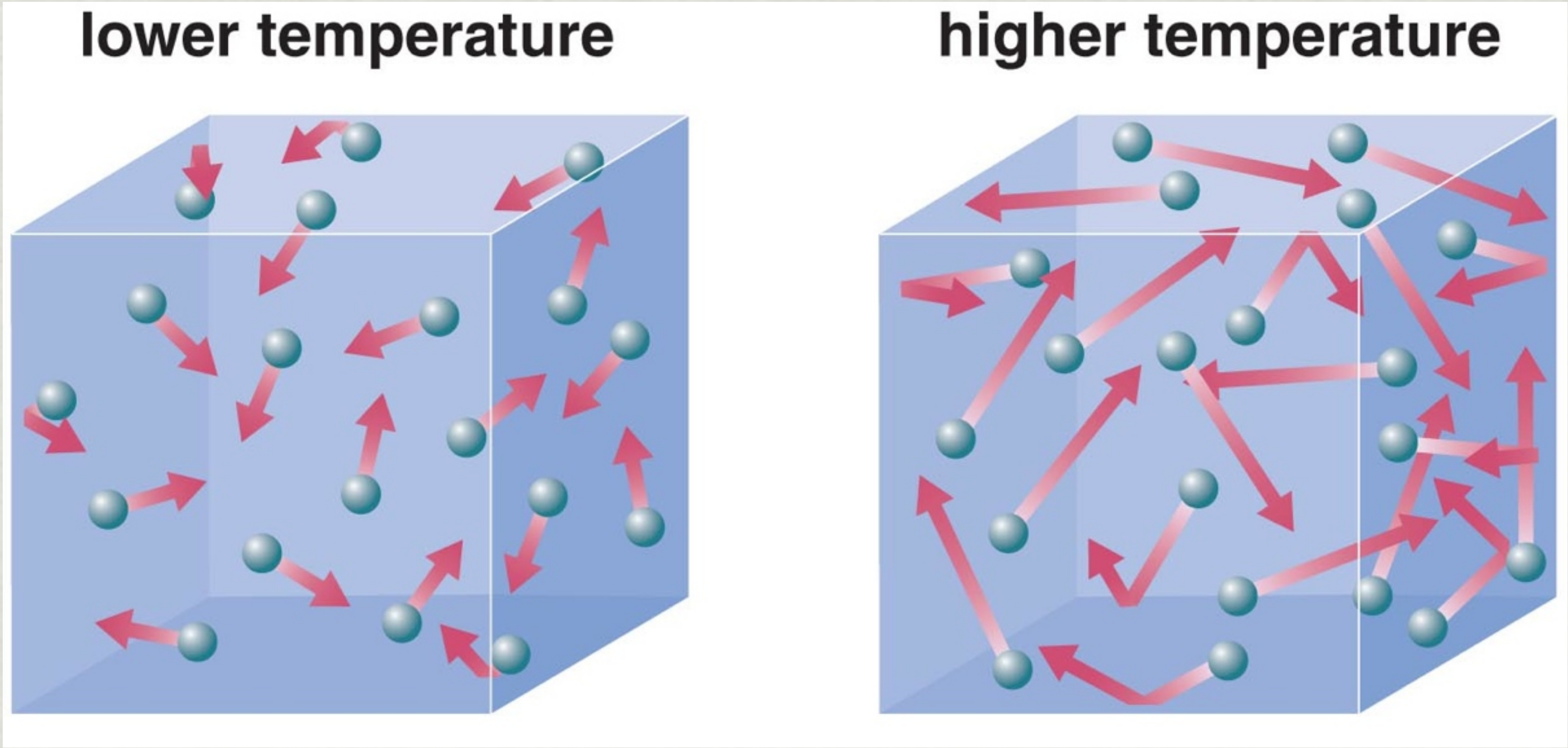
20 particles ...also 20 particles

Thermal Emission

Some definitions:

Thermal energy: combined kinetic energy of many particles
- sum of all the kinetic energy of each atoms in an object

Temperature: average kinetic energy of each particle in some object or system



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Thermal Emssion

Some definitions:

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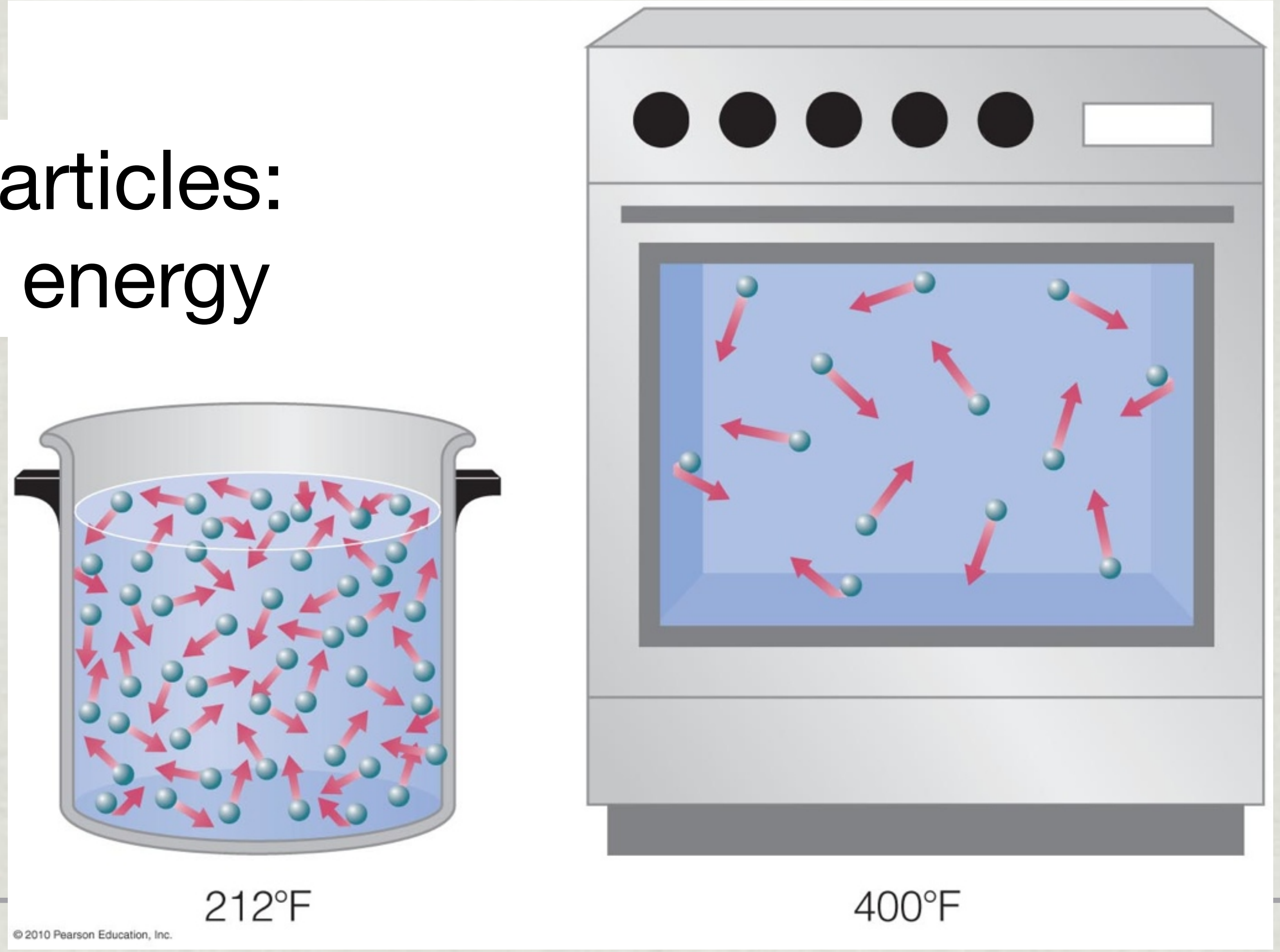
- sum of all the kinetic energy of each atoms in an object

Temperature: average kinetic energy of each particle in some object or system

Many more particles: more thermal energy



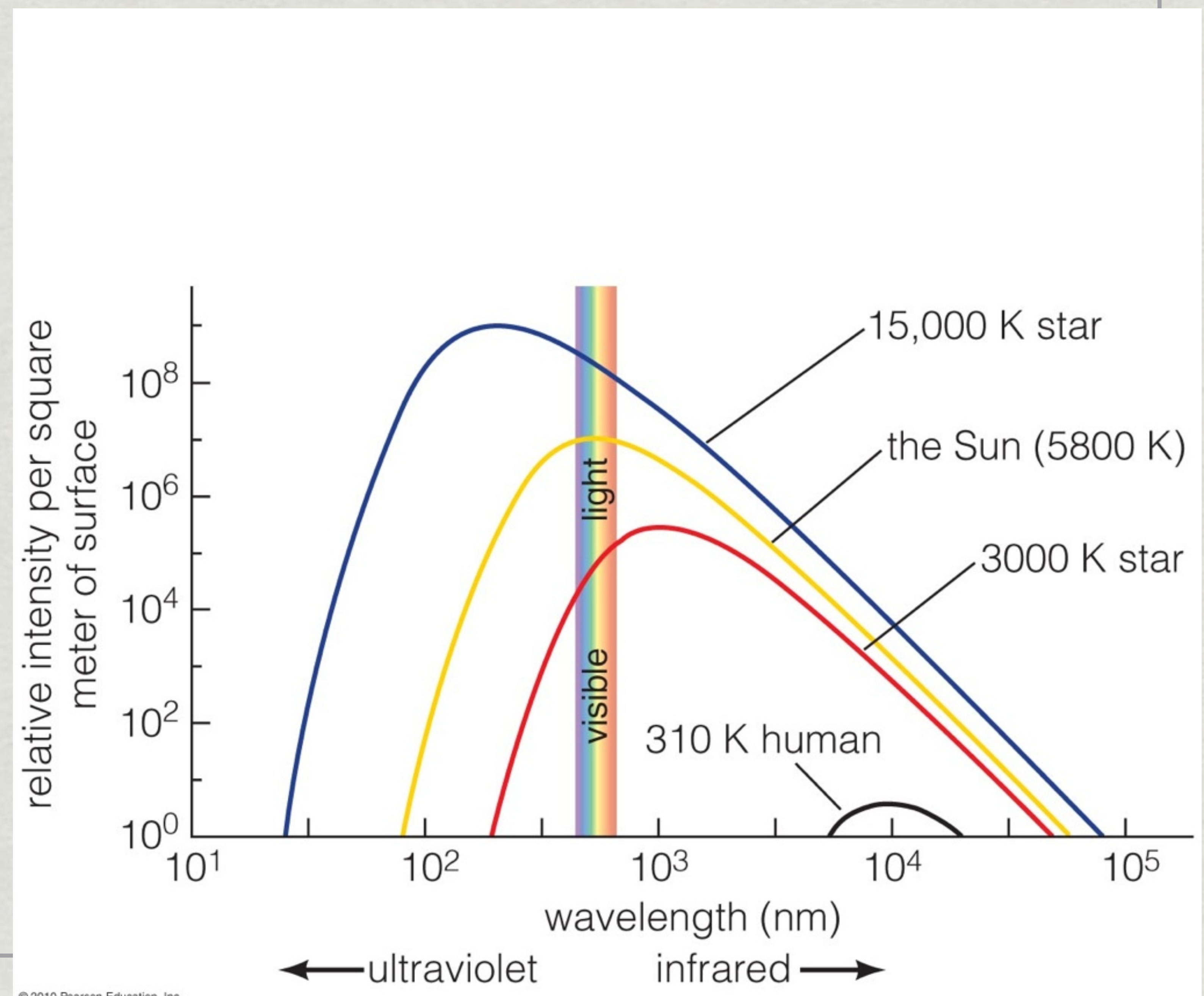
Higher average kinetic energy of a single particle: higher temperature

