Physics 161:

Physics of Energy and the Environment

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Lecture 7: Announcements

- *Reading*: Wolfson, Chapter 4
- *Homework*: Problem Set 4. Due Thurs. Oct. 23
- *Midterm*: Thurs. Oct. 30
  - Covers material through Oct. 23 & PS4
  - Short answer + simple calculations
  - No books, no calculators
  - Additional advice, comments later.
- *RP's office hours next week*:
  - *Monday*: 12.30-2.00 pm
  - *Tuesday*: Cancelled.

Last Lecture

- Thermodynamics: a fundamental limit on the conversion of thermal energy to "mechanical work" (any low entropy form of energy):

Carnot efficiency

e = Work out / Heat In

$$e_{max} = 1 - \frac{T_C}{T_H}$$

- Depends on ratio of "hot & cold" temperatures
- Actual efficiency must be less than this.
- Necessarily: waste heat.

Heat

- Heat: Energy that flows due to a temperature difference.
- How does heat flow? ("Heat transfer")
  - Three mechanisms
  - Conduction
  - Convection
  - Radiation

First, a quick overview.

Conduction of Heat

- **Conduction**: Collisions between atoms and molecules transfer kinetic energy, and hence thermal energy.
- Example: Hot stove burner → Hot pot → Hot water.
- Note: all in contact.
- We'll return to this shortly

Convection

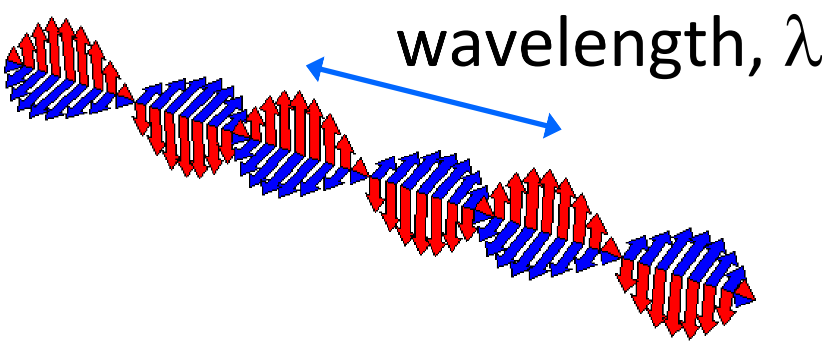
- **Convection**: bulk motion of a fluid (liquid or gas)
- E.g. hot gas becomes less dense, rises, and conveys thermal energy to higher regions.
- [Demo: candle and air flow]
- General behaviors:
  - Bigger temperature difference $\rightarrow$ more convection
  - Smaller "pores" $\rightarrow$ convective flow more difficult (wool sweater)

Radiation

- **Radiation.** The sun... a fireplace... a hot stove burner...
- All objects emit electromagnetic radiation
- It need not be visible EM radiation. You, for example, mostly emit infrared radiation.
- "Night vision," Infrared thermometers (*demo*)

Radiation

- EM radiation can travel through vacuum – doesn't need "stuff." (E.g. sunlight)
- Recall: Any EM radiation has a particular wavelength.



Source: Leiden University

Radiation

- Quantum physics (early 20th century): In some ways, light behaves like a particle ("photon") that carries a particular amount of energy
- Shorter wavelength ↔ higher energy

Radiation

- All objects radiate EM waves
  - because atoms, molecules always in motion, and made of charged particles
- Higher *T* (More thermal energy) $\rightarrow$
  - More photons emitted *AND*
  - Photons with shorter wavelengths

Note that "thermal radiation" isn't the *only* way to emit light. A fluorescent bulb, for example, emits light unrelated to its temperature.

Radiation

- Based on what we've learned (properties of radiation; you emit mostly IR, etc.) which should have a longer wavelength: visible light or infrared radiation?

- A. Infrared
- B. Visible

Radiation

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- A. Infrared
- B. Visible

You: IR radiation.

The sun: visible light.

You are cooler than the sun.

Cooler = longer wavelength.

Radiation

- The Earth receives EM radiation from the sun (mostly visible) and emits radiation to space (mostly infrared).
- As we'll see later, altering the balance of radiated power to & from the Earth's surface is the essence of the greenhouse effect.

