Conceptual Physics
Heat Capacity
Heat Transfer

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Last time

- Bernoulli's principle
- plasmas
- temperature
- heat

Overview

- heat capacity
- thermal expansion
- heat transfer mechanisms
- Newton's law of cooling
- the greenhouse effect
- phases of matter and phase change

Heat

Heat, Q

An amount of internal energy that is *transferred* from one object to another.

Units of heat:

1 calorie = 4.18 Joules.

Specific Heat Capacity

It requires less energy to raise the temperature of some objects compared to others.

Obviously, a small amount of water requires less heat to raise its temperature by 1 degree than a large amount of water.

But even two objects of the same mass may require different amounts of heat to change their temperature by 1 degree if they are made of different materials.

Different materials have different **heat capacities**.

Specific Heat Capacity

Specific Heat Capacity, c

of a substance is the quantity of heat required to change the temperature of a unit mass of that substance by 1 degree (as long as the substance stays in the same phase).

For example, water has a specific heat capacity $c = 4.18 \text{ J g}^{-1} \text{ K}^{-1}$.

$$Q = cm\Delta T$$

where ΔT is the change in temperature, m is the mass of the object, and Q is the heat.

$$Q \propto \Delta T$$

and $c \times m$ is the constant of proportionality.

Specific Heat Capacity

Different materials have different heat capacities.

- for Lead, $c = 0.129$ J g^{-1} K^{-1}
- for Hydrogen, $c = 14.30$ J g^{-1} K^{-1}

Hydrogen's heat capacity is phenomenally high.

Most substances are in the range 0.5 - 2 J g^{-1} K^{-1}.

This means that water also has quite a high heat capacity. This has an effect on Earth's weather and climate, since oceans make most of Earth's surface.

Heat Problem

10 g of cold water at 8°C is added to an insulated mug of 50 g of water at 20°C.

What is the final temperature of the water once it has mixed?

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Ans: 18°C

Thermal Expansion

Most substances (solid, liquid, or gas) expand when heated.

This is due to the fact that in substances at higher temperatures, the molecules move around faster and more violently, so they spread out more.

This has some important consequences in engineering.

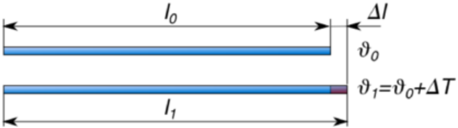
Thermal Expansion

Thermal expansion has been a common cause of derailments of trains.

Thermal Expansion

Different rates of thermal expansion can cause glass to shatter.

Thermal Expansion



A **coefficient of linear expansion** α for a solid relates how much it will expand when its temperature changes by an amount ΔT.

$$\Delta L = \alpha L_0 \Delta T$$

L_0 is the original length of the solid before the temperature change.

α takes different values for different substances.

Thermal Expansion

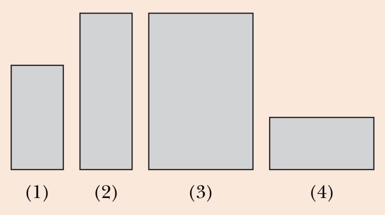
$$\Delta L = \alpha L_0 \, \Delta T$$

The expansion depends on the change in temperature, not the amount of heat transferred to the object.

Notice that the expansion varies linearly with the change of temperature. This is a good approximation for many substances if the temperature range involved is not too large.

Thermal Expansion Question

The figure here shows four rectangular metal plates, with sides of 1 m, 2 m, or 3 m. They are all made of the same material, and their temperature is to be increased by the same amount. Rank the plates according to the expected increase in their vertical heights, greatest first.



(A) 1, 2, 3, 4

(B) (2 and 3), 1, 4

(C) 3, 2, (1 and 4)

(D) all the same

[1] Halliday, Resnick, Walker, page 483.