Thermal Emission

What is this graph? Number of photons (amount of energy) emitted at each wavelength

Total number of photons: add up intensity at each wavelength

Peak: wavelength where maximum number of photons emitted



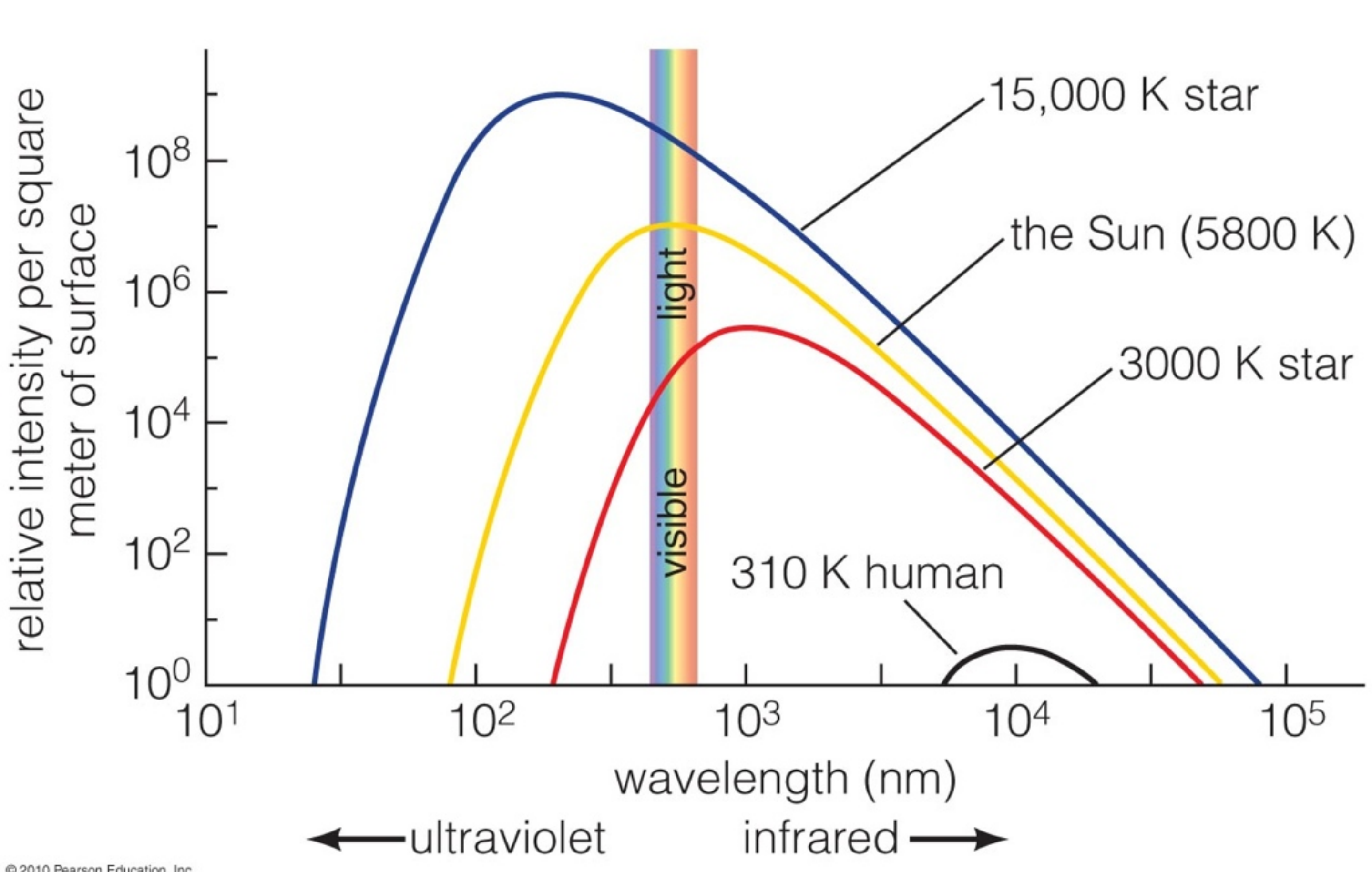
Thermal Emission

Cooler object:

- peak number of photons is emitted at red wavelengths: red color
- fewer total photons emitted: dim

Hotter object:

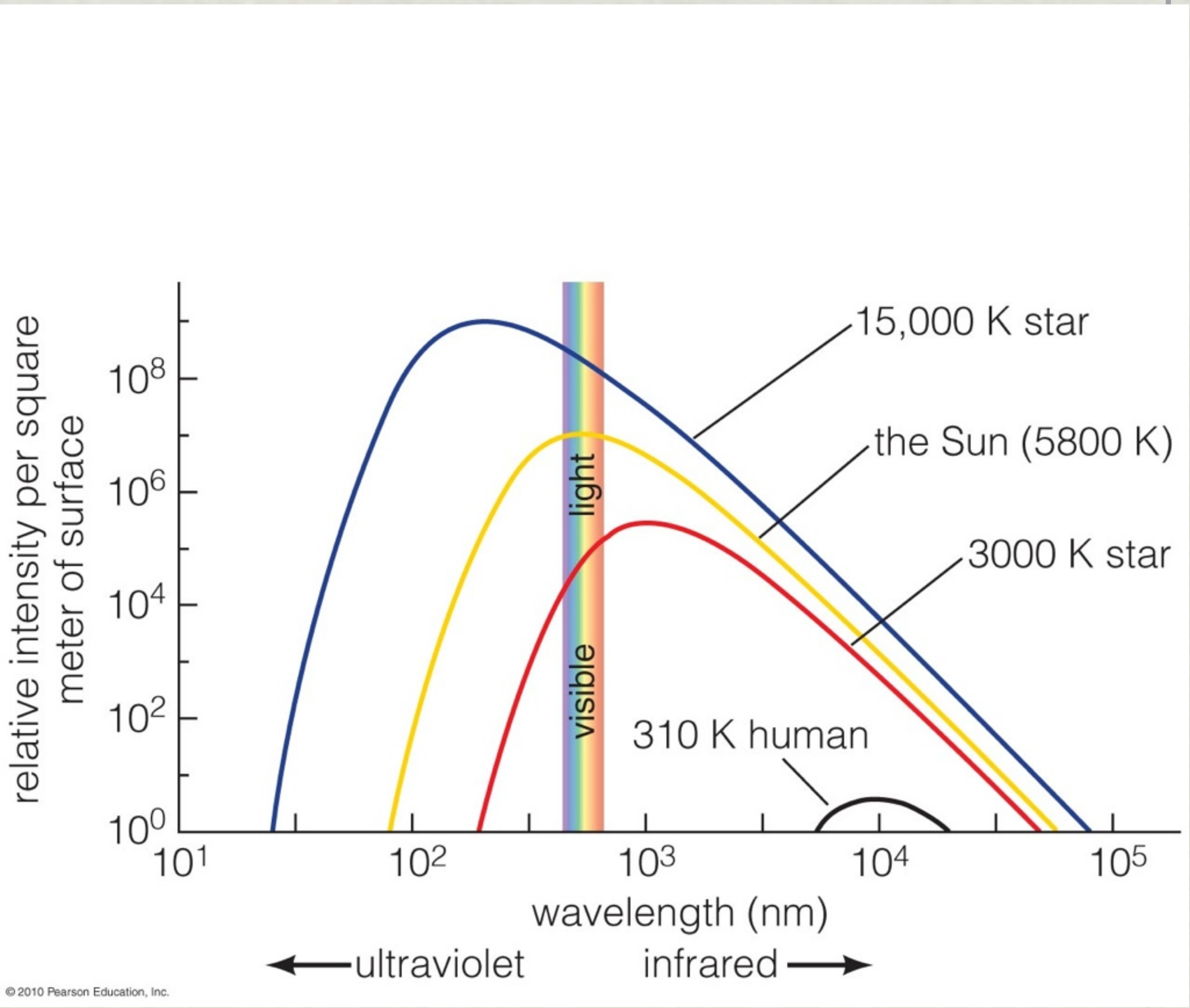
- peak number of photons is emitted at blue wavelengths: blue color
    - we see white because our eyes aren't good at seeing very blue light
- more total photons emitted: bright



Thermal Emission

Cooler object: peak number of photons is emitted at red wavelengths, fewer total photons emitted

Hotter object: peak number of photons is emitted at blue wavelengths, more total photons emitted



iClicker Question

We're dense and opaque. Do we glow in the dark?

A People don't emit any light
B We do glow in the dark. You just can't see it with your (lame) eyes
C People are too small to emit enough light for us to see
D People do not contain enough radioactive material

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Properties of Thermal Radiation

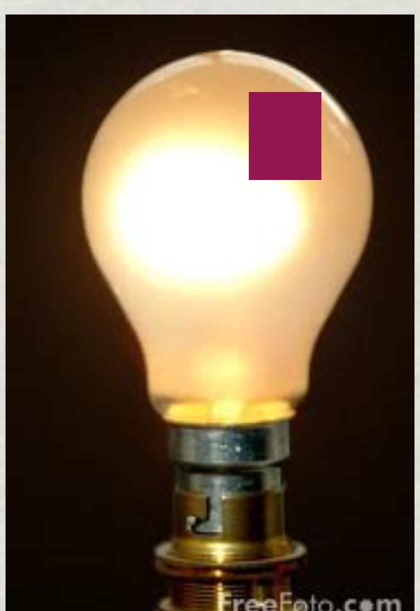
For any patch (area, m^2) on an object emitting thermal radiation:

Stefan - Boltzmann Law: hotter = brighter, more intensity: more energy flow out of any patch on the surface of the object

