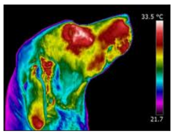
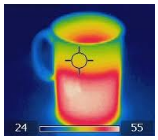
light bulbs, spectra, power

Why do night vision goggles see? And why?

Lecture 18 :
Blackbody spectrum
Improving light bulb efficiency

Reminders:
HW 7 due Monday 29th at midnight
Reading for Tuesday: Section 10.1

Props to all ya'll who are getting' on it!

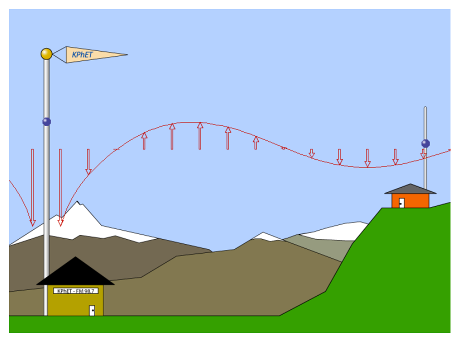
EM radiation so far

- EM radiation is a periodic modulation of the electric field: travels as a wave
- Wavelength (or frequency) determines:
  - type of EM radiation
  - if in visible range, wavelength determines color of light
- Spectrum of a source : plot of EM power (or intensity) emitted as a function of λ
- White light:
  - Light appears white when it contains all visible colors at roughly equal intensity
  - Technically defined as the spectrum of light emitted from sun

Today

- Look at EM radiation emitted by all objects – black body spectrum
  - Total power emitted
  - Range of wavelengths emitted
- Why are incandescent light bulbs inefficient?
- Why is it difficult to improve light bulb efficiency?
- IR radiation

Questions about Electric Field? what is oscillating? or Light?



http://phet.colorado.edu/en/simulation/radio-waves

Speed, wavelength, frequency

Speed = "c" in a vacuum

Wavelength (lambda), or how wide each oscillation is (meters)

$$v = f\,\lambda$$

$$v = \nu\lambda$$

Either wavelength or frequency will tell you the color of light

Units:
m/s = waves/sec * meters/wave

Frequency, or oscillations per second (Hertz). *v* or *f*

Clicker Question

Your microwave oven operates at a frequency of: f = 3 GHz = $3\text{x}10^9$ Hz (note: Hz = 1/s)
then the wavelength is :

A) 1 cm B) 0.3 cm C) 3 cm D) 30 cm

E) None of these.

$c = \lambda f$

$f = c / \lambda$

$\lambda = c / f$

$\lambda = [3 \times 10^8 \text{ m/s}] / [3\text{x}10^9 \text{ 1/s}]$

$\lambda = 0.1$ m Or 10cm

Reading Quiz

1.The black body spectrum describes
   a. The wavelengths and intensities of EM radiation emitted by black objects
   b. The wavelengths and intensities of only visible light emitted by hot black objects
   c. The intensity of visible light emitted by black objects only
   d. The wavelengths and intensities of EM radiation emitted by objects that are glowing hot.
   e. Something that you might meet on Halloween

2. A thin nylon windbreaker helps keep you warm on a breezy day by
   a. Preventing thermal radiation,
   b. Maintaining a layer of insulting air near your skin,
   c. Absorbing sunlight

3. You are lost in outer space with no power. As long as you have enough air to breathe in your air tank you will survive and be comfortably warm. (Because space is a vacuum and so will act as a good insulator.)
   a. true
   b. false.

Reading Quiz

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   a. true
   b. false.

Blackbody spectrum and temperature

Look at light bulb with variac to control how much electrical power goes into it.

If I put half as much electrical power into it, what will happen?

a. color will change, get whiter, brightness decrease
b. color will stay the same, brightness decrease
c. color will get redder, brightness decrease
d. color will get redder, brightness the same
e. color will get whiter, brightness the same.

c. color will get redder, brightness decrease

- Why? Less electrical energy into it, it heats up less.
- The temperature of the object affects both
  - The total amount of EM emitted by the object (brightness)
  - The range of wavelengths emitted (color)
- Lower temperature is redder and dimmer.

