Thermodynamics
Thermal Equilibrium
Temperature

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Last time

- Torricelli's Law
- applications of Bernoulli's equation

Overview

- heat, thermal equilibrium, and the 0th law
- temperature
- temperature scales

HW Problem #18

A solid sphere of brass (bulk modulus of 14.0×10^{10} N/m^2) with a diameter of 3.00 m is thrown into the ocean. By how much does the diameter of the sphere decrease as it sinks to a depth of 1.00 km? ($\rho_{\text{seawater}} = 1030$ kg/m^3)

Introducing Thermodynamics

Now something different. (Chapter 19)

Thermodynamics is the study of temperature, head transfer, phase changes, together with energy and work.

It focuses on relating the **bulk properties** and **behavior** of substances. These bulk properties are usually easily measured.

Introducing Thermodynamics

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Why is this interesting?

- it is a little surprising (philosophically) that it works so well
- it can help us to understand how the universe is evolving
- it is really important for technology

Heat

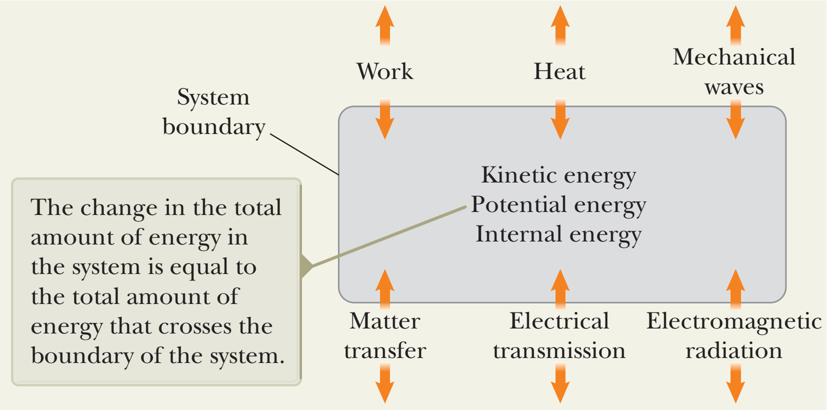
Heat is a kind of **energy transfer** into our out of a system.

In the same way we say that something *does work* on an object, we say that *heat flows* from one object to another.

Technically, an object does not “contain heat”, heat is just energy being transferred.

The symbol for heat is Q, and units are Joules, J.

Heat



The change in the total amount of energy in the system is equal to the total amount of energy that crosses the boundary of the system.

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[1] Figure from Serway & Jewett, 9th ed., page 214.

The Zeroth Law of Thermodynamics

Thermodynamic Equilibrium

Two systems are in thermodynamic equilibrium when they would not exchange energy by heat or EM radiation, even when placed in thermal contact.

0th Law

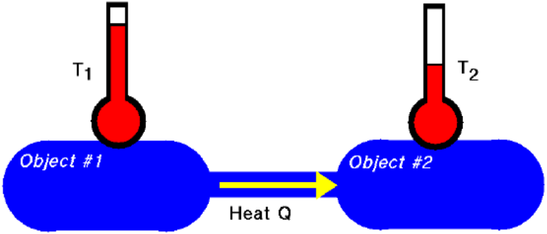
If two systems are each in thermodynamic equilibrium with a third system, then the are in thermodynamic equilibrium with each other.

This means that thermodynamic equilibrium is transitive, a bit like the equal sign.

Temperature

We can go beyond simply saying that two systems are in equilibrium.

We can also compare two systems that are *not* in equilibrium by analyzing which way heat is transferred when they are brought into contact.



We create a scale for thermodynamic systems to compare them: **temperature**, T.

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[1] Figure: Tom Benson, Glen Research Center, NASA, www.grc.nasa.gov.

Temperature

If two systems, A and B are in thermal equilibrium then their temperatures are equal,

$$T_A = T_B$$

If system A transfers heat energy to system B, then

$$T_A > T_B$$

(Or, system A is "hotter" than system B.)

If system B transfers heat energy to system A, then

$$T_A < T_B$$

Temperature

It is not possible to rigorously compare the temperature of objects just by touching them.

Some substances like metal or ceramic tiles at room temperature may feel cool to the touch, while wool at room temperature does not feel cool at all.

This is due to the fact that some substances transfer heat more quickly than others, and our sense of “hotness” or “coolness” has more to do with the rate at which heat is transferred to or from us than actual the temperature.