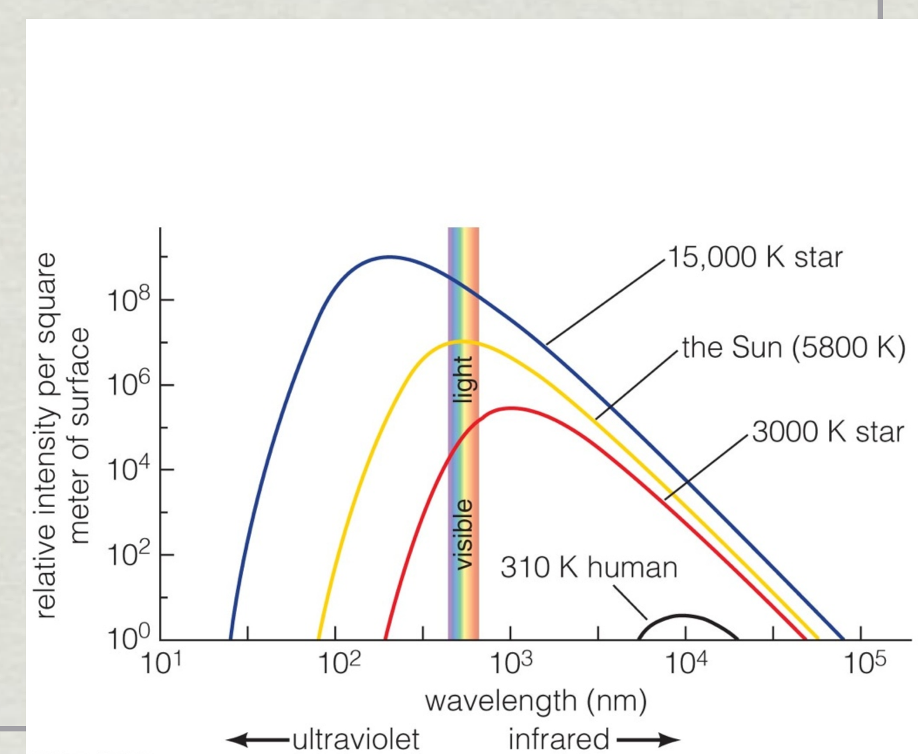
Stefan - Boltzmann Law: Energy output per patch of area on the surface of an object = σT^4

Universal constant:
$\sigma = 5.7 \times 10^{-8}$ J/(s m^2 K^4)

Stefan-Boltzmann law: energy per second out of a patch on the lightbulb depends only on its temperature:



Energy/sec/patch = σT^4

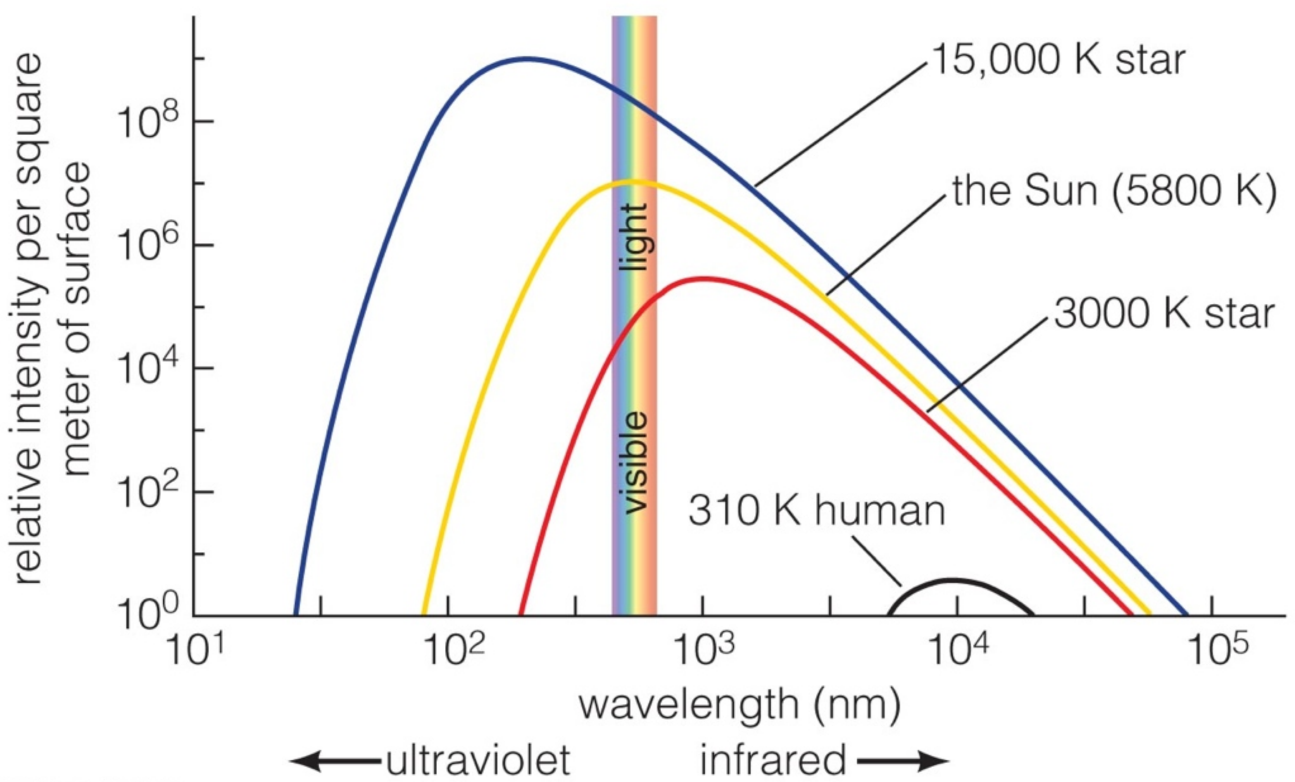


Properties of Thermal Radiation

Wien's Law: hotter object: wavelength were most of the photons are emitted is bluer

$$\lambda_{peak} = \frac{2.9 \text{ mm K}}{T}$$

← divide 2.9 by temperature in K to get peak wavelength in mm



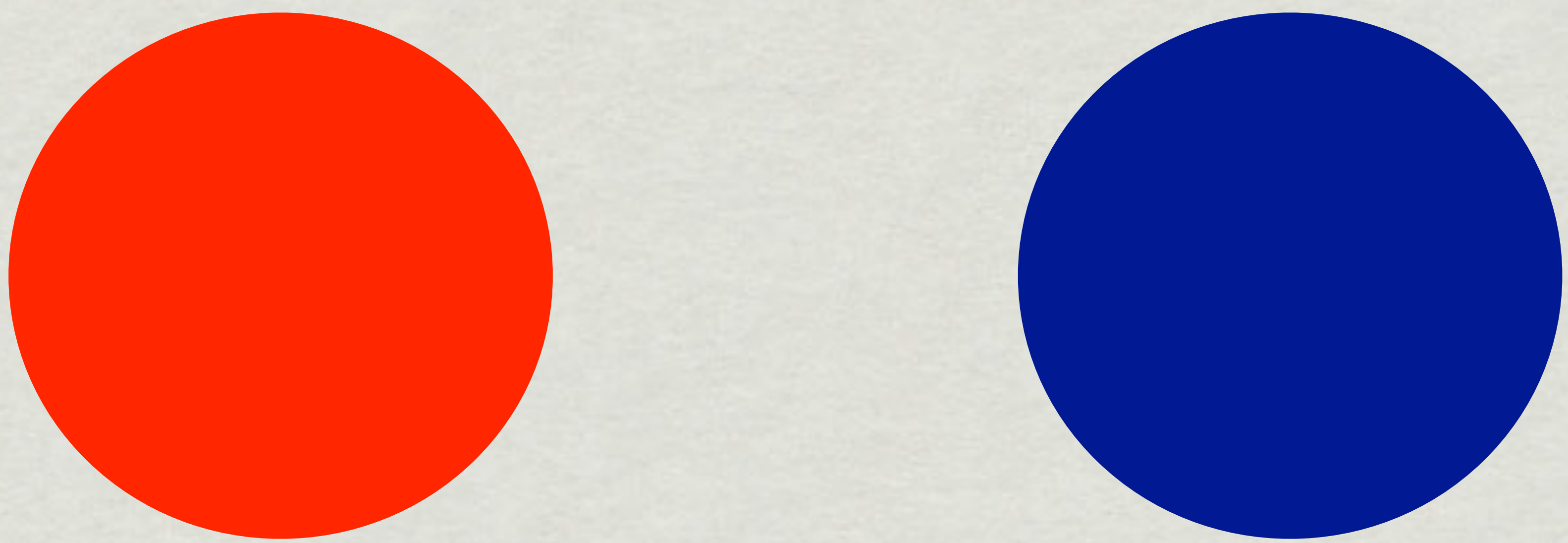
Or:

Rearrange and rewrite Wein's Law as:

$$T = \frac{2.9 \text{ mm K}}{\lambda_{peak}}$$

divide 2.9 by peak wavelength in mm to get temperature in K

Which object is hotter?



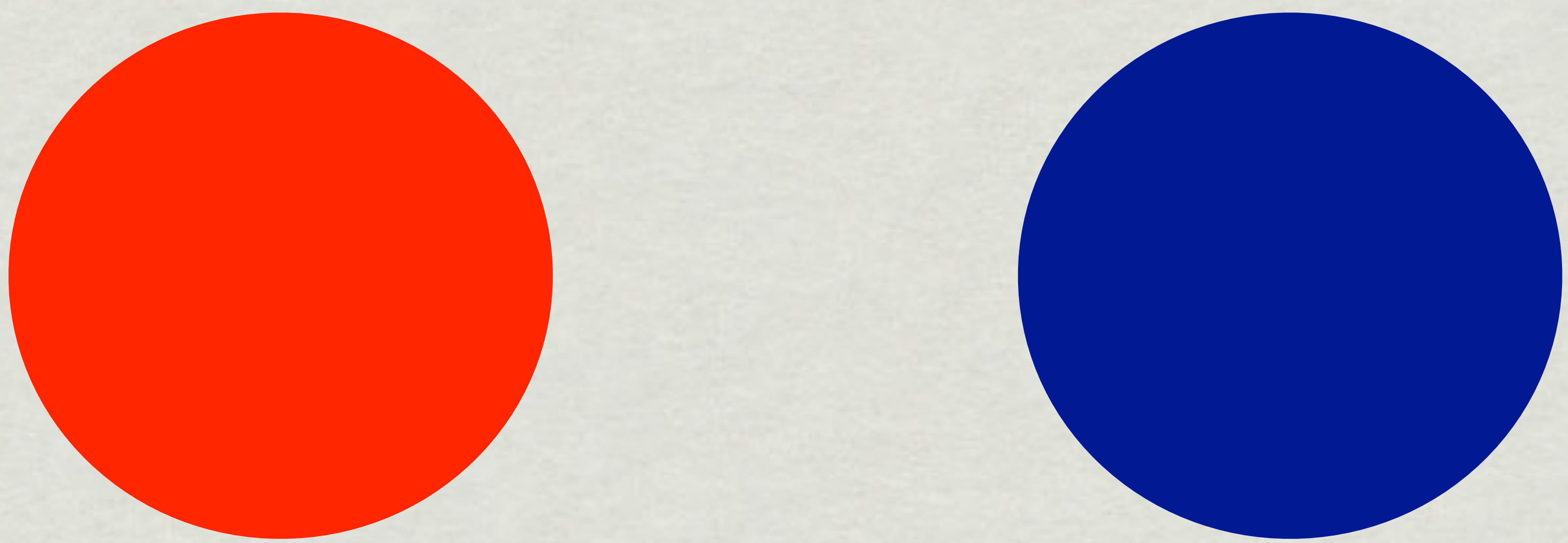
Wein’s Law:

$$\lambda_{peak} = \frac{2.9 \text{ mm K}}{T}$$

Which object is hotter?