Blackbody spectrum and temperature

- Everything that has a non-zero temperature emits a spectrum of EM radiation
- The spectrum of EM radiation coming from a black object is called the "blackbody spectrum."
- Black object: Absorbs and emits all EM λ easily
- Go to the blackbody spectrum simulation
- BB spectrum determined by temperature only.
- The temperature of the object affects both
  - The total power of EM radiation emitted by the object
  - The range of wavelengths emitted (the spectrum)

Temperature and total emitted power (brightness)

Stefan-Boltzman law gives total electromagnetic power (energy/second) out of a hot object at temperature T

Power $= e \times \sigma \times T^4 \times a$

Area of surface

Temperature of object (in Kelvin!)

Stefan-Boltzmann constant,
$\sigma = 5.67 \times 10^{-8}$ J/(s m^2 K^4)

e = "emissivity"; how well the light gets out

Two burners on the stove are at the same temperature, but the left-hand burner has twice the area. How much more infrared radiation is it putting out?

a) The same amount
b) Twice as much
c) Half as much
d) Four times as much
e) Sixteen times as much.

Power $= e \times \sigma \times T^4 \times a$

Answer b: twice as much; radiation is linear in area.

Comments on Stefan-Boltzman Law

Power = **e** X σ X T⁴ X a

1. Emissivity (e)

- Property of surface,
- Scale of 0 to 1.
- 1 (BB) means radiates well, 0 is lousy.

area, a
e = 0.9

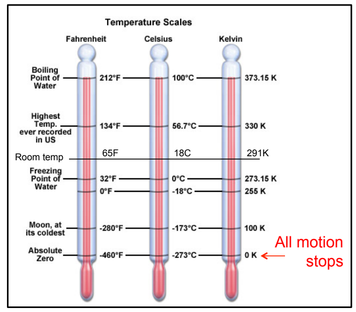
same T so same color.

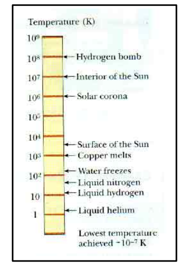
area, a
e = 0.3

2. T in Kelvin (= T Celsius +273)

3. Emitted power rises very quickly with temperature

The Kelvin Temperature Scale: Links T to motion





- 1 degree Kelvin = 1 degree Celsius = 9/5 degree Fahrenheit
- 0 degree Celsius = 273 K

A particular light bulb's filament is at 2000 C. What is its temperature in Kelvin?

a) 2000 K
b) 2273 K
c) 1727 K
d) 2500 K

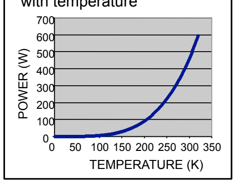
Answer b:

0C = 273K
1 degree K = 1degree C
⇒ T in K = T in C +273
= 2000 +273 K

How does temperature affect emitted power (brightness)?

P = eσT^4a
σ = 5.67 x 10^{-8} J/(s m^2 K^4).
T in Kelvin (= T Celsius +273)

Emitted power rises rapidly with temperature



If I raise temperature of heating coil on stove from 450K to 500K, by what fraction will power emitted by coil increase?

⇒ Power at 500K / Power at 450K

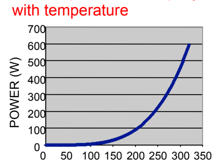
(note: emissivity and coil area will cancel!)

a. Power is 1.11 times larger.
b. Power is 250 times larger.
c. Power is 1.52 times larger.
d. Power is 5.0 times larger.
e. Power is 50 times larger

How does temperature affect emitted power (brightness)?

P = eσT^4a
σ = 5.67 x 10^{-8} J/(s m^2 K^4).
T in Kelvin (= T Celsius +273)

Emitted power rises rapidly with temperature



If I raise temperature of heating coil on stove from 450K to 500K, by what factor will power emitted by coil increase?

Answer is c: factor of 1.52

Power at 500K = eσ(500)⁴a / Power at 450K = eσ(450)⁴a

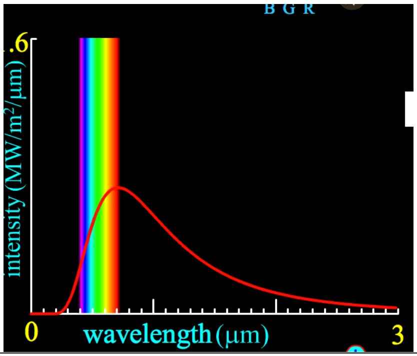
= 6.25E10 / 4.10E10 = 1.52

Temp increase by ~11%,
Power increase by 52%

Blackbody spectrum

- Everything that has a non-zero temperature emits EM radiation
- The spectrum of EM radiation coming from a heated object is called the "blackbody spectrum." (Although it isn't black!)
- Go to the blackbody spectrum simulation
- The temperature of the object affects both
  - The total power of EM radiation emitted by the object (P∝ T⁴) ✓
  - The range of wavelengths emitted (the spectrum)

Where does this Spectrum Come From?

