Physics 1501

Fall 2008

Mechanics, Thermodynamics, Waves, Fluids

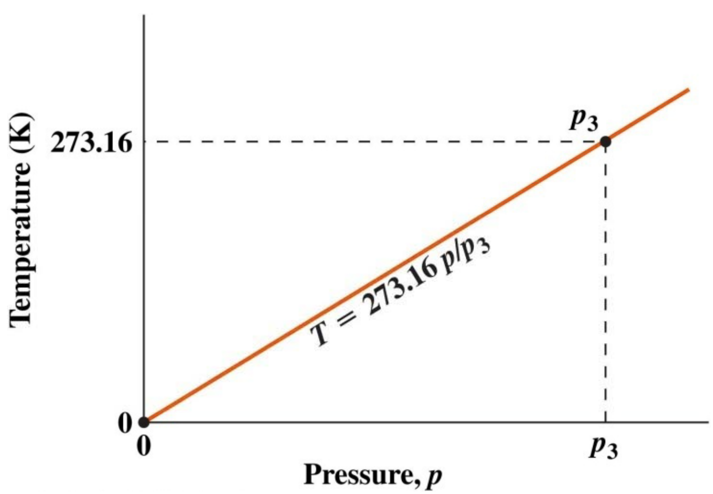
Lecture 29: Temperature and heat II

Recap: thermodynamic equilibrium

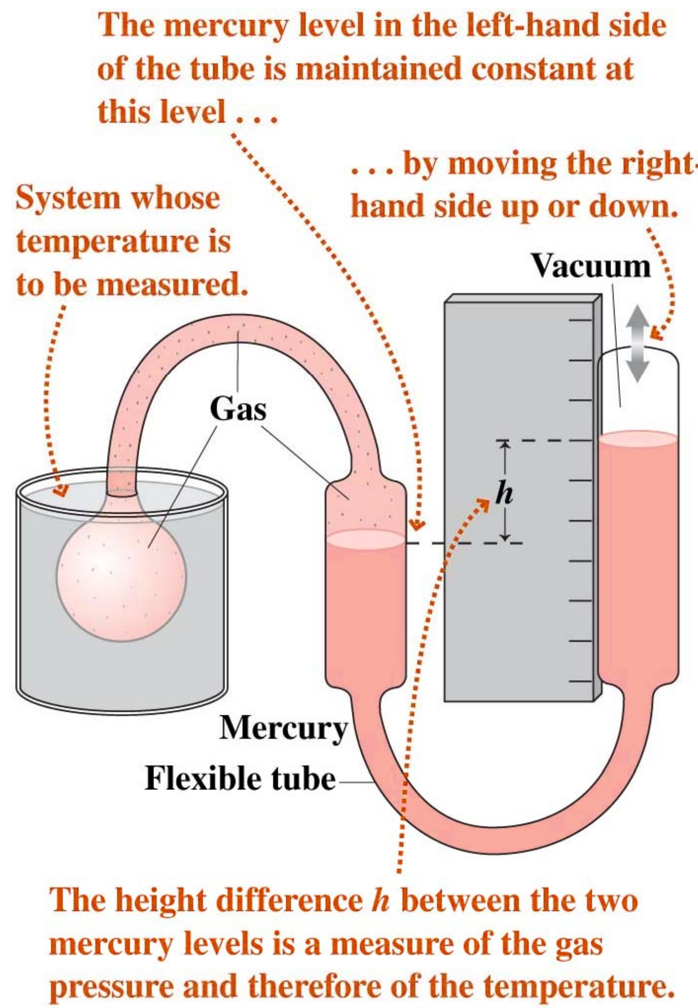
- Two systems placed in contact may undergo changes in macroscopic properties like length, pressure, electrical resistance, etc.
- When such macroscopic changes cease, the two systems are in **thermodynamic equilibrium.**
- By definition, systems in thermodynamic equilibrium are at the same **temperature.**
- Any convenient macroscopic property can be used as a measure of temperature.
    - A **thermometer** is a small system with some macroscopic property whose value is used as an indication of temperature.

Recap: the kelvin scale

- The SI temperature scale is defined using the **triple point of water**, the unique temperature where solid, liquid, and gas can coexist.
  - The temperature at the triple point is defined to be 273.16 K.
  - The point of zero pressure in a gas defines a second temperature, namely **absolute zero.**
  - Together, the two defined temperatures establish the kelvin scale.