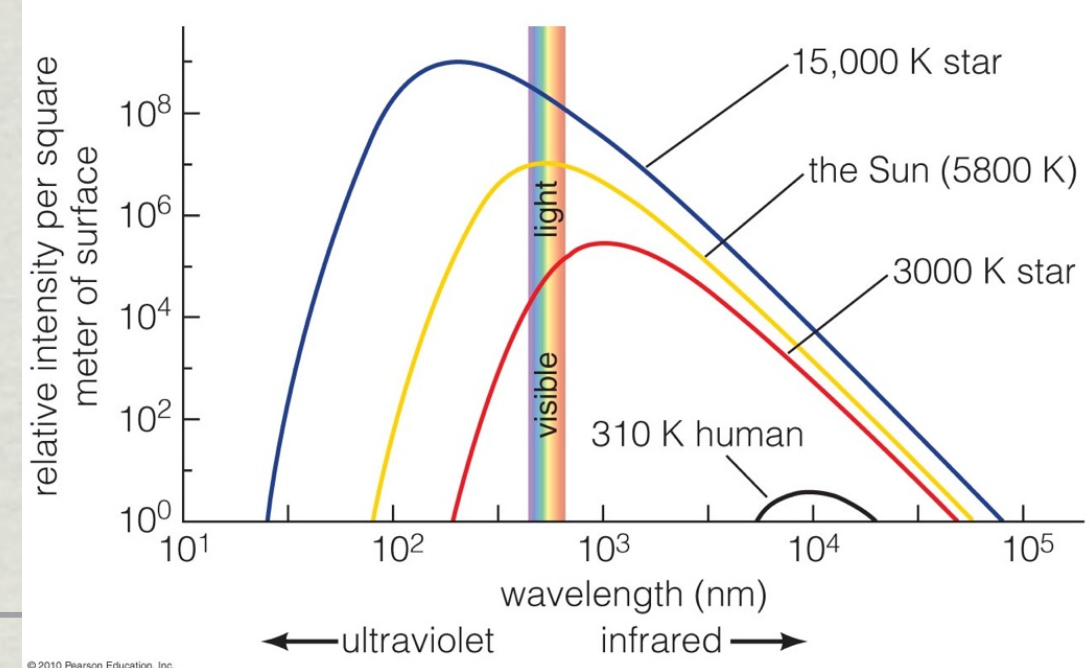
A

B



Wien's Law: $\lambda_{peak} = \frac{2.9 \text{ mm K}}{T}$

Wien's Law: things that are bluer are hotter (have a larger temperature)

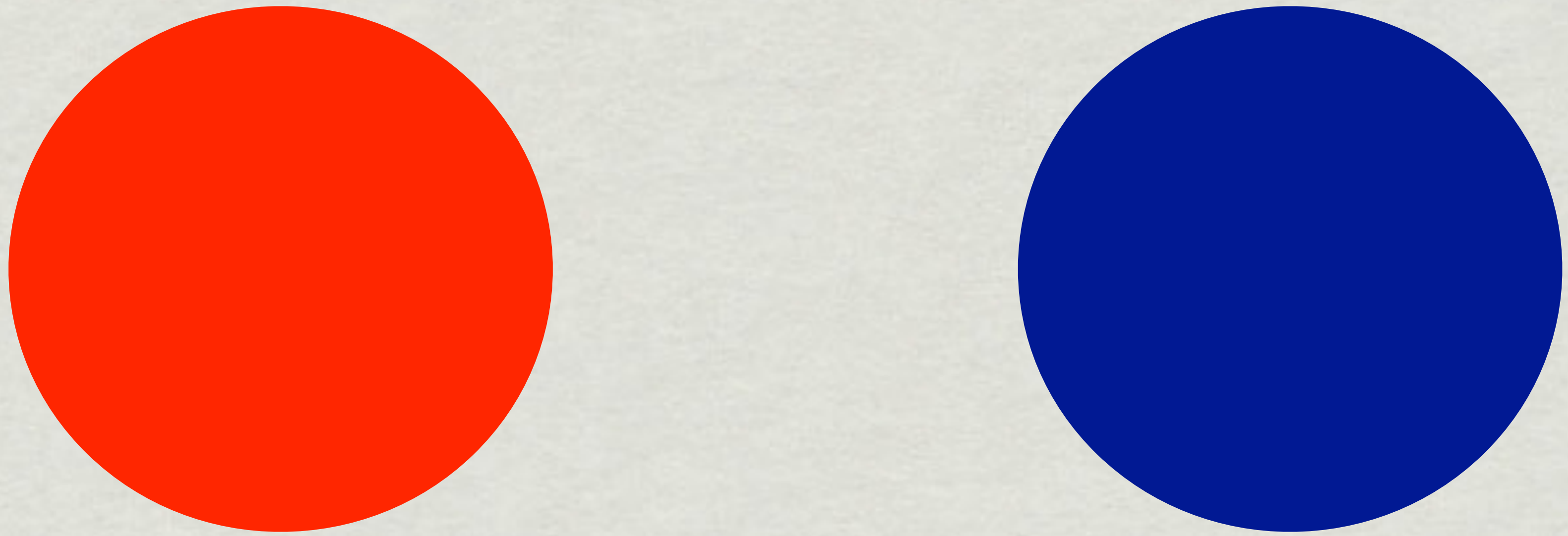


Which object is brighter?

Brighter = more energy emission, more luminous

Which object has larger luminosity?

A B



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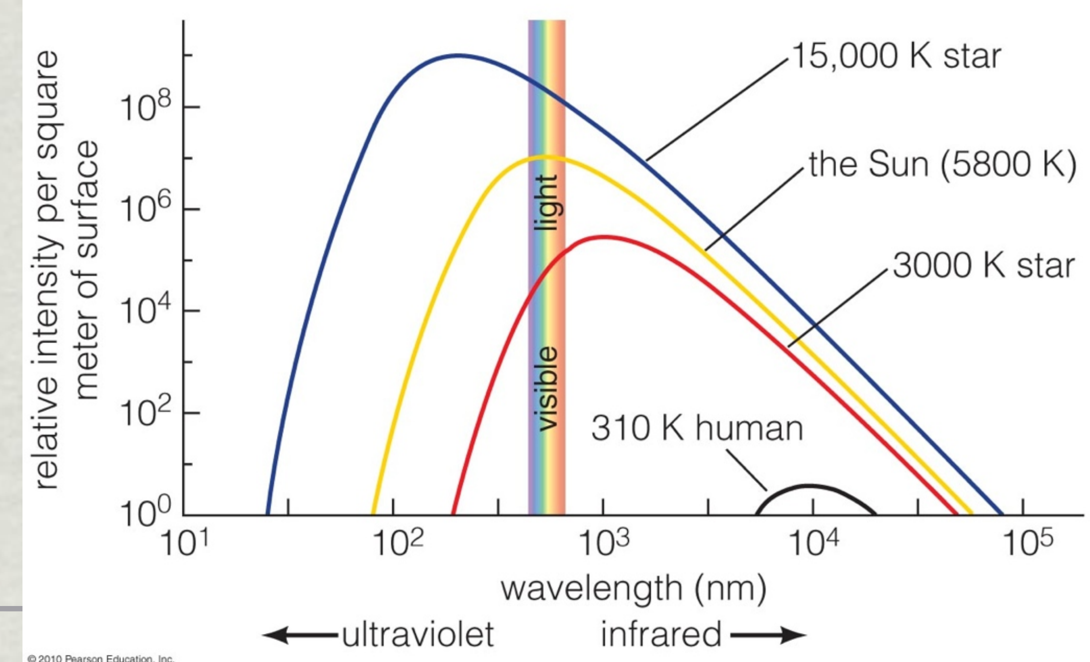
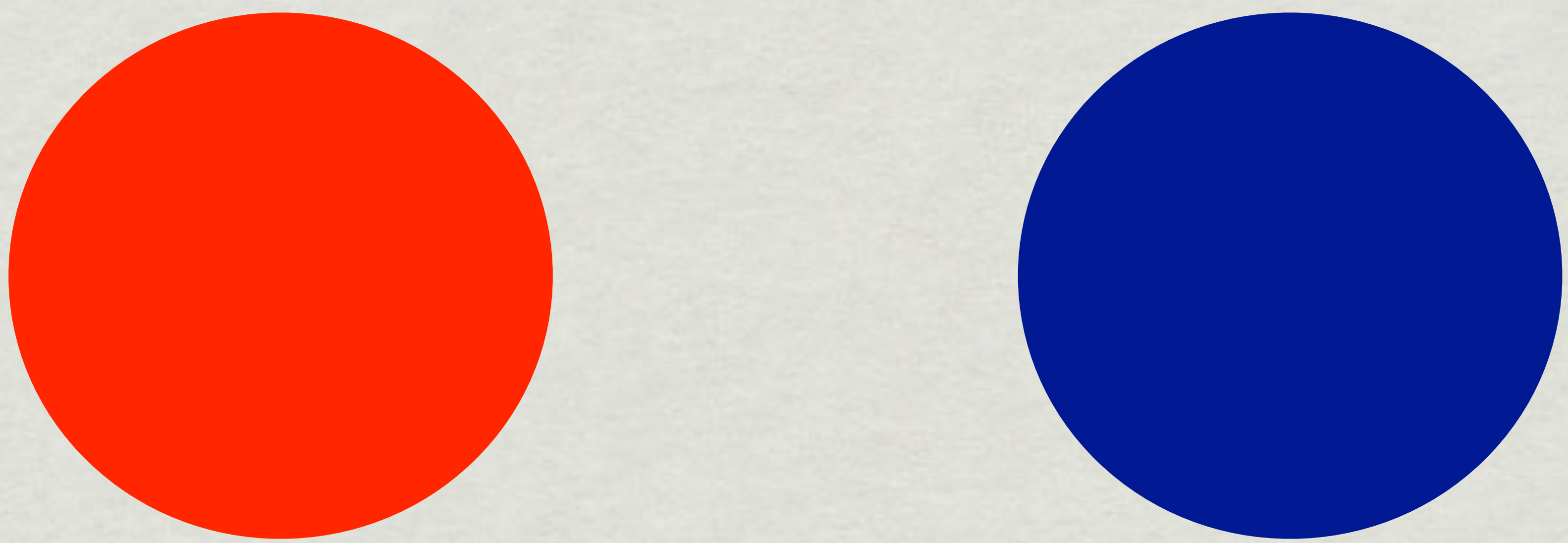
Thermal Spectrum