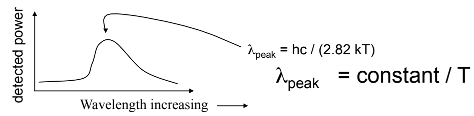


The funny shape of the black body spectrum

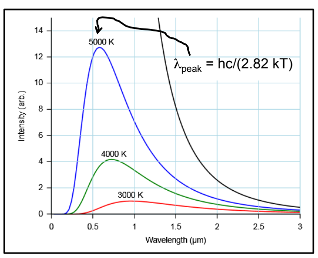
The shape of the spectrum for the thermal radiation of an object is rather complicated, but with some eff... ibes it. That is **beyond** ... t in case you are interested, the ... f an electromagnetic wave is given ... where k is the ... c is the speed ... J·s), and the temperature T is in units of Kelvin.

From this equation it is possible to show that the wavelength where the power is highest is given by $\lambda_{peak} = hc/(2.82\ kT)$

$$P = \frac{(8\pi h/c3)\nu^3}{(eh\nu/kT - 1)},$$



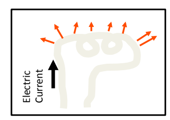
Black body spectrum at different temperatures



T increases - Power at all λ increases
- Proportionally more power at shorter λ
- λ_{peak} shifts to shorter λ ($\propto 1/T$)

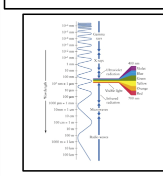
Why are light bulbs inefficient?

How does an incandescent light bulb work:
- Electric current flows through filament
- Filament gets hot
- Hot filament emits EM radiation
- Electrical energy → EM radiation energy



An efficient light bulb:

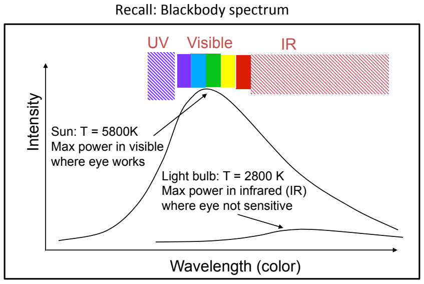
Electrical power in → 100% conversion → EM energy at visible λ



- But.....visible light is only a very small part of the EM spectrum
- Only 18% EM radiation from bulb is visible
- Rest is IR radiation (heat)
- Go to the blackbody spectrum simulation

Why are light bulbs inefficient?

Recall: Blackbody spectrum



Higher temperature
- More power ($\propto T^4$)
- Peak power at shorter wavelengths

How do could you make light bulbs more efficient?

Back to light bulbs.

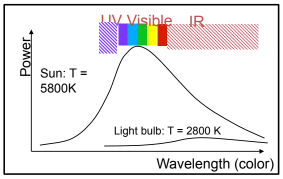
What would the ideal temperature be for a bulb filament?

a. Temp of standard bulb filament (2800 K).
b. Temp of the sun (5800 K).
c. Hotter than the sun.

Back to light bulbs.

What would the ideal temperature be for a bulb filament?
b. Temp of the sun (5800 K).

- At temperature of sun, λ_{peak} is in the visible, so the fraction of power emitted at visible wavelengths is maximized.
  - Max. visible light per watt of electrical power used
- At lower temp than sun too much power is wasted as IR radiation (heat)
- At higher temp than sun too much power is produced in the UV – also invisible and dangerous for eyes and skin



Note: Overall much more power in Sun that Light bulb too!

How can we improve light bulb efficiency?

If hotter is better, why are filaments in standard bulb not heated to 5800 K?

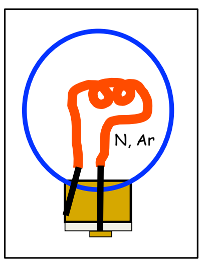
a. because they melt if heated up any hotter
b. because they vaporize if heated up any hotter
c. because they oxidize ("burn up") if heated any hotter
d. would be too expensive to build

a is a reasonable answer:
Tungsten (which is what light bulb filaments are actually made of) melts at 3700 K.
Carbon (which Edison originally used) melts at 3800 K.
But bulbs much cooler than melting temp (2800 K) – so this is not the limiting factor

c is a reasonable answer:
Oxygen can attach itself to the filament, especially when it's hot. Then you don't have tungsten any more, you have tungsten oxide.