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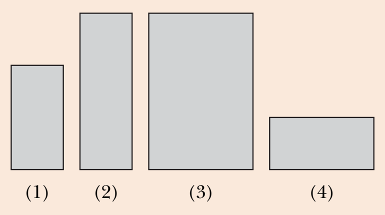

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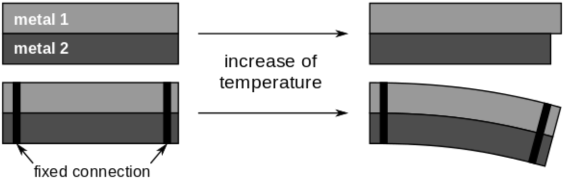
Thermal Expansion: Bimetallic Strip

A bimetallic strip is a strip made of two kinds of metal, very often brass and iron, that have quite different coefficients of linear expansion.



The strip curves downward when heated and can curl upward when it is chilled.

Used in thermostats and thermometers.

Bimetallic Strip Question

Suppose a bimetallic strip is composed of 0.10 m of brass and iron bound together at room temperature (20°C).

The strip is heated 15°C. How much longer is the brass part than the iron part?

$\alpha_{\text{brass}} = 19 \times 10^{-6} (^\circ\text{C})^{-1}$
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1.05×10^{-5} m $= 0.0105$ mm

Thermal Expansion and Water

Water has a strange behavior with temperature change.

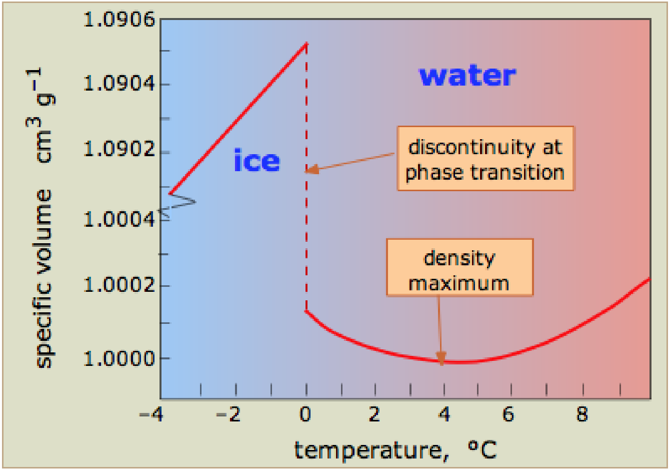
Ice is less dense than water, but even in its liquid phase, water *expands* as it cools between 4°C and 0°C.

Water forms crystals as it freezes. Those crystals have a greater volume than liquid water.

Between 4°C and 0°C some small crystals begin to form, expanding the volume of the water.

[1] Image from its.caltech.edu.

Thermal Expansion and Water



[1]Figure from Chemwiki ucdavis.edu.

Heat Transfer

When objects are in thermal contact, heat is transferred from the hotter object to the cooler object

There are various mechanisms by which this happens.

Conduction

Heat can flow along a substance.

When it does, heat is said to be transferred by **conduction** from one part of the substance to another.

Some materials allow more heat to flow through them in a shorter time than others.

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Some materials allow more heat to flow through them in a shorter time than others.

These materials are called “good conductors” of heat:

- metals (copper, aluminum, etc)
- diamond

Conduction

In solids, conduction happens via

- vibrations
- collisions of molecules
- collective wavelike oscillations (phonons)
- diffusion and collisions of free electrons

In liquids and gases, conduction happens through diffusion and collisions of molecules.

Conduction

Some materials are not good conductors and are referred to as **thermal insulators**.

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Examples:

- air (and hence down feathers, wool)
- styrofoam
- wood
- snow

Convection

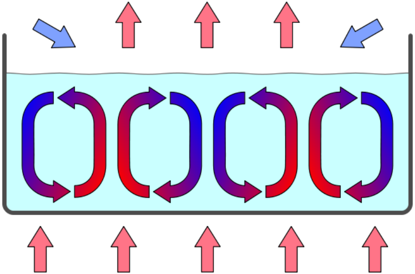
In liquids and gases convection is usually a larger contributor to heat transfer.