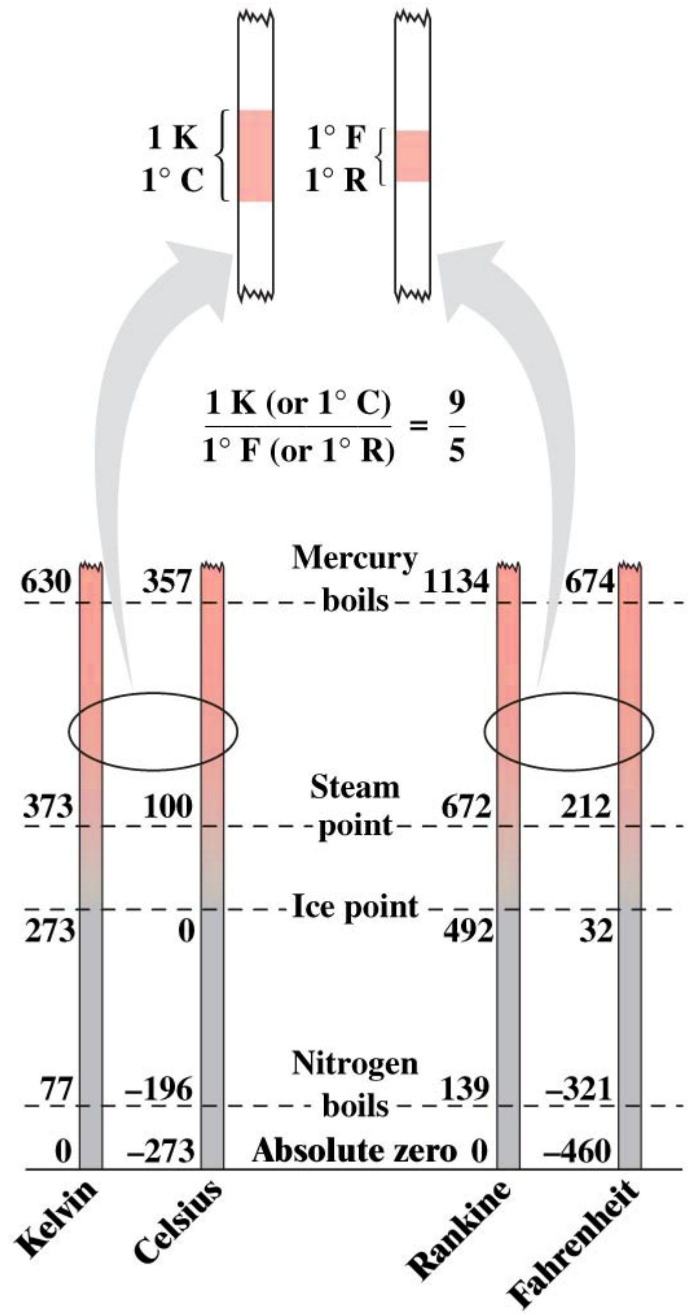
Two points establish the kelvin temperature scale



A constant-volume gas thermometer

Other temperature scales

- One celsius degree is the same size as one kelvin, but the zero of the celsius scale is at 273.15 K —the freezing point of water under normal conditions.
- One Fahrenheit degree is 5/9 the size of a celsius degree, and the zero of Fahrenheit is 32˚F below the freezing point.
    - The Rankine scale has its zero at absolute zero, and its degrees the same size as those on the Fahrenheit scale.



Heat and temperature

- **Heat** is energy being transferred from one object to another because of a temperature difference alone.
  - In SI, heat is measured in joules.
  - An older unit, the calorie, is equal to 4.184 J.
- The **heat capacity** C of an object is a measure of the heat ΔQ required per unit temperature change: $\Delta Q = C\,\Delta T$.
  - The **specific heat** c of a substance is the heat capacity per unit mass: $\Delta Q = mc\,\Delta T$.
  - When two substances at different temperatures are brought into thermal contact without any loss of energy, they come to equilibrium at a temperature determined by their masses and specific heats:
  $$m_1c_1\Delta T_1 + m_2c_2\Delta T_2 = 0$$
  Here the ΔT's are the changes from the original temperatures to the final, common equilibrium temperature.

question

- A hot rock with mass 250 g is dropped into an equal mass of cool water. Which temperature changes more, that of the rock or that of the water?

