

8.6: Dissipation of Energy and Thermal Energy

Thermal Energy

From all the foregoing, it is clear that when an interaction can be completely described by a potential energy function we can define a quantity, which we have called the total mechanical energy of the system, $E_{mech} = K + U$, that is constant throughout the interaction. However, we already know from our study of collisions that this is rarely the case. Essential to the concept of potential energy is the idea of “storage and retrieval” of the kinetic energy of the system during the interaction process. When kinetic energy simply disappears from the system and does not come back, a full description of the process in terms of a potential energy is not possible.

Processes in which some amount of mechanical energy disappears (that is, it cannot be found anywhere anymore as either macroscopic kinetic or potential energy) are called *dissipative*. Mysterious as they may appear at first sight, there is actually a simple, intuitive explanation for them. All macroscopic systems consist of a great number of small parts that enjoy, at the microscopic level, some degree of independence from each other and from the body to which they belong. Macroscopic motion of an object requires all these parts to move together as a whole, at least on average; however, a collision with another object may very well “rattle” all these parts and leave them in a more or less disorganized state. If the total energy is conserved, then after the collision the object’s atoms or molecules may be, on average, vibrating faster or banging against each other more often than before, but they will do so in random directions, so this increased “agitation” will not be perceived as macroscopic motion of the object as a whole.

This kind of random agitation at the microscopic level that I have just introduced is what we know today as *thermal energy*, and it is by far the most common “sink” or reservoir where macroscopic mechanical energy is “dissipated.” In our example of an inelastic collision, the energy the objects had is not gone from the universe, in fact it is still right there inside the objects themselves; it is just in a disorganized or incoherent state from which, as you can imagine, it would be pretty much impossible to retrieve it, since we would have to somehow get all the randomly-moving parts to get back to moving in the same direction again.

We will have a lot more to say about thermal energy in a later chapter, but for the moment you may want to think of it as essentially *noise*: it is what is left (the residual motional or configurational energy, at the microscopic level) after you remove the average, macroscopically-observable kinetic or potential energy. So, for example, for a solid object moving with a velocity v_{cm} , the kinetic part of its thermal energy would be the sum of the kinetic energies of all its microscopic parts, calculated *in its center of mass* (or zero-momentum) *reference frame*; that way you remove from every molecule’s velocity the quantity v_{cm} , which they all must have in common—on average (since the body as a whole is moving with that velocity).

In order to establish conservation of energy as a fact (which was one of the greatest scientific triumphs of the 19th century) it was clearly necessary to show experimentally that a certain amount of mechanical energy lost always resulted in the same predictable increase in the system’s thermal energy. Thermal energy is largely “invisible” at the macroscopic level, but we detect it indirectly through an object’s *temperature*. The crucial experiments to establish what at the time was called the “mechanical equivalent of heat” were carried out by James Prescott Joule in the 1850’s, and required exceedingly precise measurements of temperature (in fact, getting the experiments done was only half the struggle; the other half was getting the scientific establishment to believe that he could measure changes in temperature so accurately!)

Fundamental Interactions

At the most fundamental (microscopic) level, physicists today believe that there are only four (or three, depending on your perspective) basic interactions: gravity, electromagnetism, the strong nuclear interaction (responsible for holding atomic nuclei together), and the weak nuclear interaction (responsible for certain nuclear processes, such as the transmutation of a proton into a neutron¹ and vice-versa). In a technical sense, at the quantum level, electromagnetism and the weak nuclear interactions can be regarded as separate manifestations of a single, consistent quantum field theory, so they are sometimes referred to as “the electroweak interaction.”

All of these interactions are conservative, in the sense that for all of them one can define the equivalent of a “potential energy function” (generalized, as necessary, to conform to the requirements of quantum mechanics and relativity), so that for a system of elementary particles interacting via any one of these interactions the total kinetic plus potential energy is a constant of the motion. For gravity (which we do not really know how to “quantize” anyway!), this function immediately carries over to the macroscopic domain without any changes, as we shall see in a later chapter, and the gravitational potential energy function I introduced earlier in

this chapter is an approximation to it valid near the surface of the earth (gravity is such a weak force that the gravitational interaction between any two earth-bound objects is virtually negligible, so we only have to worry about gravitational energy when one of the objects involved is the earth itself).

As for the strong and weak nuclear interactions, they are only appreciable over the scale of an atomic nucleus, so there is no question of them directly affecting any macroscopic mechanical processes. They are responsible, however, for various nuclear reactions in the course of which *nuclear energy* is, most commonly, transformed into electromagnetic energy (X- or gamma rays) and thermal energy.

All the other forms of energy one encounters at the microscopic, and even the macroscopic, level have their origin in electromagnetism. Some of them, like the electrostatic energy in a capacitor or the magnetic interaction between two permanent magnets, are straightforward enough scale-ups of their microscopic counterparts, and may allow for a potential energy description at the macroscopic level (and you will learn more about them next semester!). Many others, however, are more subtle and involve quantum mechanical effects (such as the exclusion principle) in a fundamental way.

Among the most important of these is *chemical energy*, which is an extremely important source of energy for all kinds of macroscopic processes: combustion (and explosions!), the production of electrical energy in batteries, and all the biochemical processes that power our own bodies. However, the conversion of chemical energy into macroscopic mechanical energy is almost always a dissipative process (that is, one in which some of the initial chemical energy ends up irreversibly converted into thermal energy), so it is generally impossible to describe them using a (macroscopic) potential energy function (except, possibly, for electrochemical processes, with which we will not be concerned here).

For instance, consider a chemical reaction in which some amount of chemical energy is converted into kinetic energy of the molecules forming the reaction products. Even when care is taken to “channel” the motion of the reaction products in a particular direction (for example, to push a cylinder in a combustion engine), a lot of the individual molecules will end up flying in the “wrong” direction, striking the sides of the container, etc. In other words, we end up with a lot of the chemical energy being converted into *disorganized microscopic agitation*—which is to say, *thermal energy*.

Electrostatic and quantum effects are also responsible for the elastic properties of materials, which *can* sometimes be described by macroscopic potential energy functions, at least to a first approximation. They are also responsible for the adhesive forces between surfaces that play an important role in friction, and various other kinds of what might be called “structural energies,” most of which play only a relatively small part in the energy balance where macroscopic objects are involved.

¹Plus a positron and a neutrino

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