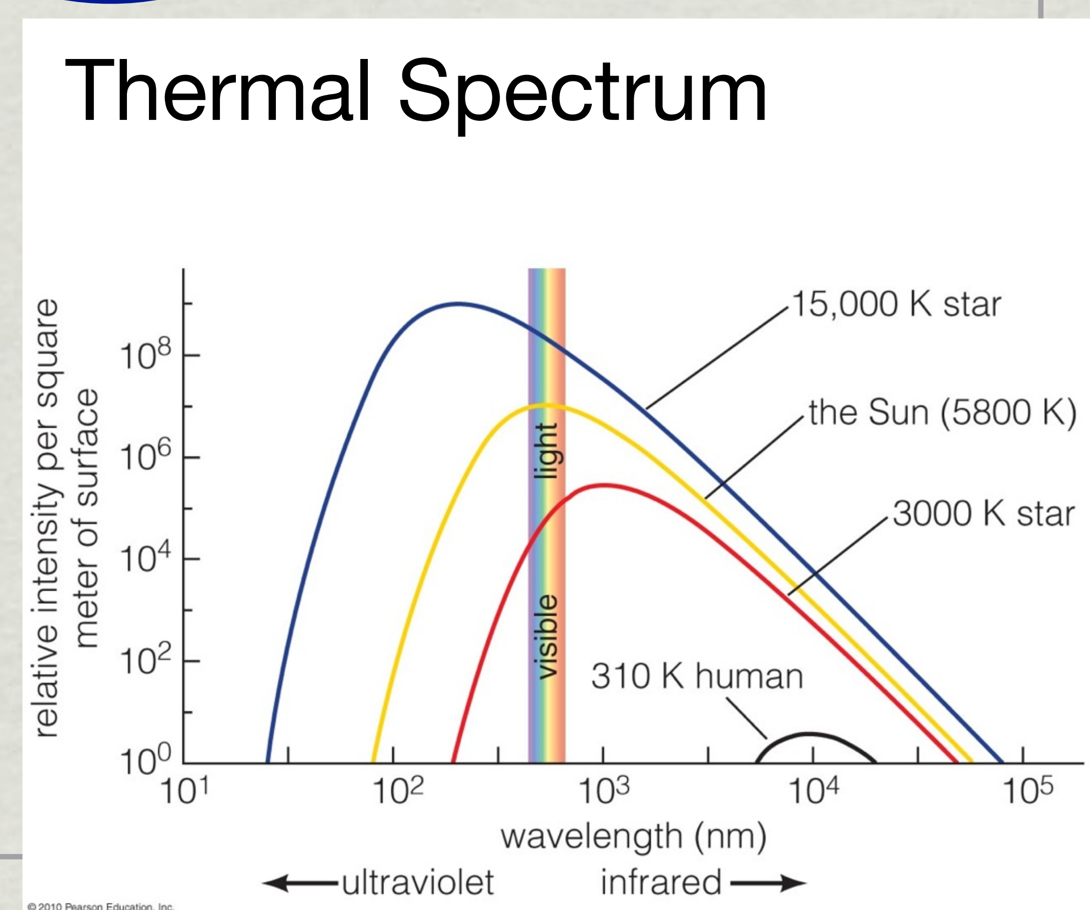
Which object has larger lumiosity?

A B



Wien’s Law: $\lambda_{peak} = \dfrac{2.9 \text{ mm K}}{T}$

Thermal emission: hotter objects emit more photons at all wavelengths



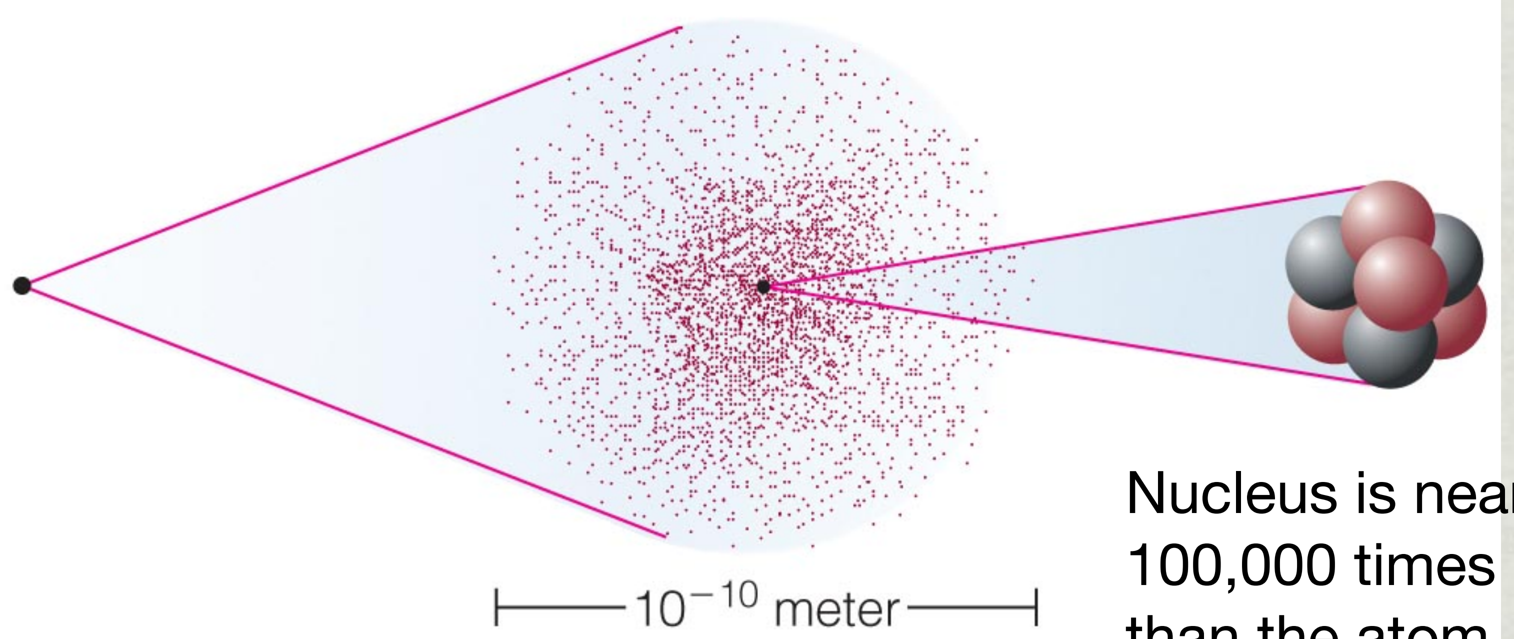
Light and Atoms

Particles: Electrons, protons and neutrons combine to make atoms.

Protons and neutrons are in the nucleus

Electrons are in a “cloud” that sort of orbits the nucleus

10 million atoms would fit end-to-end across a typical print-sized period in a book



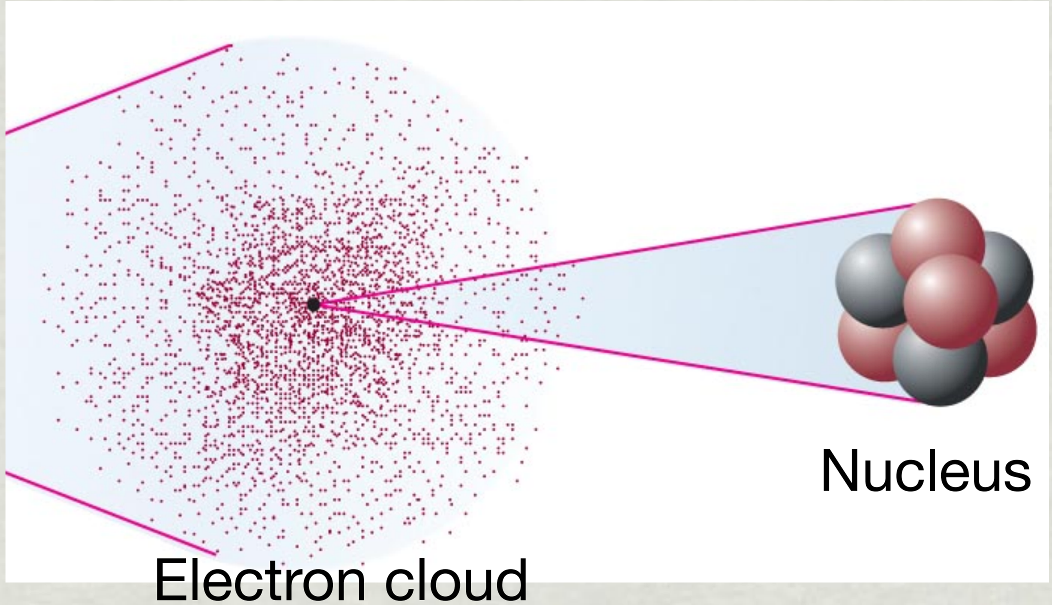
Nucleus is nearly 100,000 times smaller than the atom, but contains most of its mass

Electrons are smeared out in a cloud around the nucleus

Light and Atoms

Protons and electrons have electrical charge:

Proton +1
Electron -1
Neutron 0



Atoms are neutral: equal numbers of protons and electrons

Electromagnetic Force: $$F_{EM} = \frac{K\, q_1\, q_2}{r^2}$$

q = charge
r = distance between the particles
K = a number

(You don't need to know this formula, but notice it is a lot like the formula for gravitational force)

- Opposite charges (proton-electron) attract (just like F_{Grav})
- Two particles with the same charge repel each other: proton-proton or electron-electron push each other apart
  - Different from Gravity. Gravity *always* attracts. Mass doesn't have charge!

Light and Atoms

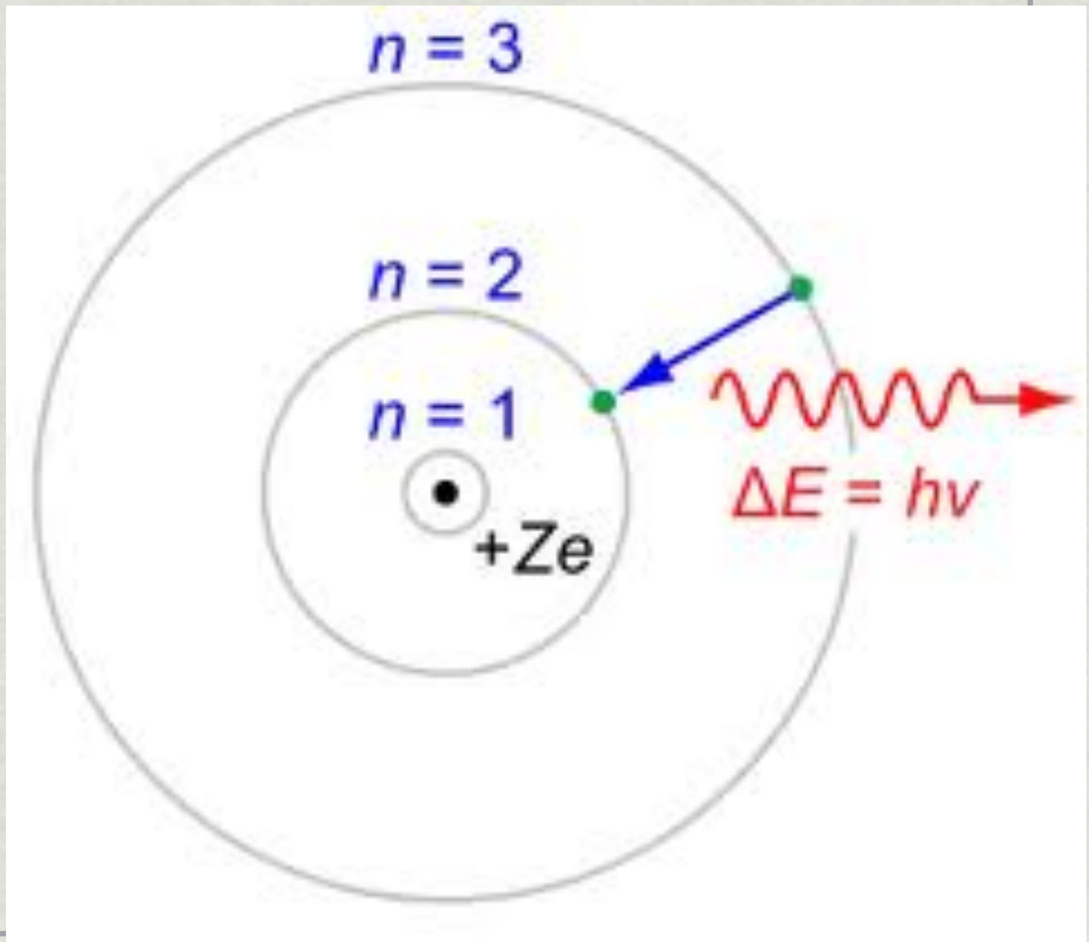
Can store electromagnetic potential energy by working against the electromagnetic force.