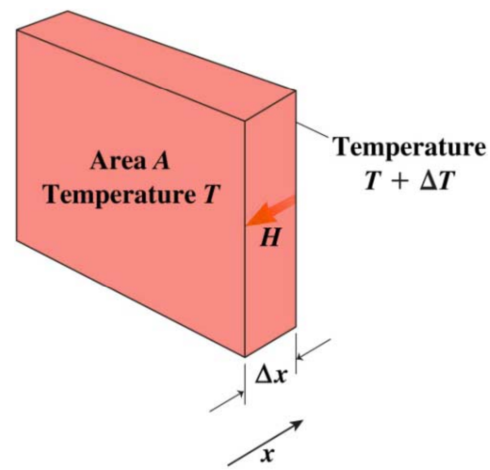
A. The temperature of the rock changes more.

B. The temperature of the water changes more.

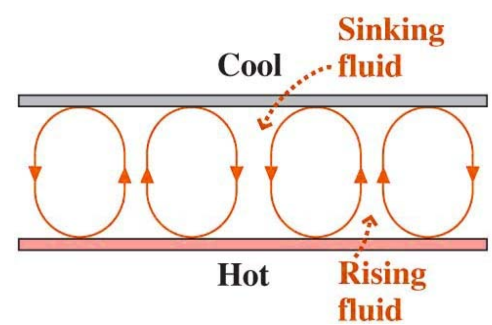
C. The temperatures of the water and the rock change equally.

Heat transfer: three common mechanisms

- **Conduction** is heat transfer through direct physical contact.
  - The conductive heat flow rate H, in watts, is $$H = -kA\frac{\Delta T}{\Delta x}$$ where k is the **thermal conductivity** of the material.



- **Convection** is heat transfer through the bulk flow of a fluid.



- **Radiation** is heat transfer by electromagnetic radiation.
  - The power loss from area A at temperature T is $P = eA\sigma T^4$.
  - Here e is the emissivity, which lies between 0 and 1, and $\sigma = 5.67\times10^{-8}$ W/m$^2\cdot$K^4.

Clicker question

- Name the dominant form of the transfer of heat energy from the bottom to the top of a pan of water on the stove, once it has begun to boil.

  A. Convection

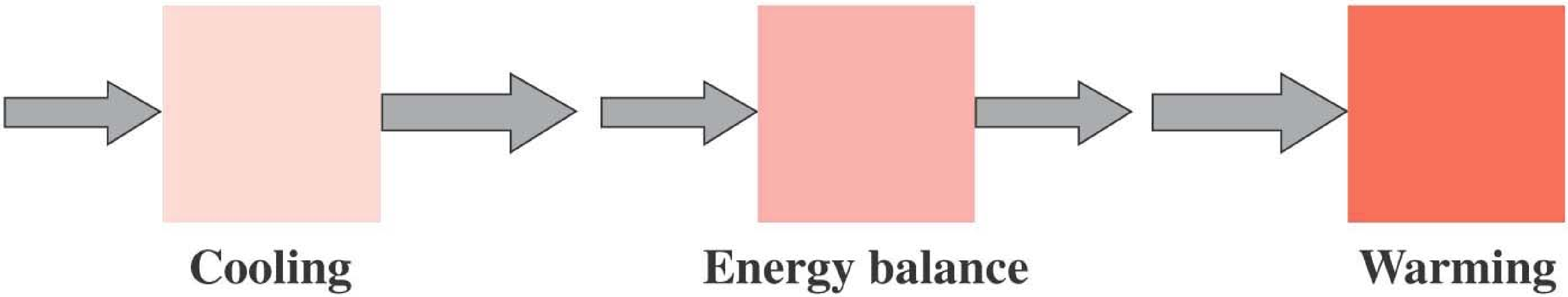
  B. Conduction

  C. Advection

  D. Radiation

Thermal energy balance

- A system is in thermal energy balance when its rate of energy gain is equal to its rate of energy loss.
  - A system in energy balance maintains a constant temperature.
  - If loss exceeds gain, the system cools.
  - If gain exceeds loss, the system warms.



