Heat & Temperature

Unit: Thermal Physics (Heat)

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS3-1, HS-PS3-2, HS-PS4-3a

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 9.1.B, 9.1.B.1, , 9.1.B.1.i, 9.1.B.1.ii

Mastery Objective(s): (Students will be able to…)

- Explain heat energy in macroscopic and microscopic terms.

Success Criteria:

- Descriptions & explanations account for observed behavior.

Language Objectives:

- Explain the difference between heat and temperature.

Tier 2 Vocabulary: heat, temperature

Labs, Activities & Demonstrations:

- Heat a small weight and large weight to slightly different temperatures.
- Fire syringe.
- Steam engine.
- Incandescent light bulb in water.
- Mixing (via molecular motion/convection) of hot *vs.* cold water (with food coloring).

Vocabulary:

heat: energy that can be transferred by moving atoms or molecules via transfer of momentum.

temperature: a measure of the average kinetic energy of the particles (atoms or molecules) of a system.

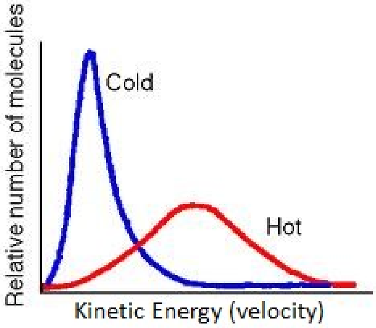
thermometer: a device that measures temperature, most often via thermal expansion and contraction of a liquid or solid.

Notes:

Heat is energy that is stored as the translational kinetic energy of the particles that make up an object or substance.

As you (should) recall from chemistry, particles (atoms or molecules) are always moving (even at absolute zero), and that energy can transfer via elastic collisions between the particles of one object or substance and the particles of another. (We will explore these concepts in more detail in the topic *Kinetic-Molecular Theory*, starting on page 92.)

Note that heat is the energy itself, whereas temperature is a measure of the quality of the heat—the average of the kinetic energies of the individual molecules:



Note that the particles of a substance have a range of kinetic energies, and the temperature is the average. Notice that when a substance is heated, the particles acquire a wider range of kinetic energies, with a higher average.

When objects are placed in contact, heat is transferred from each object to the other via the transfer of momentum that occurs when the individual molecules collide. Molecules that have more energy transfer more energy than they receive. Molecules that have less energy receive more energy than they transfer. This means three things:

1. Individual collisions transfer energy in both directions. The particles of a hot substance transfer energy to the cold substance, but the particles of the cold substance also transfer energy to the hot substance.

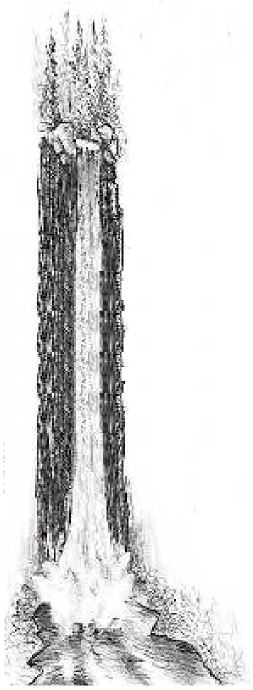
2. The net (overall) flow of energy is from objects with a higher temperature (more kinetic energy) to objects with a lower temperature (less kinetic energy). *I.e.,* more energy is transferred from the hot substance to the cold substance than *vice versa*.

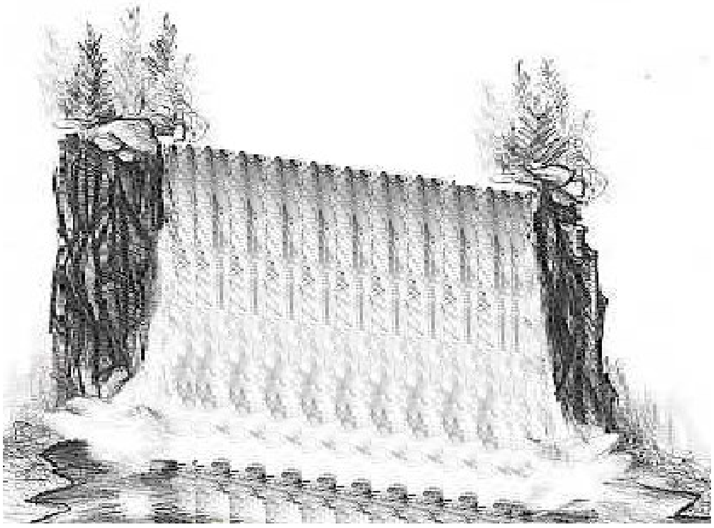
3. If you wait long enough, all of the molecules will have the same temperature (*i.e.,* the same average kinetic energy).

This means that the ***temperature*** of one object relative to another determines which direction the heat will flow, much like the way the elevation (vertical position) of one location relative to another determines which direction water will flow.

However, the total heat (energy) contained in an object depends on the mass as well as the temperature, in the same way that the total change in energy of the water going over a waterfall depends on the mass of the water as well as the height.

Consider two waterfalls, one of which is twice the height of the second, but the second of which has ten times as much water going over it as the first:





$\Delta U = mg(2h)$

$\Delta U = (10m)gh$

In the above pictures, each drop of water falling from the waterfall on the left has more gravitational potential energy, but more total energy goes over the waterfall on the right.

Similarly, each particle in an object at a higher temperature has more thermal energy than each particle in another object at a lower temperature.

If we built a waterway between the two falls, water could flow from the top of the first waterfall to the top of the second, but not *vice versa*.

Similarly, the net flow of heat is from a smaller object with higher temperature to a larger object with a lower temperature, but not *vice versa*.

Heat Flow

system: the region or collection of objects under being considered in a problem.

surroundings: everything that is outside of the system.

E.g., if a metal block is heated, we would most likely define the system to be the block, and the surroundings to be everything else.

We generally use the variable Q to represent heat in physics equations.

Heat flow is always represented in relation to the system.

Heat Flow	**Sign of *Q***	**System**	**Surroundings**
from the surroundings into the system	+ (positive)	gains heat (gets warmer)	lose heat (get colder)
from the system out to the surroundings	− (negative)	loses heat (gets colder)	gain heat (get hotter)

A positive value of Q means heat is flowing *into* the system. Because the heat is transferred from the molecules outside the system to the molecules in the system, the energy of the system increases, and the energy of the surroundings decreases.

A negative value of Q means heat is flowing *out of* the system. Because the heat is transferred from the molecules in the system to the molecules outside the system, the energy of the system decreases, and the energy of the surroundings increases.

This can be confusing. Suppose you set a glass of ice water on a table. When you pick up the glass, your hand gets colder because heat is flowing from your hand (which is part of the surroundings) into the system (the glass of ice water). This means the system (the glass of ice water) is gaining heat, and the surroundings (your hand, the table, *etc.*) are losing heat. The value of Q would be positive in this example.

In simple terms, you need to remember that your hand is part of the *surroundings*, not part of the system.

thermal equilibrium: when all of the particles in a system have the same average kinetic energy (temperature). When a system is at thermal equilibrium, no net heat is transferred. (*I.e.,* collisions between particles may still transfer energy, but the average temperature of the particles in the system—what we measure with a thermometer—is not changing.)