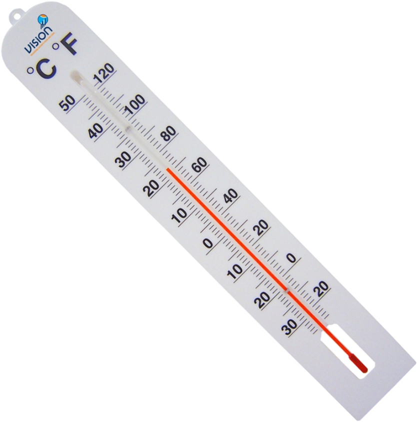
Measuring Temperature

Devices for measuring temperatures are called **thermometers**.

All such devices work by employing a substance that changes its properties as it changes temperature.

Measuring Temperature

The most familiar tool for measuring temperature is the mercury thermometer.



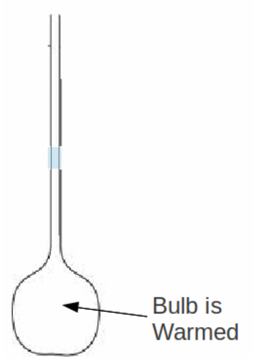
As the bulb warms, the mercury expands into a thin capillary tube.

Temperature and Absolute Zero

Ancient Greek and Egyptian scientists understood that gases expand when heated.

Galileo Galilei used this idea to make a thermoscope – a temperature sensing device without a scale.

Air is the expanding gas, drawing water up or down in a tube.



Temperature and Absolute Zero

Air thermometer in use:

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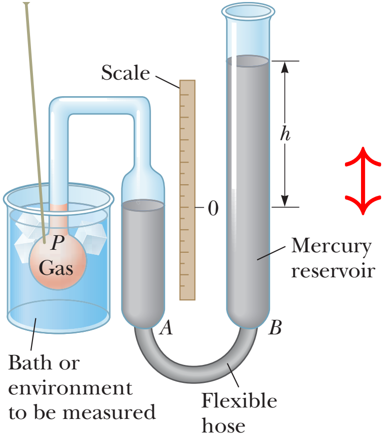
[1] Photos from Washington State LASER org website.

Measuring Temperature

Another way to use a gas to measure temperature is to keep a gas at constant volume as its pressure changes.



↕ move reservoir B up or down

This is a constant-volume gas thermometer.

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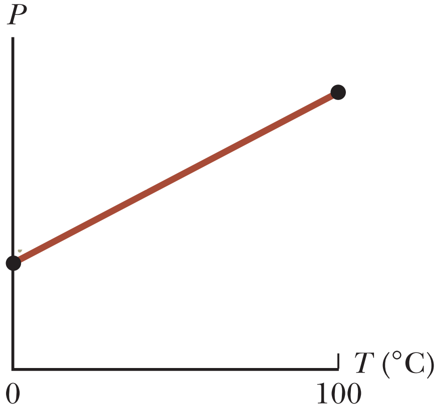
[1] Diagram from Serway & Jewett, 9th ed.

Measuring Temperature

In a constant-volume gas thermometer, the pressure, as measured by the height *h*, varies linearly with the temperature.



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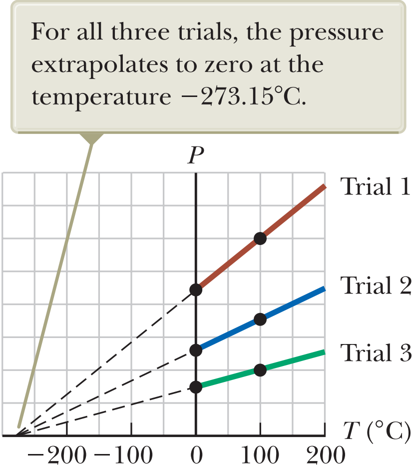
[1] Diagram from Serway & Jewett, 9th ed.

Measuring Temperature

Different gas samples can have different pressures at the same temperature, and different slopes $\frac{dP}{dT}$.



For all three trials, the pressure extrapolates to zero at the temperature −273.15°C.

All have the same *x*-intercept, however.

Temperature and Absolute Zero

Robert Boyle (1655) speculated there might be a minimum possible temperature.

Guillaume Amontons (1702) made improvements to the air thermometer.

He noticed that his thermometer would not be able to register temperatures below the value where the air was compressed to (effectively) zero volume.

He proposed this as a zero-point of temperature scales.