Thermos

- Mechanisms of heat flow
- A thermos: minimize heat flow
  - – low conduction: vacuum
  - – low convection: vacuum
  - – low radiation: reflective

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Heat

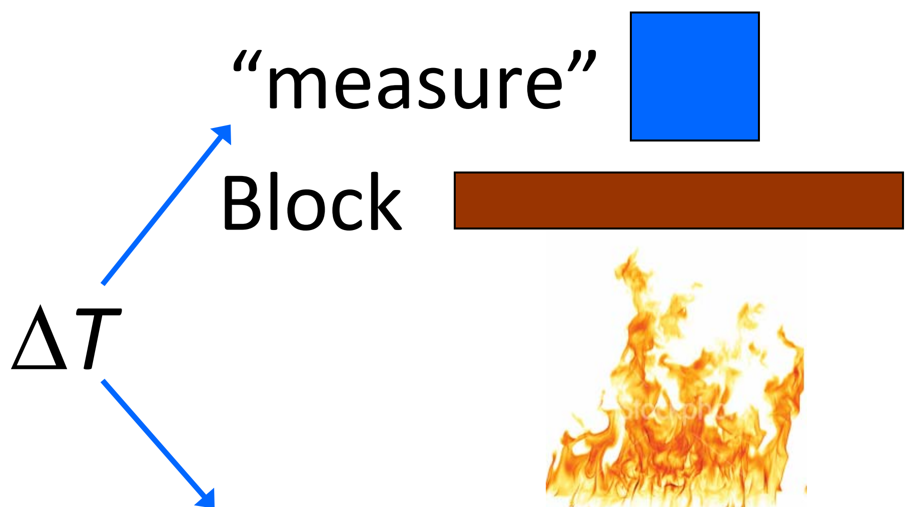
- Heat: Energy that flows due to a temperature difference.
- Heat transfer mechanisms
  - Conduction
  - Convection
  - Radiation

Some more detail.

Conduction of Heat

- **Conduction**: collisions of particles
- What physical parameters should heat transfer depend on?
- (Ask)

Imagine, e.g. you're the blue box, and you get to pick which block to use avoid getting burned



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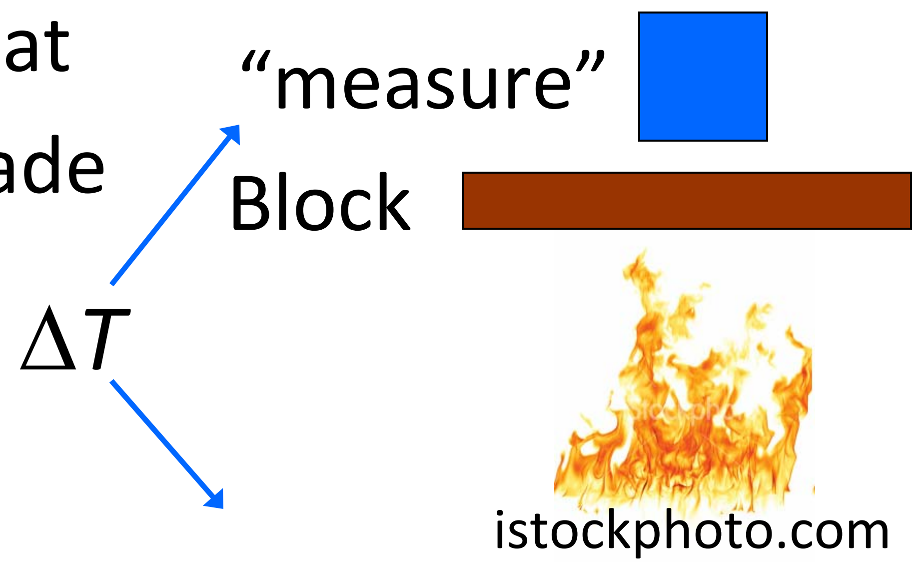
Conduction of Heat

- What physical parameters should heat transfer depend on?

- Temperature difference: $\Delta T = T_{hot} - T_{cold}$
- Thickness of the block: thicker $\rightarrow$ less heat
- Area: wider $\rightarrow$ more heat
- Material the block is made of



Conduction of Heat

- What's the simplest expression we could make that captures this?

- ΔT
- Thickness of the block, *d*
- Area of the block, *A*
- Material the block is made of – some "intrinsic property," call it "thermal conductivity" *k*.

proportional to

- Heat *H*
- $H \propto \Delta T$
- $H \propto 1/d$
- $H \propto A$
- $H \propto k$

Conduction of Heat

- Combining all this:
  - Heat H
  - $H \propto \Delta T$
  - $H \propto 1/d$
  - $H \propto A$
  - $H \propto k$

$$H = \frac{k\,A\,\Delta T}{d}$$

In fact, this is the correct expression for heat flow by conduction!

