5.1: Temperature

Up to now the major types of change we have considered are phase changes (solid to liquid, liquid to gas, etc.) Now we will look at the elements of a phase change in greater detail starting with temperature. If you look up the definition of temperature you will probably find something like “the degree of heat of an object” and think to yourself, “Well, that’s not very illuminating, is it?” However, it is actually quite difficult to give a simple definition of temperature, (typically abbreviated as T). If you were already taught about temperature in physics courses, please bear with us (a chemist and a cell and molecular biologist) as we work our way through it, sometimes it it helpful to think about things you already know in new ways!

A useful macroscopic way of thinking about temperature is that it tells you in which direction thermal energy (often called heat) will move—energy always moves from a hotter (higher-temperature) object to a cooler (lower-temperature) one. This may seem like an obvious statement about how the physical world works but do you really know why it must be the case? Why doesn’t heat flow from cooler to warmer? Is there some principle that will allow us to to explain why? We will be coming back to these questions later on in this chapter.

Students often confuse temperature and thermal energy and before we go on we need to have a good grasp of the difference between them. The temperature of an object is independent of the size of the object, at least until we get down to the atomic/molecular level where temperature begins to lose its meaning as a concept.[1] The temperature of a drop of boiling water is the same as the temperature of a pan (or an ocean) of boiling water: $100^{\circ}\mathrm{C}$ at sea level. At the same time the total amount of thermal energy in a drop of water is much less than that in a large pot of water at the same temperature. A drop of boiling water may sting for a moment if it lands on you, but a pan of boiling water will cause serious damage if it splashes over you. Why? Even though the two are at the same temperature, one has relatively little thermal energy and the other has a lot; the amount of energy is related to the size of the system. In addition, the amount of thermal energy depends on the type, that is, the composition of the material. Different amounts of different substances can have different amounts of thermal energy, even if they are at the same temperature (weird but true).

Kinetic Energy and Temperature

Another way of thinking about temperature is that it is related to the energy of the particles in the sample: the faster the particles are moving, the higher the temperature. It may well take different amounts of energy to get particles moving at the same average kinetic energy. For a simple monoatomic gas, like helium or neon, the only motion that the atoms can do is to move from one place to another in a straight line until they bump into something else, such as another atom or molecule.[2] This kind of motion is called translational motion and is directly linked to the kinetic energy of the atom or molecule through the relationship $\mathrm{KE}=\frac{1}{2} m v(\mathrm{bar})^{2}=\frac{3}{2} k \mathrm{T}$ where $v(\mathrm{bar})$ is the average velocity of all of the molecules in the population[3], m is the mass, k is a constant, known as the Boltzmann constant, and T is the temperature. That is, the average kinetic energy of a gas is directly related to the temperature. In any given gaseous sample of moving atoms there are many collisions per unit time but these collisions do not alter the total energy of the system (it is conserved).[4] What these collision can, and often do, alter is the relative kinetic energies of the two (or more) colliding atoms: if one slows down, the other will speed up (remember, we are now talking only about monoatomic species; things get more complicated with more complex molecules).

Any single atom or molecule has kinetic energy, but not a temperature. This is an important distinction. Populations of molecules have a temperature related to their average velocity but the concept of temperature is not relevant to individual molecules, they have kinetic energy but not a temperature. This is a important idea, temperature as a characteristic of a system not its individual components. While a system has a unique temperature, the individual molecules that make up the system can have quite different kinetic energies. Because of collisions between molecules, an individual molecule’s kinetic energy can be changing rapidly, even though the temperature of the system is constant. When it comes to chemical reactions, it is individual kinetic energies that will be critical (we consider this point in greater detail in Chapter 7).