How can we improve light bulb efficiency?

Solution to the "burning up" problem:
- Put the filament inside a bulb that has no oxygen
- Fill bulb with an inert gas like pure nitrogen or argon



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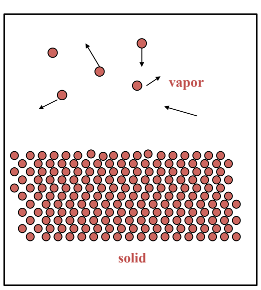
- b is actually the correct reason.
- You could go up to 3800 K before the filament melts.
- But, even before they melt, filaments can vaporize due to *sublimation*.

What is sublimation?

Sublimation - direct solid to gas transition
- no liquid phase involved



Examples:
- Cold dry sunny day in Boulder - snow vanishes before melting
- "Dry ice" → carbon dioxide gas

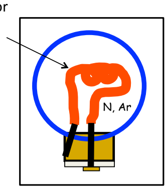
Rate of sublimation increases rapidly with temperature of solid

How can we improve light bulb efficiency?

So, if we increase the filament temperature:
⇒ more visible light, better efficiency.
⇒ faster sublimation, shorter lifetime.

Filament temperature is a trade off between efficiency (<20%) and lifetime

Tungsten used for filament – low sublimation rate



- Eventually the filament sublimates away. You can see this in old light bulbs, where black stuff collects on the glass.
- **Light bulbs don't really "burn out", They actually "evaporate out"!**

light bulb efficiency and lifetime?

The power company's generator is malfunctioning and so it provides 130 V electricity to your house, rather than the usual 120 V. As you will learn later in the course, this means that there is more electrical power going into all your light bulbs, and so they run hotter.

What are the implications of this?

Your light bulbs now:

a. Produce more light, are redder in color, are more efficient, last longer.
b. Produce more light, are whiter, are more efficient, don't last as long.
c. Produce less light, are redder in color, are less efficient, last longer.
d. Produce more light, are whiter, are less efficient, don't last as long.

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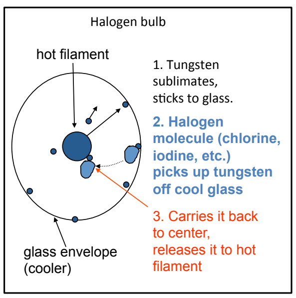
How can you improve efficiency and/or lifetime?

1. "Extended life" bulbs.
   These have thicker filaments
   ⇒ run cooler, last longer.
   ⇒ BUT less efficient

2. Halogen lamps
   - Undo sublimation so they can run hotter and more efficiently
   - Even a couple 100 C make a big efficiency improvement

3. Ditch the hot filament and use different technology
   - Florescent lights (CFLs)
   - LEDs
   - see later in course / Phys1020

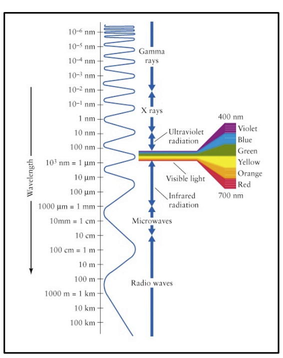


IR radiation: Thermal imaging

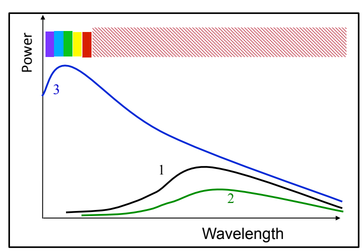
- Look at BB spectrum for a person (~ 313 K)
- No visible radiation emitted (too cold) – all in the IR
- Not detected by the eye, but detected by an IR (thermal imaging) camera

Thermal imaging – photography using non-visible EM radiation

The electromagnetic spectrum

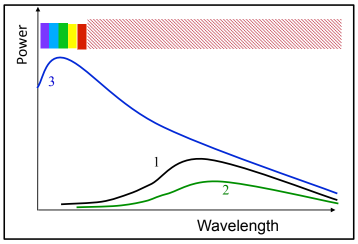


Identify spectrum of radiation given off by person (37 C) and a block of barely frozen ice (0 C).



a. 2 is person, 1 is ice,
b. 1 is person, 2 is ice,
c. None, because ice gives off no thermal radiation,
d. 1 is both ice and person because they are almost identical
e. 3 is person, one of the others is ice.