Heat = energy flow (i.e. energy / time), so same units as power

Thermal conductivity

$$H = \frac{k\,A\,\Delta T}{d}$$

- *A, d* depend on geometry
- *k* (thermal conductivity) is a characteristic of the material.
- [*Demo: wax*]
- [*Demo: blocks*]

Building Insulation and R

$$H = \frac{k\, A\, \Delta T}{d}$$

- The properties of building insulation are often described by "R"
- R = d/k
- Typically ft^2 °F h / Btu
- Annoying: R isn't an intrinsic property of the material. (Why?)

Thermal conductivity

- Table (text)
- Note:
  - Air: low *k*
  - Metals: high *k*

Material	Thermal conductivity, (W/m·K)
Air	0.026
Aluminum	237
Concrete (typical)	1
Fiberglass	0.042
Glass (typical)	0.8
Rock (granite)	3.37
Steel	46
Styrofoam (extruded polystyrene foam)	0.029
Water	0.61
Wood (pine)	0.11
Urethane foam	0.019

Thermal conductivity: example

- Suppose I have coffee (≈70°C) in a ceramic cup ($k \approx 1$ W / m / K). At what rate is the coffee's thermal energy being lost through the walls of the cup?

Source: istockphoto.com

- d ≈ 1 cm = 0.01 m
- $A \approx 10\text{ cm} \times 10\text{ cm} = 0.01\text{ m}^2$.
- $\Delta T \approx$ (70-20 °C) = 50 °C = 50 K also!
- $H = k A \Delta T/d \approx$

  $1\text{ W / m / K} \times 0.01\text{ m}^2 \times 50\text{ K} / 0.01\text{ m} \approx 50\text{ W}$

i.e. to counteract this, I'd need to supply the coffee with 50W of power

Thermal conductivity: example

- We just calculated the heat loss *through the cup walls* of my *70°C* coffee.
- If I wait, is will the heat flow *increase* or *decrease*? (*Hint*: What does H depend on? Are any of these things changing?)
- A. increase
- B. decrease

Source: istockphoto.com

Thermal conductivity: example

- We just calculated the heat loss *through the cup walls* of my *70°C* coffee.
- If I wait, is will the heat flow *increase* or *decrease*? (*Hint*: What does H depend on? Are any of these things changing?)
- A. increase
- B. decrease

Heat flow $\rightarrow$ T drops $\rightarrow$ ΔT drops $\rightarrow$ less heat flow

Source: istockphoto.com

Thermal conductivity: example

- We just calculated the heat loss *through the cup walls* of my *70°C* coffee.
- Is conduction through the walls the only mechanism by which my coffee transfers heat? List / explain others.