In convection, the fluid itself **circulates** distributing hot (fast moving) molecules throughout the fluid.

When there is gravity present, convection current circulations can occur.

Convection

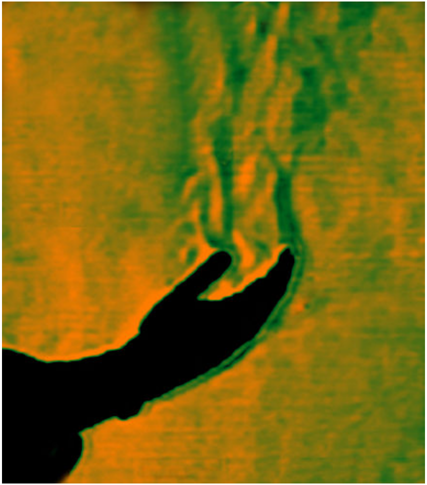
Hot fluid expands, and since it is less dense, it will have a greater buoyant force and rise.



Cooler, denser fluid will tend to sink.

Convection

Heat loss by convection from a person's hand:



This type of convection is called "free convection".

Forced Convection

External energy can also drive convection by means of a pump or fan.

This is used in convection ovens to evenly heat food.

It is also used in cooling systems to keep cool air flowing over hot components.

Radiation

Heat can also be transferred across a vacuum by **radiation**.

This radiation takes the form of electromagnetic (em) radiation, or light. However, most of this radiation is not in the range of wavelengths that are visible to us.

Light carries energy, so this an energy transfer.

Dark colored surfaces absorb and emit radiation more readily that white or shiny surfaces.

Emissivity and Absorptivity

Why are survival and rescue blankets now made out of shiny material?

Light (Electromagnetic Radiation)

Light travels at this fixed speed, $c = 3.00 \times 10^8$ m s^{-1}.

For any wave, if v is the wave propogation speed:

$$v = f\lambda$$

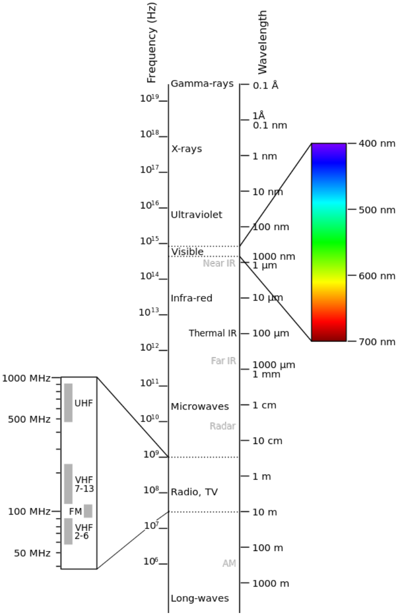
For light:

$$c = f\lambda$$

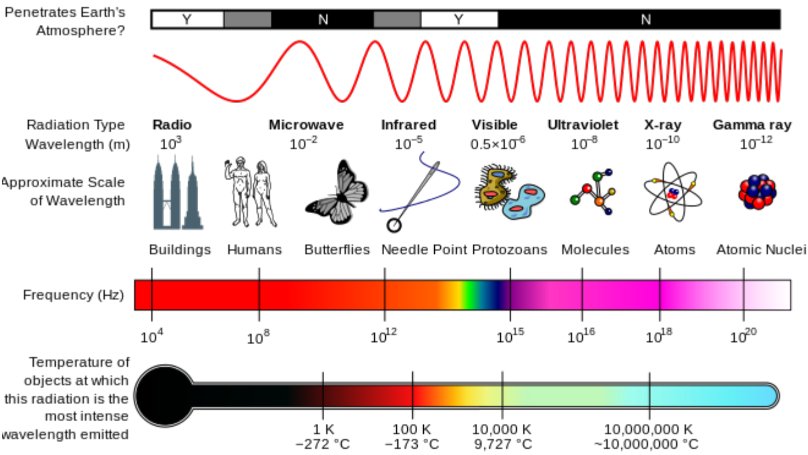
So, if the frequency of the light is given, you also know the wavelength, and vice versa.

