Temperature, T

- We associate the concept of temperature with how hot or cold an objects feels
- Our senses provide us with a qualitative indication of temperature
- Our senses are unreliable for this purpose
- We need a technical definition of temperature

Thermal Contact

- Two objects are in **thermal contact** with each other if energy can be exchanged between them
  - The exchanges we will focus on will be in the form of heat or electromagnetic radiation
  - The energy is exchanged due to a temperature difference

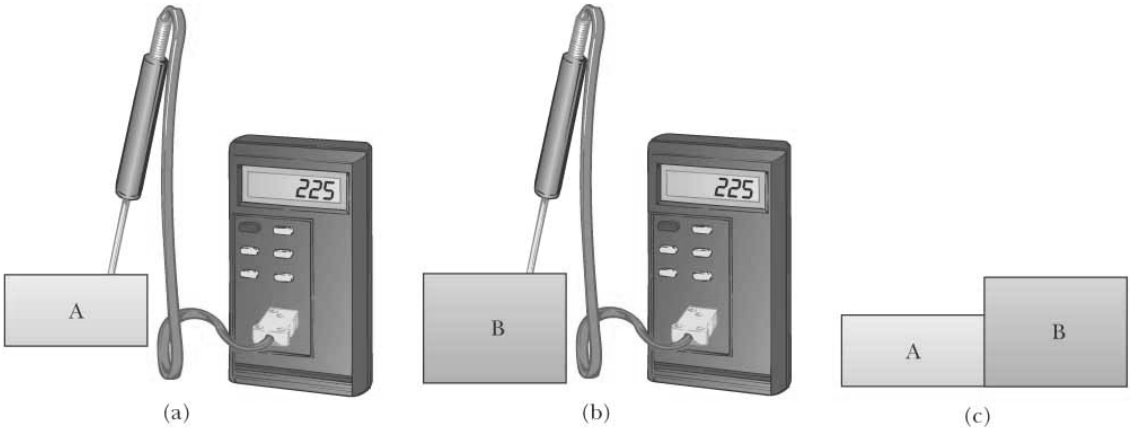
Thermal Equilibrium

- **Thermal equilibrium** is a situation in which two objects would not exchange energy by heat or electromagnetic radiation if they were placed in thermal contact
  - The thermal contact does not have to also be physical contact

Zeroth Law of Thermodynamics

- If objects A and B are separately in thermal equilibrium with a third object C, then A and B are in thermal equilibrium with each other
  - Let object C be the thermometer
  - Since they are in thermal equilibrium with each other, there is no energy exchanged among them

Zeroth Law of Thermodynamics, Example



Object C (thermometer) is placed in contact with A until they achieve thermal equilibrium

- The reading on C is recorded

Object C is then placed in contact with object B until they achieve thermal equilibrium

- The reading on C is recorded again

If the two readings are the same, A and B are also in thermal equilibrium

Temperature (Technical)

- **Temperature** can be thought of as the property that determines whether an object is in thermal equilibrium with other objects
- Two objects in thermal equilibrium with each other are at the same temperature
  - If two objects have different temperatures, they are not in thermal equilibrium with each other

Thermometers

- A **thermometer** is a device that is used to measure the temperature of a system
- Thermometers are based on the principle that some physical property of a system changes as the system’s temperature changes

Thermometers

- These properties include:
  - The volume of a liquid
  - The dimensions of a solid
  - The pressure of a gas at a constant volume
  - The volume of a gas at a constant pressure
  - The electric resistance of a conductor
  - The color of an object

- A temperature scale can be established on the basis of any of these physical properties

Thermometer, Liquid in Glass

- A common type of thermometer is a liquid-in-glass
- The material in the capillary tube expands as it is heated
- The liquid is usually mercury or alcohol

Calibrating a Thermometer

- A thermometer can be calibrated by placing it in contact with some natural systems that remain at constant temperature
- Common systems involve water
  - A mixture of ice and water at atmospheric pressure
    - Called the **ice point** of water
  - A mixture of water and steam in equilibrium
    - Called the **steam point** of water

Fahrenheit Scale

- A common scale in everyday use in the US
- Named for Daniel Fahrenheit
- Temperature of the ice point is 32^{o}F
- Temperature of the steam point is 212^{o}F
- There are 180 divisions (degrees) between the two reference points

Fahrenheit wrote in 1724 how he determined three fixed points of temperature.

The zero point is determined by placing the thermometer in a mixture of ice, water, and sodium chloride (or sea salt). The mixture automatically stabilizes its temperature at 0 degrees F.

He then put an alcohol or mercury thermometer into the mixture and let the liquid in the thermometer descend to its lowest point. The second point is the 32nd degree found by mixing ice and water without the salt.

His third point, the 96th degree, was the level of the liquid in the thermometer when held in the mouth or under the armpit. Fahrenheit noted that, using this scale, mercury boils at around 600 degrees.

Celsius Scale

- The ice point of water is defined to be 0^{o} C
- The steam point of water is defined to be 100^{o} C
- The length of the column between these two points is divided into 100 increments, called degrees

Problems with Liquid-in-Glass Thermometers

- An alcohol thermometer and a mercury thermometer may agree only at the calibration points
- The discrepancies between thermometers are especially large when the temperatures being measured are far from the calibration points
- The thermometers also have a limited range of values that can be measured
  - Mercury cannot be used under –30^{o} C
  - Alcohol cannot be used above 85^{o} C

Joseph Louis Gay-Lussac and Jean-Baptiste Biot in their balloon on 24 August 1804.

First flight by Prof. Jacques Charles with Ainé Roberts, **December 1**, **1783**. Illustration from the late 19th Century.

Charles' Law

- Charles' law has a more complex history. It was discovered by Joseph Gay-Lussac in 1802, but since he referenced unpublished work by Charles from 1787, it ended up bearing his name instead.

- Incidentally, Jacques Charles made the first flight in a hydrogen balloon in 1783 (only a week or two after Montpellier's first flight), and while Boyle's law was about learning the properties of air, this discovery was all about flying balloons, which were all the rage in France at the time.

- Their finding was that the volume of a gas is directly proportional to its temperature at constant pressure, or more simply $V = kT$, where k is a constant (n.b., not the Boltzmann constant, which I will always write as k_B). We can also write this as:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

In addition to hot-air ballooning, Charles' law is central to convection, which appears in many places from heat transport in liquids to thunderstorm cells.

Constant Volume Gas Thermometer

- The physical change exploited is the variation of pressure of a fixed volume gas as its temperature changes

- The volume of the gas is kept constant by raising or lowering the reservoir B to keep the mercury level at A constant