- Conduction through bottom, top
- Convection of heated air above
- Radiation

Source: istockphoto.com

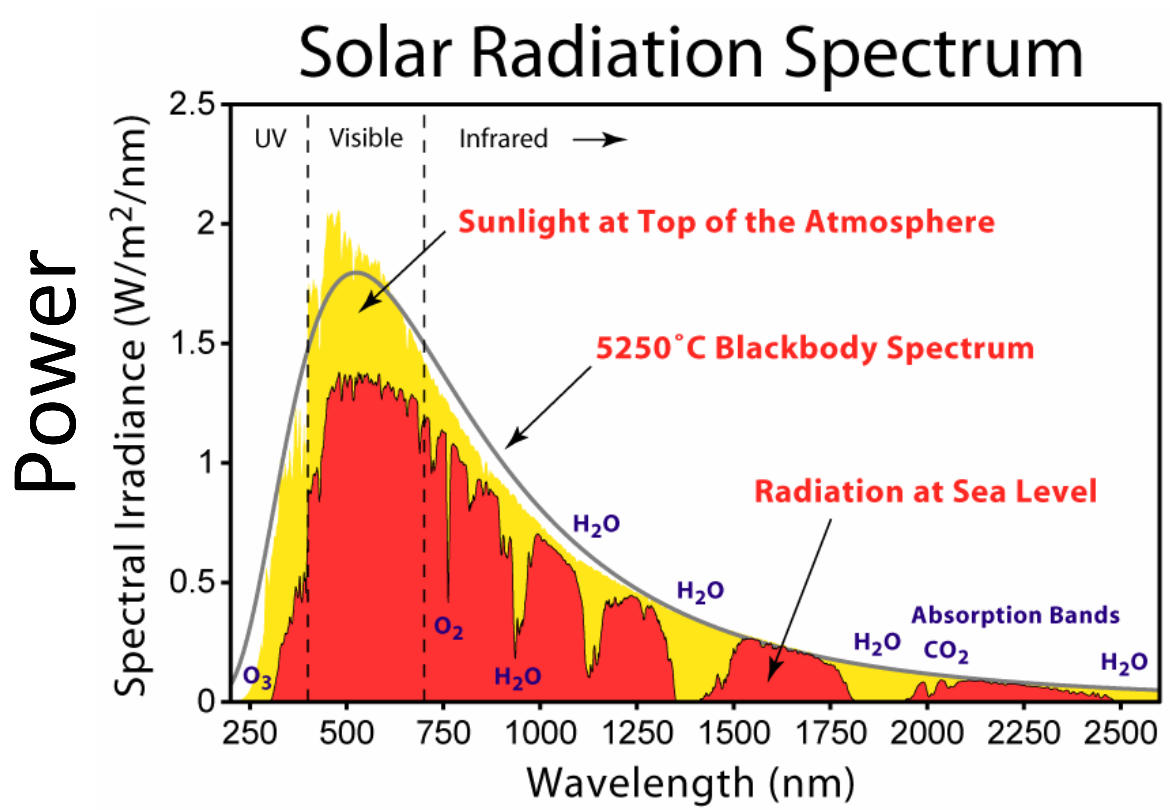
Thermal Radiation

- Thermal radiation emitted by everything
- Many different wavelengths are emitted
- E.g. the sun:

• "Spectrum" Power vs. wavelength

• Total power depends on temperature

• Peak wavelength depends on temperature



http://en.wikipedia.org/wiki/Image:Solar_Spectrum.png

Thermal Radiation

- Total emitted power depends strongly on temperature:

$$P = \varepsilon \sigma A T^4$$

?

σ is a constant, the "Stefan Boltzmann Constant"

$\sigma = 5.67 \times 10^{-8}$ $W/m^2/K^4$

Temperature (K)

A, Surface area of the object

emissivity

- Total emitted power depends strongly on temperature:

$$P = \varepsilon \sigma A T^4$$

[Demo]

ε = emissivity; describes how well EM radiation is absorbed or emitted (same)

Black = perfect absorber, perfect emitter; ε = 1.

Shiny = bad absorber, emitter. ε near zero.

Transparent = bad absorber, emitter. ε near zero.

emissivity

- Total emitted power : $P = \varepsilon \sigma A T^4$

ε = emissivity;

Emissivity can vary with wavelength.

For example: coatings on windows:

high ε in infrared wavelength range,

low ε (transparent) in visible range

Very important to climate!