$$\lambda = \frac{c}{f} \quad ; \quad f = \frac{c}{\lambda}$$

Electromagnetic spectrum

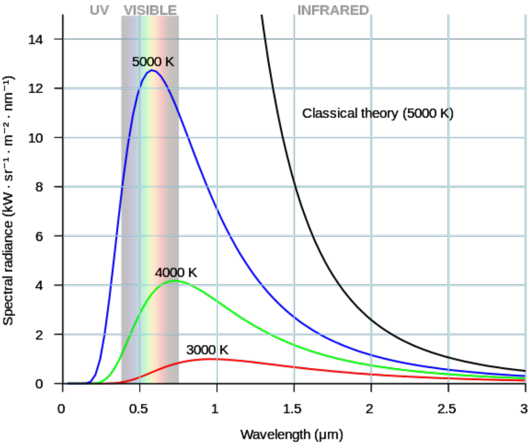


Electromagnetic spectrum



Radiation

All objects radiate light with characteristic wavelengths depending on the object's temperature.



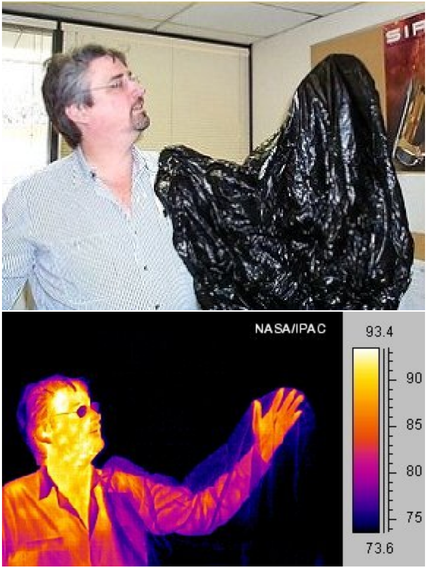
Hotter objects emit light with shorter wavelengths.

Radiation

People emit light as well, but the wavelengths corresponding to our body temperature are longer than what we can see with the naked eye.

Humans and warm-blooded animals radiate **infrared radiation**. ("below red")

Visible vs. Infrared radiation



Radiation

Objects much hotter than the human body will radiate at shorter wavelengths that are visible to us.

Newton's Law of Cooling (thermal conduction)

Newton found a relation between the rate that an object cools and its temperature difference from its surroundings.

Objects that are much hotter than their surroundings lose heat much faster than objects that are only a bit hotter than their surroundings.

$$\text{Rate of cooling} \propto \Delta T$$

or, using Q for heat:

$$\frac{\Delta Q}{\Delta t} \propto \Delta T$$

Newton's Law of Cooling (Applies for thermal conduction)

$$\text{rate of loss of heat} = \frac{\mathrm{dQ}}{\mathrm{dt}} \propto \Delta T$$

If there is no phase change in the substance, then we can use the relation for heat capacity:

$$Q = -mc\,\Delta T$$

where in this case the heat is transferred out of the hot object to the environment.
to get:

$$\text{rate of cooling} = \frac{\mathrm{d}(\Delta \mathrm{T})}{\mathrm{dt}} = -r\,\Delta T$$

where r is a constant.

Newton's Law of Cooling Example

Problem 3, page 299.

In a 25°C room, hot coffee in a vacuum flask cools from 75°C to 50°C in 8 hours. Why might you predict that its temperature after another 8 hours will be 37.5°C?

[1] See also Problem 3, page 299, Hewitt.

The Greenhouse Effect

Gardeners use greenhouses, huts made of glass or transparent plastic, to keep plants warm.