Store energy: go to high potential energy by pushing an electron away from the protons in the nucleus.

Remember + and - charges attract each other, so this is working against the electromagnetic force

Release energy: the electron "falls back down"

Gravitational potential energy: store energy by working against the gravitational force



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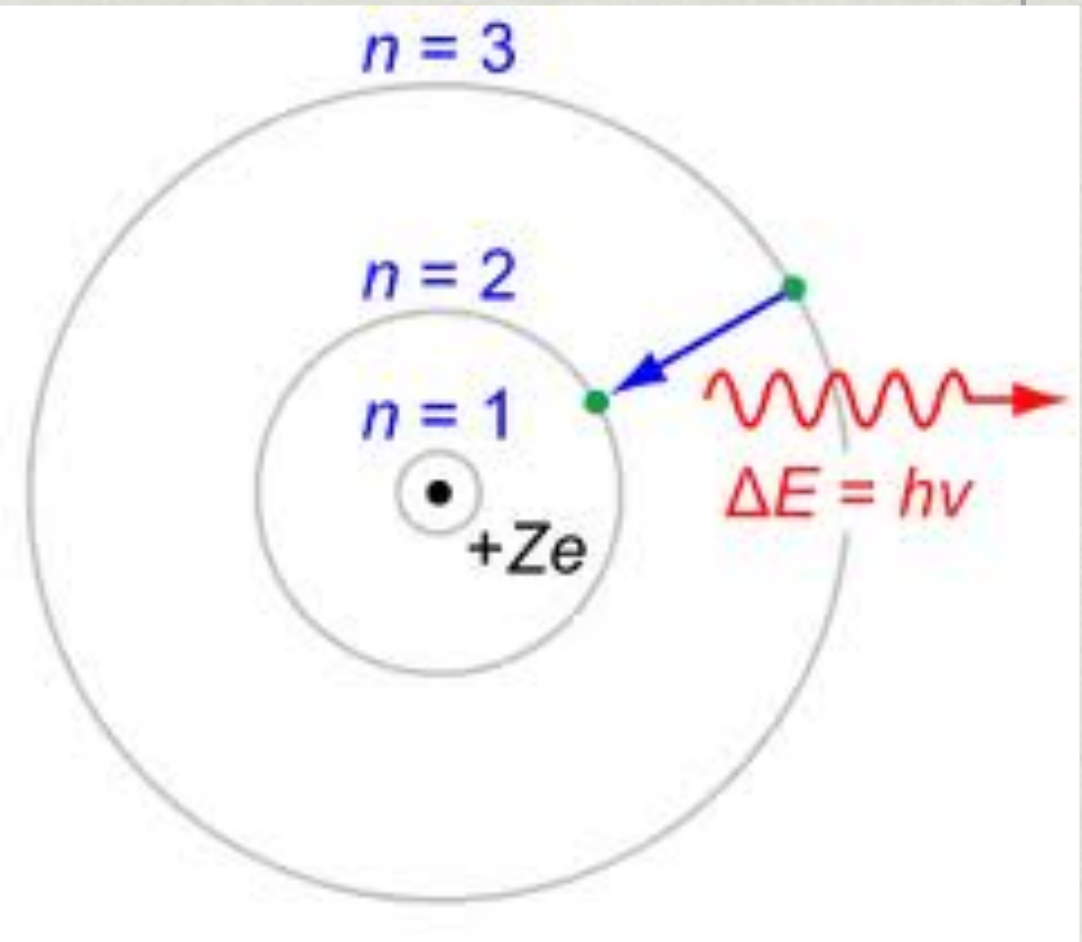


BUT: the orbits of electrons can only be at certain, fixed distances from the nucleus: "Energy Levels"

→ potential energy can only be stored at certain specific values.

quantized Energy Levels

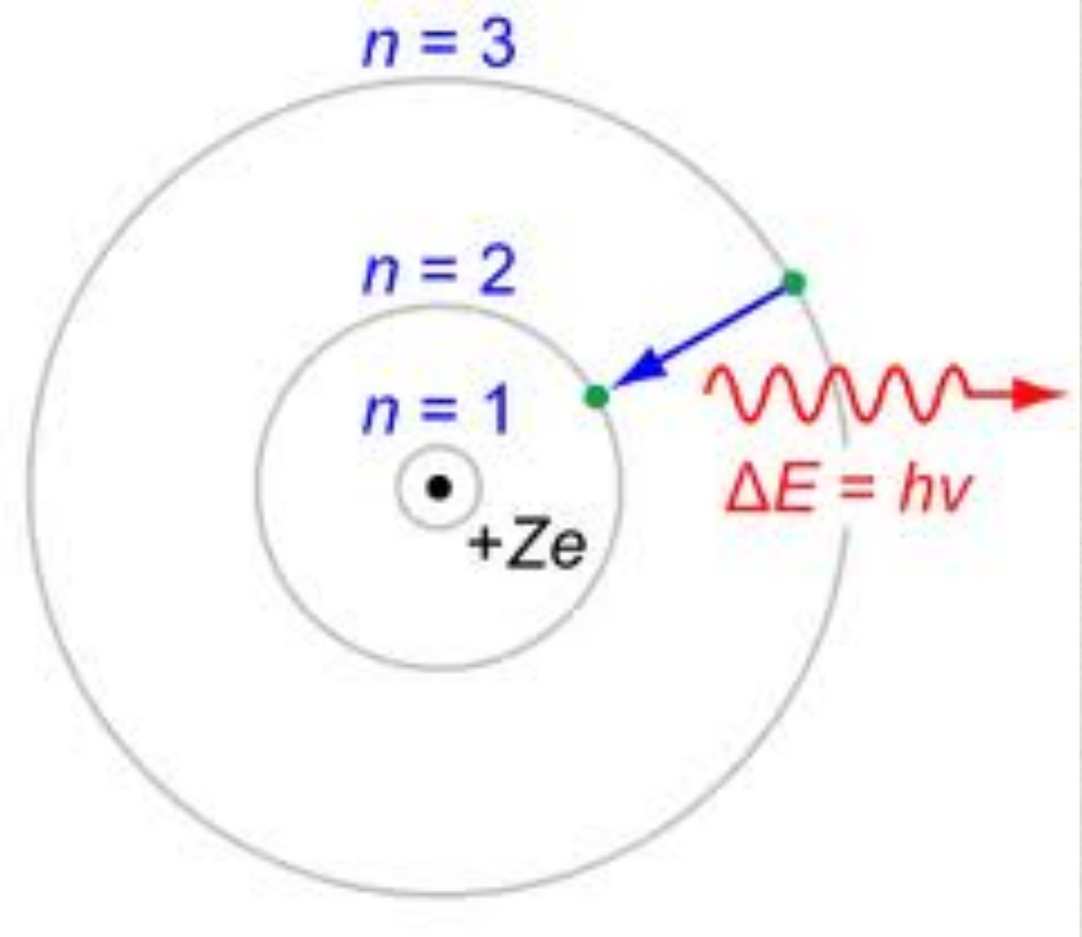
Light and Atoms

The orbits of electrons can only be at certain, fixed distances from the nucleus: "Energy Levels"

→ potential energy can only be stored at certain specific values.

quantized Energy Levels

Like having your couch jump from one floor to the next and never be between floors



Light and Atoms

Atoms interact with light is by absorbing and emitting photons.

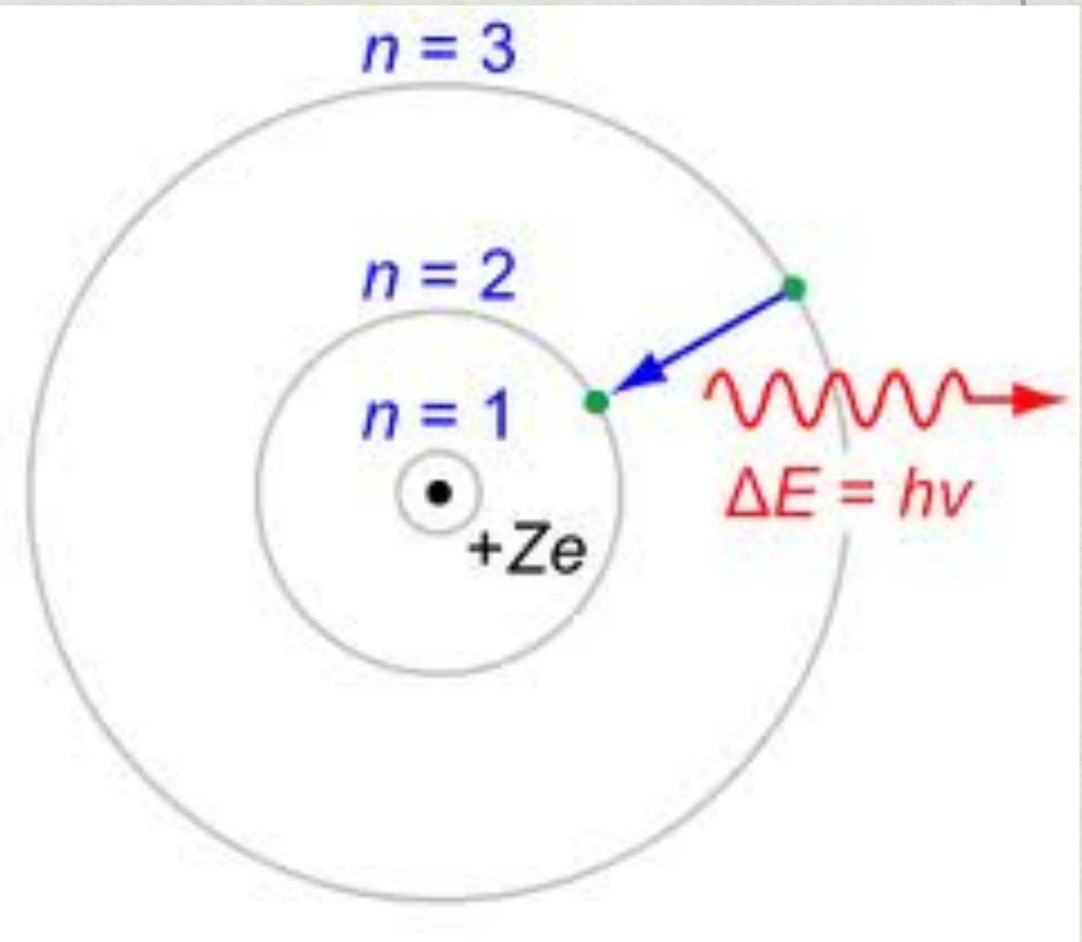
Absorb a photon: store the energy of the photon by moving an electron to a higher energy level

Emit a photon: electron "falls down" to a lower energy level. Release the electromagnetic potential energy as a photon

Electrons can only move between discrete energy levels.