Thermal Radiation

- Peak wavelength depends on temperature

- Higher $T \rightarrow$ More energy per photon $\rightarrow$ shorter wavelength

  - The sun: T = 6000 K; peak $\lambda \approx 0.5 \times 10^{-6}$ m

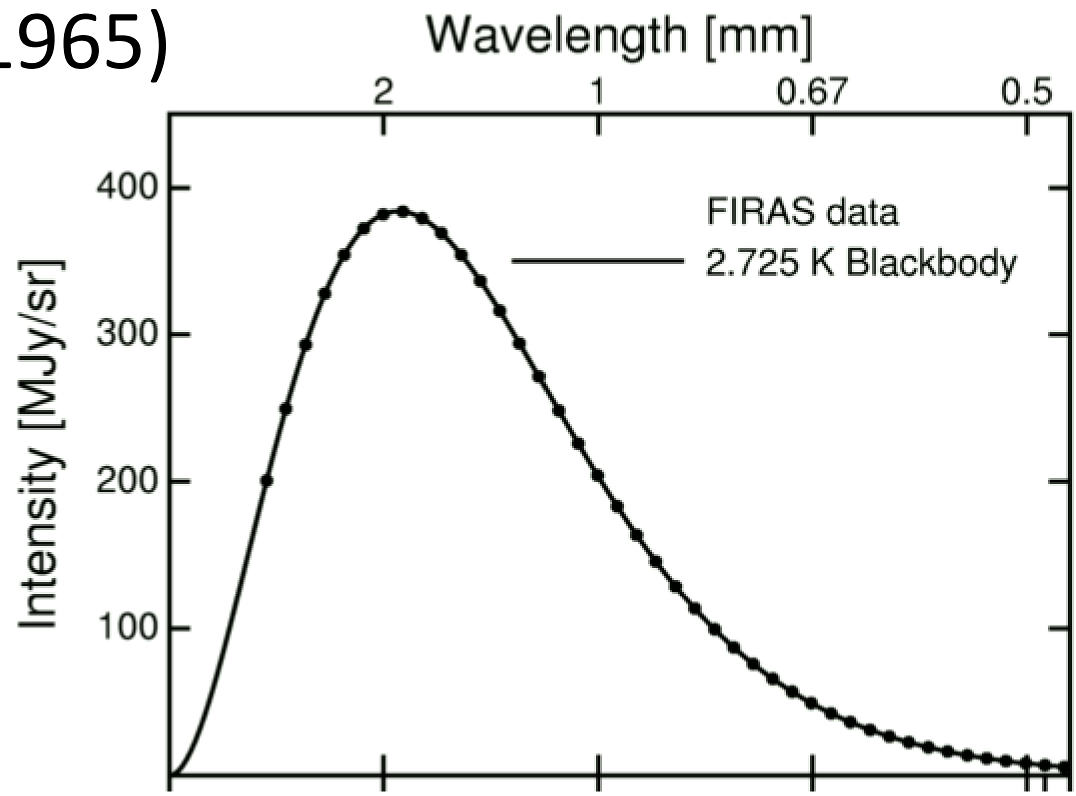
  - You: T = 300 K; peak $\lambda \approx 10 \times 10^{-6}$ m

  - The Universe: T = 2.7 K; peak $\lambda \approx$ 2 mm

?

Thermal Radiation

- The Universe: T = 2.7 K; peak $\lambda \approx$ 2 mm
- "Cosmic Microwave Background"
- (Penzias & Wilson, 1965)



from the COBE Satellite
(launched 1989)

Heat

- Heat: Energy that flows due to a temperature difference.
- How does heat flow? ("Heat transfer")
  - Three mechanisms
  - Conduction
  - Convection
  - Radiation

Heat Capacity

- We've discussed how $\Delta T \rightarrow$ heat transfer
- What about the opposite: Suppose you supply energy (*of any form*), how much does *T* change?
- The relation between energy, *Q*, and ΔT depends on
  - how much material there is: Mass, *M*
  - intrinsic property: "specific heat," *c*

text's symbol, also commonly used for heat.

Heat Capacity

- The relation between energy, *Q*, and ΔT depends on
  - how much material there is: Mass, *M*
  - intrinsic property: "specific heat," *c*
- $Q = M c \Delta T$
- What (SI) units should *c* have?

A. kg × K × J

B. W / K / kg ← note: both kg and K in denominator

C. J / kg / K

Heat Capacity

- The relation between energy, Q, and ΔT depends on
  - how much material there is: Mass, M
  - intrinsic property: "specific heat," c
- $Q = M\, c\, \Delta T$
- What (SI) units should c have?

A. kg × K × J

B. W / K / kg

C. J / kg / K

$$J = kg \times (J/kg/K) \times K$$

Heat Capacity

- $Q = M\,c\,\Delta T$
- Specific heat: units of J/kg/K (or J/kg/°C)
- Shows the energy needed to raise *T* of 1 kg of the material by 1 °C
- Note: Water has a very high specific heat!

Table 4.3 Specific Heats (J/kg/K) of Some Common Materials

Aluminum	900
Concrete	880
Glass	753
Steel	502
Stone (granite)	840
Water	
Liquid	4,184
Ice	2,050
Wood	1,400

?

- Heat Input → Temperature rises (usually)
- Can you think of a situation in which adding heat does not lead to a change in temperature?...

Latent Heat

- Phase transitions (e.g. ice → water, water → steam) often involve a "heat of transformation" or "latent heat" to alter the intermolecular arrangements
- Latent heat = Energy required per unit mass (e.g. water melting: 334 kJ/kg)
- E.g. ice at -10 °C;
  - add heat... T rises... -6°C ... -3°C ... 0 °C
  - continue to add heat. T remains at 0°C, but ice → water... all ice has melted
  - continue to add heat. T of water rises...

Physics of Energy

- Our survey of the Physics of Energy is complete
  - Energy, Power
  - Forms of Energy and Energy Conversion
  - Thermal Energy and Heat

Coming Attractions

- Next:
  - A bit of review + thoughts on how to think about physical relations
- Then:
  - Specific Sources of Energy
  - Climate and Climate Change