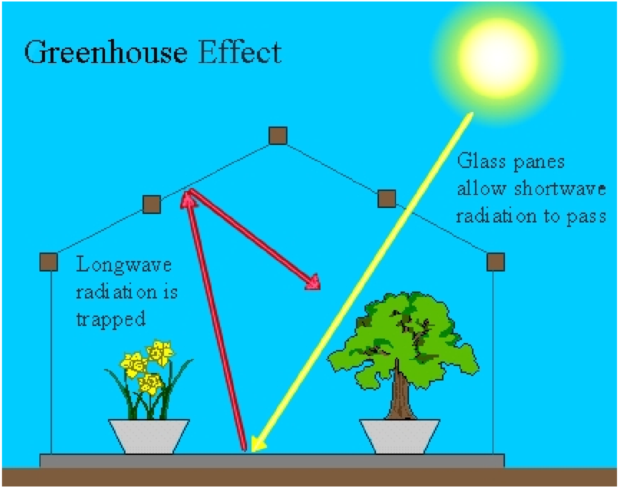
The effect that causes this to work is called the greenhouse effect.

The Sun is very hot and emits a lot of radiation in the visible (shorter) wavelengths.

Objects on Earth absorb this radiation and emit there own. However, since object on the Earth are substantially cooler than the Sun, the wavelengths re-emitted are longer.

The glass allows the shorter wavelengths through, but traps the longer wavelengths.

The Greenhouse Effect



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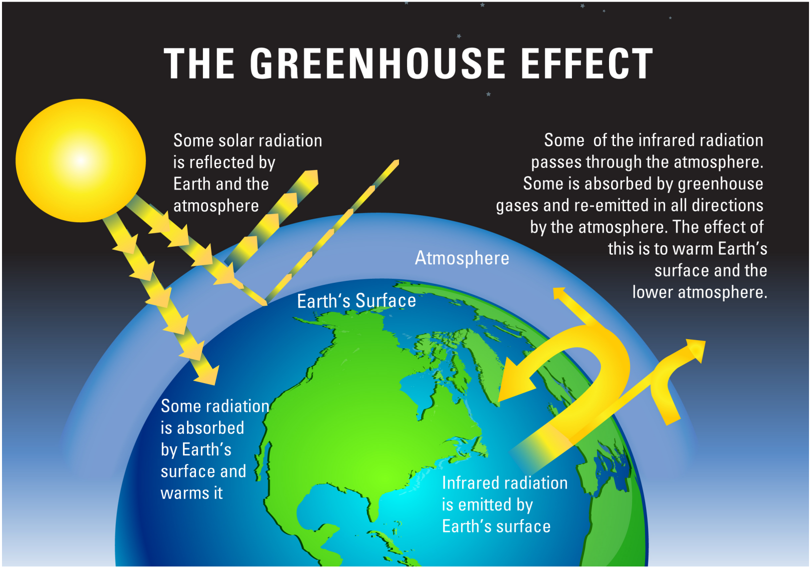

[1]Figure from the National Academy of Sciences, *America's Climate Choices*

Heat Transfer Question

Problem 5, page 299.

In a lab you submerge 100 g of 40°C iron nails in 100 g of 20°C water (the specific heat of iron is 0.12 cal/g°C).

(a) Equate the heat gained by the water to the heat lost by the nails and show that the final temperature of the water becomes 22.1°C.

(b) Your lab partner is surprised by the result and says that since the masses of iron and water are equal, the final water temperature should lie closer to 30°C, halfway between. What is your explanation?

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[1] Hewitt, 11th ed.

Phase Changes

The processes by with matter changes from one state to another.