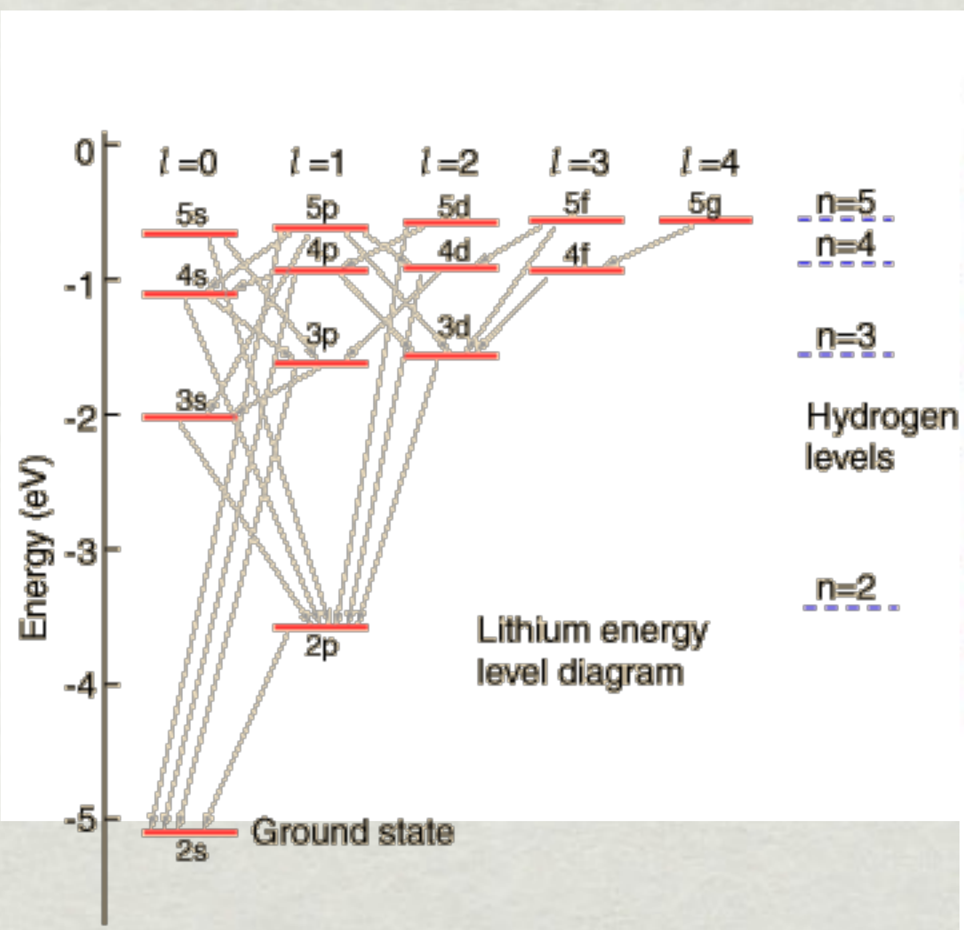
Energy is absorbed and released in discrete packets of energy as electrons move between energy levels.

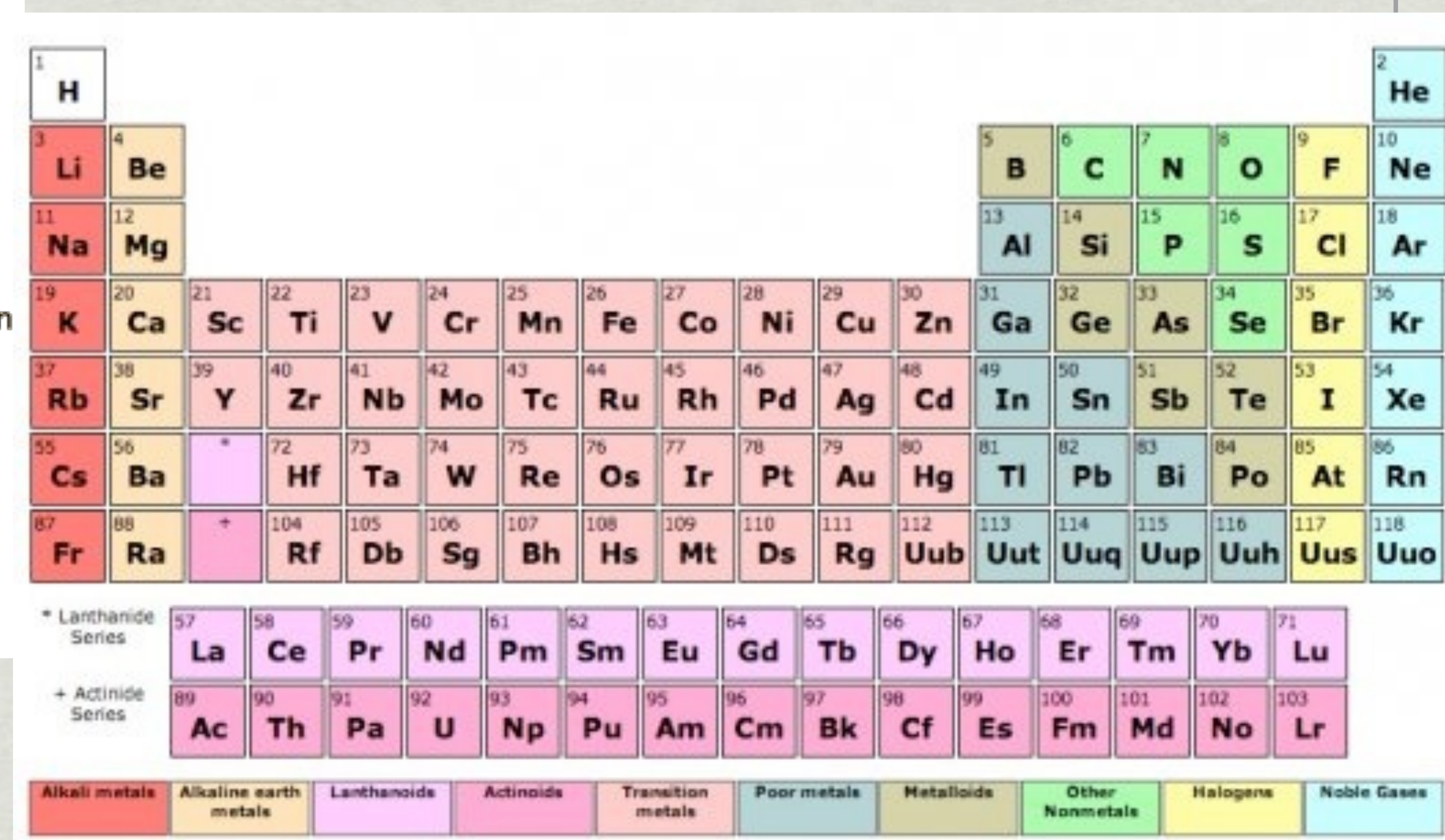
The energy packets are photons.



Light and Atoms

- Atoms: release and absorb photons only with certain energies
  - Different chemical elements: determined by number of protons and electrons
  - Each element has a unique set of energy levels that its electrons can occupy
  - Electrons can only move between available energy levels