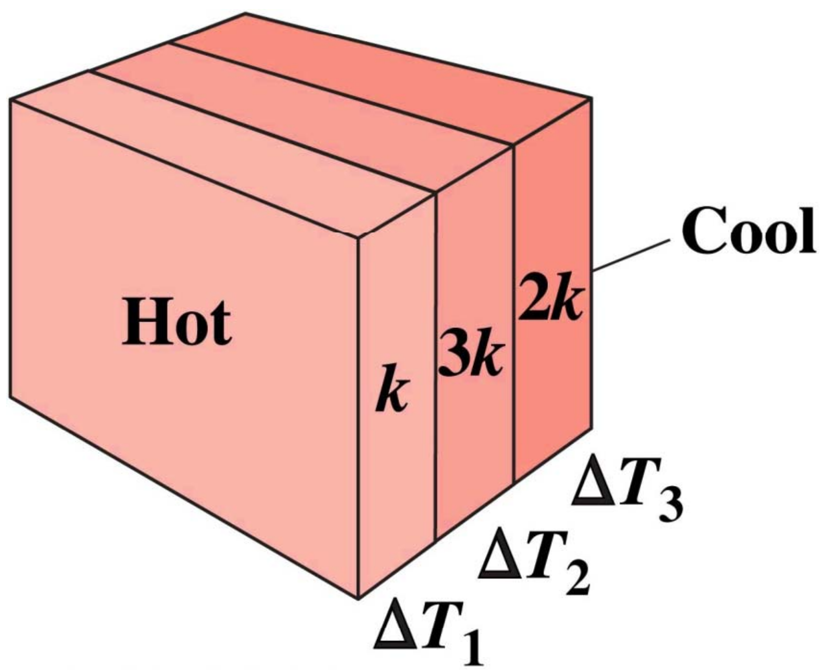
question

- The figure shows three slabs, each with one face in contact with that of the next. Their thicknesses are the same, but their thermal conductivities are different: The left side is hotter, as shown. Which slab has the greatest temperature difference between its faces?

A. ΔT_1

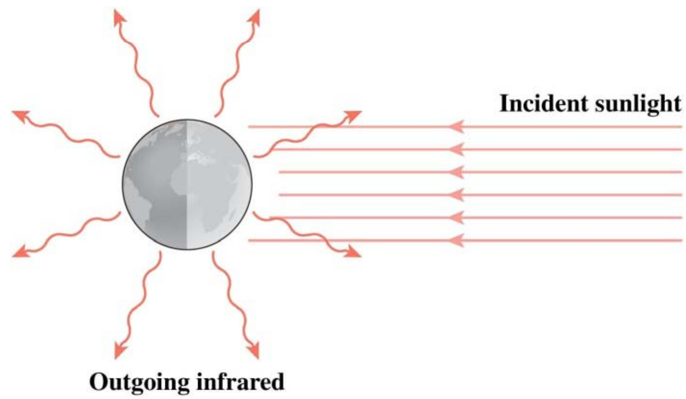
B. ΔT_2

C. ΔT_3



Example: Earth's temperature

- Earth receives energy from the Sun at the average rate of about 240 watts per square meter. Assuming its emissivity is 1, what should be Earth's average temperature?
  - INTERPRET: This is a problem about energy balance. The heat loss mechanism is radiation.



  - DEVELOP: In energy balance, the rate of energy arriving per square meter (240 W/m^2) equals the rate going out, namely $e\sigma T^4$ W/m^2. Equating the two with $e = 1$ gives 240 W/m^2 = σT^4.
  - EVALUATE: Solving gives $T = \left(\dfrac{240\ \mathrm{W/m^2}}{5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}} \right)^{1/4} = 255\ \mathrm{K}$
  - ASSESS: Make sense? This temperature seems in the right ballpark, but a bit low for a global average; it's –18˚C or 0˚F. In fact, the natural greenhouse effect keeps Earth some 33˚C warmer, at about 288 K or 15˚C.

Summary

- **Thermodynamic equilibrium** is the state reached when macroscopic properties of a system or systems don't change.
- Systems in thermodynamic equilibrium are at the same **temperature.**
  - The **kelvin** (K) is the SI unit of temperature.
- **Heat** is energy in transit because of a temperature difference alone.
  - The heat required to heat an object by an amount ΔT depends on its mass and its **specific heat**, c: $\Delta Q = mc\,\Delta T$.
  - Heat transfer mechanisms include conduction, convection, and radiation.
  - **Thermal energy balance** is a state in which the rate at which energy is delivered to a system is equal to the rate at which the system loses energy. A system in energy balance maintains a constant temperature.