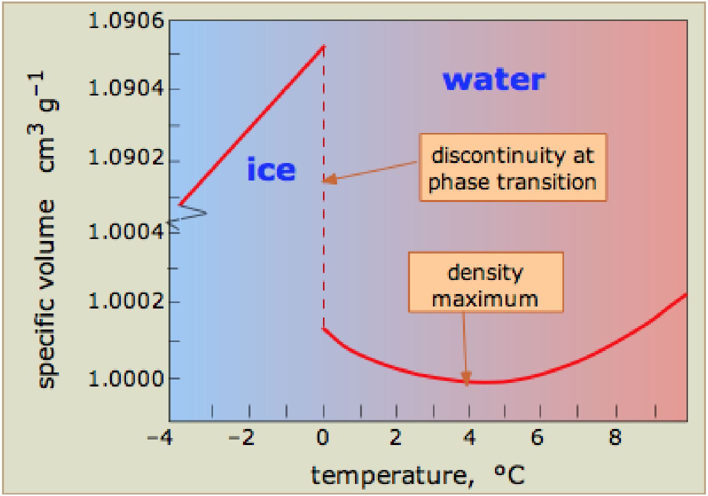
The different states of matter: solid, liquid, gas, plasma, are also called *phases* of matter.

Phase Changes

Phase changes tend to be dramatic.

If sudden, obvious changes in the properties and behaviors of a substance did not occur as we vary the temperature, we would probably have no need to refer to different states of matter!

Phase Changes



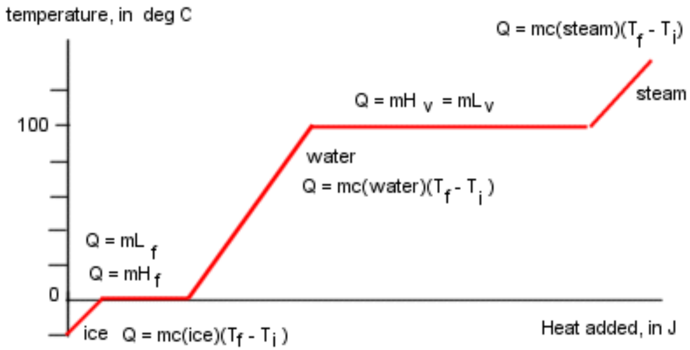
Notice the discontinuity!

Phase Changes

We know that as we heat a solid it will eventually melt to form a liquid and if we keep heating the liquid will boil off as a gas.

But how does the temperature change during these processes?

Phase Changes



During a phase change, temperature doesn't change, even when heat is added!

Phase Changes

What's happening?

We add heat, but the temperature doesn't increase. Where does the energy go?

Phase Changes

What's happening?

We add heat, but the temperature doesn't increase. Where does the energy go?

The energy goes to breaking bonds attracting molecules, atoms, or ions to each other.

$$\text{internal energy} = \text{thermal energy} + \text{bond energy}$$

Latent Heat

latent heat of fusion, L_f

The amount of energy (heat) per unit mass required to change a solid to a liquid.

$$\text{heat, } Q = mL_f$$

latent heat of vaporization, L_v

The amount of energy (heat) per unit mass required to change a liquid to a gas.

$$Q = mL_v$$

Summary

- heat capacity
- thermal expansion
- heat transfer mechanisms
- Newton's law of cooling
- the greenhouse effect

Essay due Thursday, Aug 3rd.

Talks! Aug 8-9.

Homework Hewitt,

- PREV: Ch 15, onward from page 281. Exercises: 3, 9, 15, 29, 35, 49; Problems: 1, 3
- Ch 16, onward from page 296. Exercises: 21, 23; Problems: 1

Essay

Essay due Thursday, Aug 3rd.

Explain using physics concepts the different ways that a hot air balloon, an airship (zepplin), and an airplane can allow a person to fly. Comment on the the advantages and disadvantages of each as a method of flight, and any uses for each method.

Essay Tips

You get points based on your physics explanations, ideas, and structure / clarity.

Structure your essay as an essay: have a (short) introduction paragraph and a (short) conclusion paragraph.

Please make sure to describe the physics accurately. Do not say things like, "velocity is the force that moves a plane forward," because velocity is not a force. Or, if an object is in the process of stopping, do not say its acceleration is stopped - it is decelerating, so its acceleration is not zero.