Identify spectrum of radiation given off by person (37 C)
and a block of barely frozen ice (0 C).

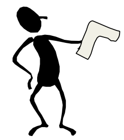


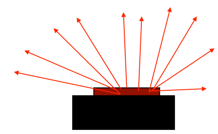
b. 1 is person, 2 is ice,

Anything with a non–zero temperature emits EM radiation. The ice and the person are both so cold that the radiation is not visible. The person is a bit hotter than ice, so gives off more radiation ($\propto T^4$), and has peak power at a slightly shorter λ ($\propto 1/T$).

IR radiation

This remote temperature sensor works by measuring the infrared spectrum of the thing I point it at.



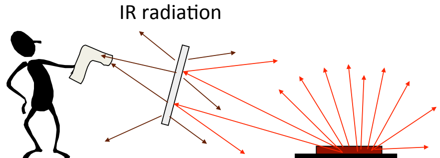


Try it out.

Now we put a piece of glass in the way.
What will temperature sensor read?

a. Same temperature,
b. Slightly less,
c. Much less,
d. Absolute zero

IR radiation



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What will temperature sensor read?

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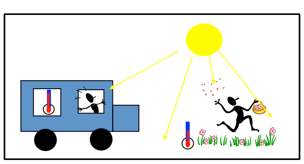
c. Much less,
d. Absolute zero

Answer c: Much less, in fact about room temperature.

- Sensor detects IR radiation emitted by the glass which is at room temperature.
- The glass transmits visible light (I can see hot plate through it) but not IR
- IR radiation from the hot plate is blocked from reaching the sensor

Different wavelengths interact differently with matter

Your car is sitting in the bright sun. The inside of the car gets much hotter than the air next to it. Why?



a. The car absorbs light energy from sun better than the pavement.
b. Sunlight causes chemical reactions in car materials that give off heat.
c. Electrical appliances such as clock that run all the time in car causes it to heat up.
d. The windows let in energy but do not let it escape.
e. None of the above make sense, must be different explanation.

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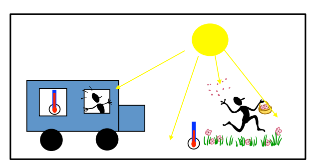

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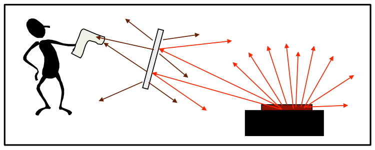
This is the greenhouse effect:
- Sunlight passes through glass to inside of car, heating us, seats, dashboard, etc
- These hot things emit IR radiation, which is *not* able to leave through the glass

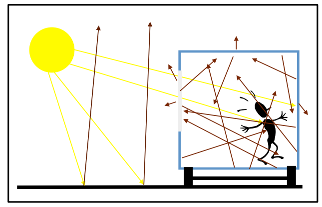
The greenhouse effect in your car

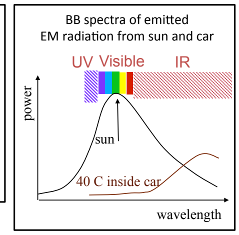
EM energy gets into car but can't get out? How does that happen?

- We all know visible light travels easily through glass (windows!)
- But remember this? The glass blocked the IR from the hot plate, so we could not detect the IR from the hot plate.



The greenhouse effect in your car





- Remember effect of T on shape of BB spectrum
- Sun is very hot (5800K) and emits most power as visible light, which goes through the car window.
- The interior of the car absorbs this energy and heats up.
- Inside of car is less hot than sun (310 K) so emits most power in the IR, which cannot go out through the glass.
- Extra energy is trapped inside car making it hotter than the surrounding environment

How does the green house effect affect the temperature of the earth?

1) Power in: Visible light energy from hot sun hits the earth and is absorbed
2) Power out: The cool earth (at temp. T_E) radiates power out mainly as IR radiation
3) If earth remains at a constant temperature, it must have constant thermal energy:

Power in from sun = Power out from earth, radiated into space.

Since power out depends on T_E, we can calculate temperature of earth!