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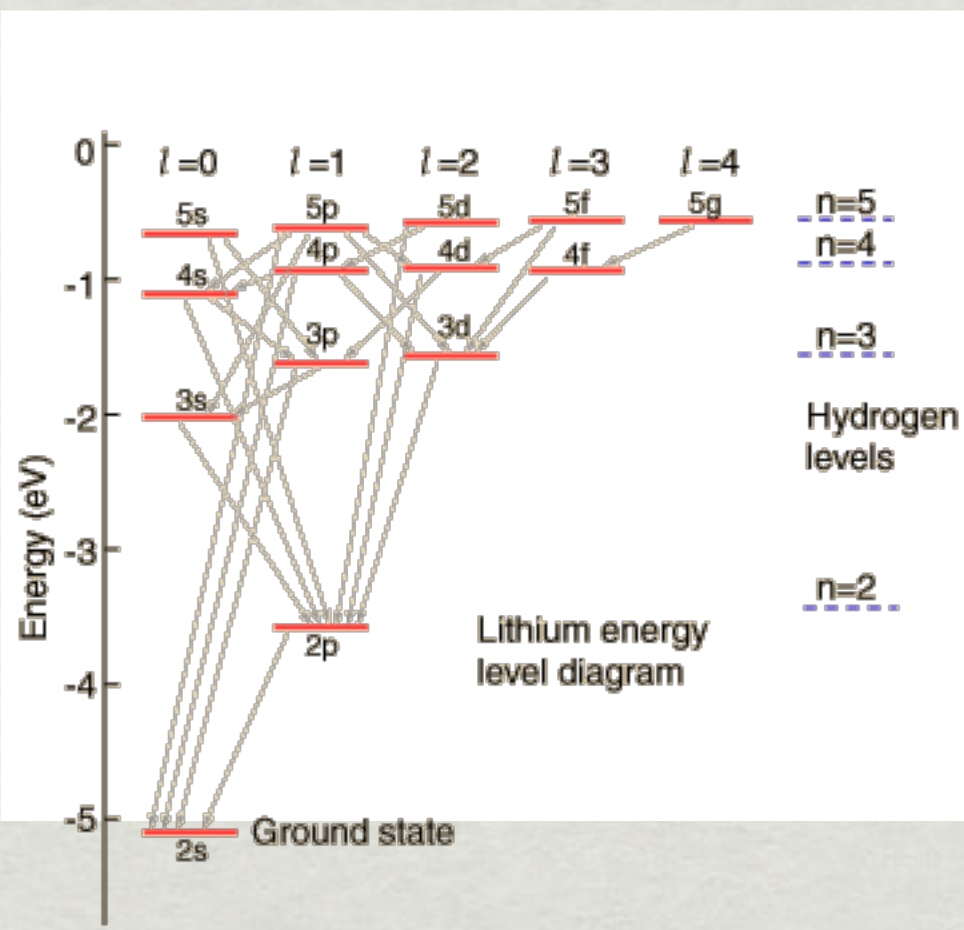
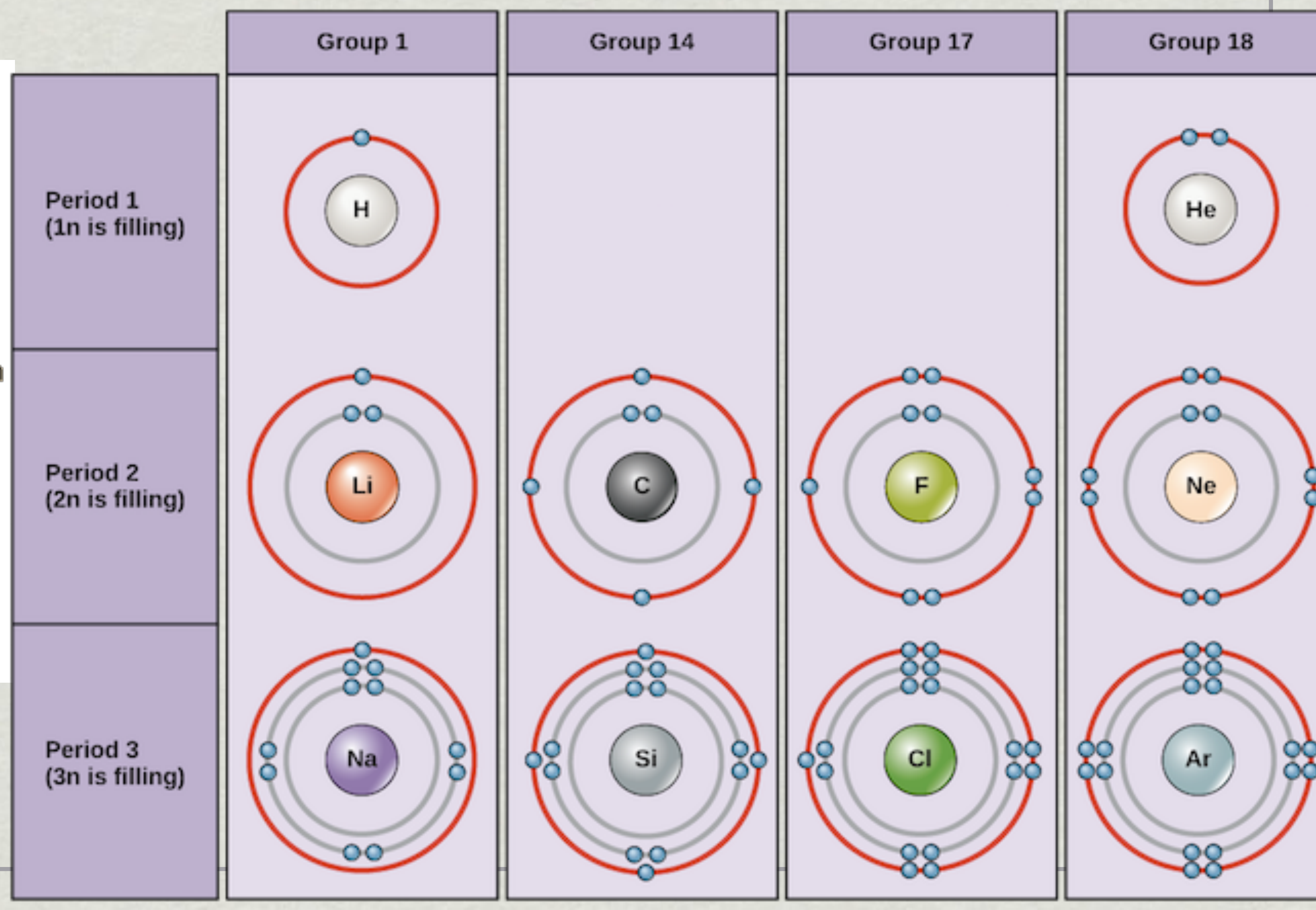
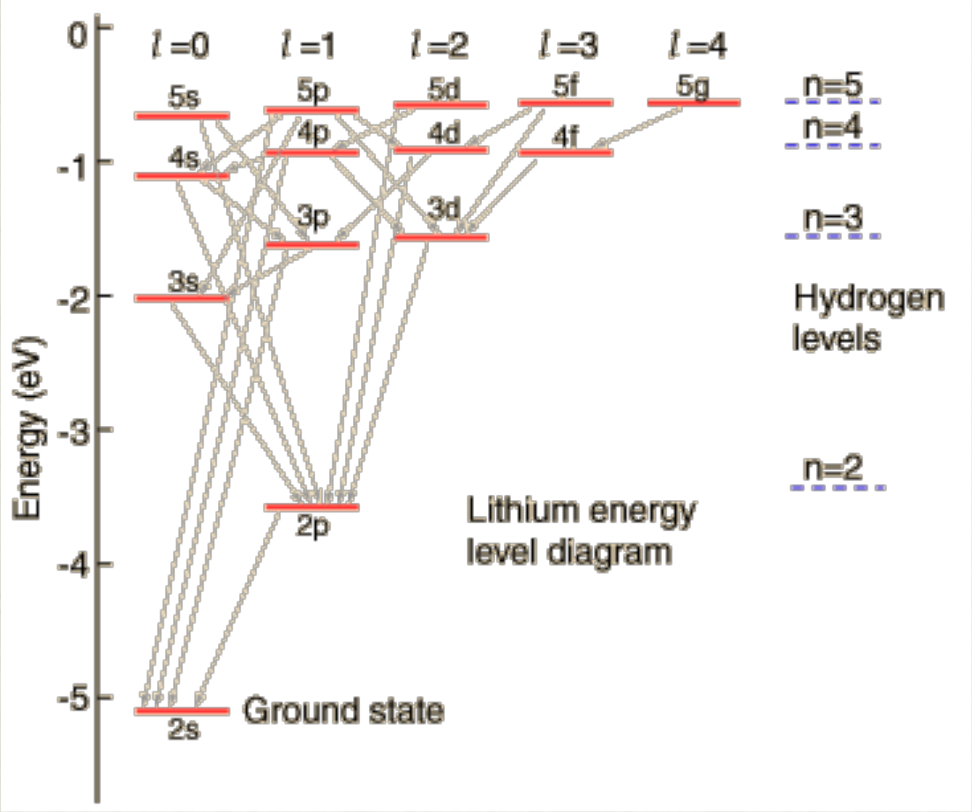
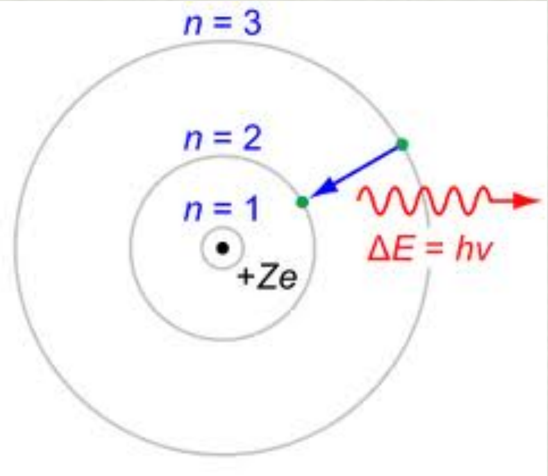




Light and Atoms

Get energy = absorb a photon, electron moves to a higher energy level
Release energy = emit a photon, electron falls to a lower energy level





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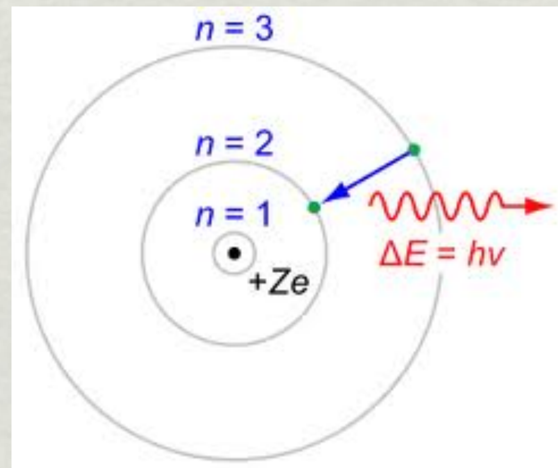
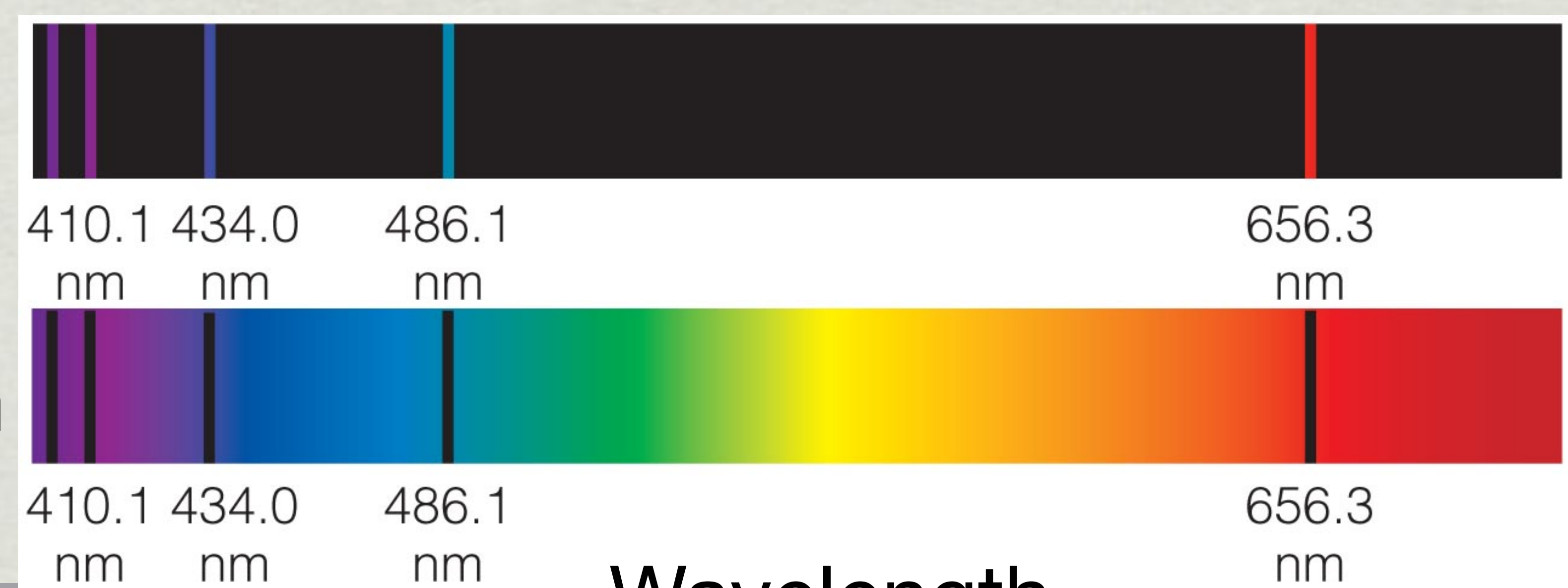


Number of photons (total amount of energy) emitted at each wavelength: a spectrum

Hydrogen Spectra:

Emission

Absorption



Wavelength