Temperature Scales

There are a few different scales in common use:

- Fahrenheit, F
- Celsius, C
- Kelvin, K

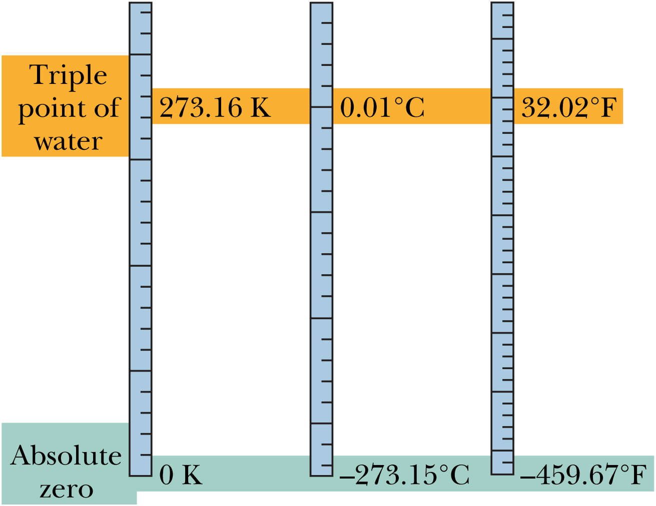
Temperature: Degrees

In all of those temperature scales the unit of temperature is the degree.

Celsius and Kelvin degrees are the same size. (A temperature rise of 1 degree C, is the same as a temperature rise of 1 degree K.)

However, Fahrenheit degrees are smaller. There are 1.8 degrees-F-scale in 1 degree-C-scale.

Temperature: Degrees



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[1] Figure from Halliday, Resnick, and Walker, 9th ed.

Fahrenheit

On the Fahrenheit scale, originally,

- 0 degrees corresponds to the coldest salt water can be before freezing
- 100 degrees is human body temperature

This is a very arbitrary choice reference points. Worse yet, different people have different body temperatures and there are many kinds of salt water.

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Now, the Fahrenheit scale is defined so that:

- 32 degrees corresponds to the freezing point of water
- 212 degrees is the boiling point of water at atmospheric pressure

These reference points are easier to reproducibly measure, but now they correspond to degree numbers that are arbitrary.

Example: room temperature in Fahrenheit is about 70°F

Celsius

On the Celsius scale,

- 0 degrees corresponds to the freezing point of water
- 100 degrees is boiling point of water

Since there are 100 degrees between water's freezing and boiling points, this is called a *centigrade* scale.

Example: room temperature in Celsius is about 21°C

Kelvin

The SI unit for temperature is the Kelvin K.

The associated Kelvin scale is appealing for scientists because 0 on the Kelvin scale (written 0 K) is the coldest possible temperature.

The triple point of water (all three phases can coexist in equilibrium) was defined to be 273.16 K.

Now the Kelvin is defined so that the Boltzmann constant is exactly:

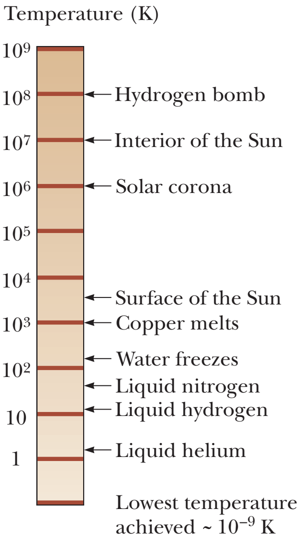
$$k_B = 1.380649 \times 10^{?23} \text{ J/K}$$

On the Kelvin scale, at standard atmospheric pressure:

- water freezes at 273.15 K
- water boils at 373.15 K.

Room temperature is about 294 K.

Kelvin Scales Examples, Log Scale



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[1] Figure from Serway & Jewett, 9th ed.

Conversions

Celsius to Kelvin:
$[^\circ\mathrm{C}] + 273.15 = [\mathrm{K}]$

Kelvin to Celsius:
$[\mathrm{K}] - 273.15 = [^\circ\mathrm{C}]$

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Fahrenheit to Celsius:
$([^\circ\text{F}] - 32) \div 1.8 = [^\circ\text{C}]$

Celsius to Fahrenheit:
$([^\circ\text{C}] \times 1.8) + 32 = [^\circ\text{F}]$

Summary

- heat, thermal equilibrium, and the 0th law
- temperature
- temperature scales

Quiz today, anytime until 10:50pm.

Test Wednesday.