PART ONE: ENTROPY AND ECOLOGY

CHAPTER 1

TWO LAWS OF THERMODYNAMICS

1.1 Things run down

Schoolchildren are sometimes shown movies of growing plants, speeded up to make leaves and blossoms unfold in a matter of seconds. Imagine a movie of this sort continuing forward to show the growth receding, with leaves and pedals falling quickly to the ground. Our concern in this chapter ties in with the latter part of the movie.

Consider in particular the case of a mature gingko tree whose leaves have yellowed and are about to fall. A notable thing about gingko trees is that they tend to lose most of their leaves within a few hours. Having brought a camcorder to the scene at the opportune time, we capture the motion of the leaves as they fall to the ground. By speeding up the display we can watch the tree lose its leaves in what appears to be just a few moments.

Let us consider the distribution of the leaves before and after. During the months of the preceding summer, there was an orderly array of leaves arranged along the branches of the tree. After their fall the leaves were spread randomly around its base. In filming their transit from the branches to the ground, we have recoded a progression from order to disorder.

Imagine next that we take a movie of an erupting volcano. First we see rock from the mountain top blasted high in the air and lava beginning to surge over the lip of the crater. Then we watch falling rocks destroying acres of forest and flowing lava igniting everything that stands in its path. Steam appears when the lava encounters water, and smoke fills the air above the shattered peak.

On this occasion we have recorded a series of transformation brought about by a massive discharge of energy. The pressure introduced by the eruption of magma is converted into the kinetic energy of the rocks being lofted above the peak. At the height of their trajectory this energy receives a gravitational boost before being dissipated with the felling of the trees. Similarly, the high-grade thermal energy of the lava sends up columns of glowing particles until finally giving way to low-grade heat. What we see, from the perspective of energy transformation, is a process of energy being expended as these effects are accomplished.

Our display of these events likewise could be reversed in the manner of the movie of the falling leaves. The point would be to dramatize the temporal sequence of the events involved. Consider the contrast between the sequence initially recorded and that presented when the display is reversed. Among other things, the reverse display would show lava flowing up the face of the mountain and rocks springing upward to form a new peak. When the sequences forward and backward are viewed in rapid progression, we have no trouble telling which corresponds to the ways of nature. Energy is expended as time advances; any reversal of this process appears unnatural.

In similar fashion, a backward viewing of the falling leaves would show them streaming upwards to rejoin their branches. Seen in rapid sequence, this backward flow of leaves would be distinctly opposed to the way the world ordinarily works. Order normally gives way to disorder. Change in the other direction runs contrary to the normal course of nature.

In our ordinary experience of the natural world, the forward progression of time (past to future) is marked both by a progressive depletion of energy and by a progressive slide from order to disorder. Other familiar examples of energy depletion include flashlight batteries running down, heated rooms becoming cold, and people becoming fatigued at the end of the day. Further examples of progressive disorder are weeds taking over gardens, machines breaking down, and dust accumulating on bedroom floors.

As we shall see in Chapter 2, to be sure, the degradation of energy and the degradation of order are equivalent processes. This is because high-grade energy and high-grade order are mutually convertible. To prepare ourselves for understanding why, our primary concern in the present chapter is with the degradation of energy. In the next section we begin to look at the scientific basis for our common experience of energy becoming degraded with the passage of time.

1.2 The First and Second Laws of Thermodynamics

Illustrations of progressive energy degradation like those above are largely anecdotal. As such, they have little scientific value. Scientific investigation of such commonplace phenomena began approximately 150 years ago with the articulation of two fundamental laws of thermodynamics.

The First Law of Thermodynamics states that the amount of energy in a closed system[1] remains constant through time. Since the universe by definition is a closed system, a consequence is that the universe contains a fixed amount of energy. While energy within a specific locale (e.g., on earth) might change both in quantity and quality, the total amount of energy remains the same overall.

The Second Law of Thermodynamics deals with changes in quality. The most important distinction to be made regarding quality is between energy capable of doing work and energy lacking this capacity. What work amounts to here, in its most general sense, is physical alteration that occurs on other than a random basis. Illustrations include lifting weights (by an athlete), synthesizing molecules (by an organism's metabolism), and increasing a body's heat content (by solar radiation). According to the Second Law, the amount of energy in a close system capable of doing work tends always to decrease with time.

An alternative formulation of the Second Law is in terms of degraded energy. Energy becomes degraded as its capacity for doing work is lost. A given quantity of energy might lose this capacity either by being wasted or by being expended in actual work. This loss typically occurs through a series of states, during which the energy becomes increasingly degraded (recalls the example of a flashlight battery gradually losing its charge).

Another way of putting the Second Law, accordingly, is that the energy in a closed system, while remaining constant in quantity (the First Law), tends to become increasingly degraded with the passage of time. An equivalent statement is that the amount of degraded energy in a closed system tends to increase with time.

Apart from carefully engineered approximations in the laboratory, the universe at large may be the only closed system in actual existence. The fact that the First and Second Laws are formulated in terms of closed systems, however, does not preclude their application to systems that are to some extent open. Otherwise thermodynamics would have no practical applications.

Application to open systems is assured by an important consequence of the two laws taken together. The Second Law says that energy in the universe tends to be degraded in use. The First Law says that the total amount of energy in the universe remains constant. The consequence is that degraded energy remains part of the universe. Energy, once used, does not just “go away,” but remains present in degraded form.

This consequence holds for energy expenditures generally, obviously including those occurring in open systems. There is no thermodynamic requirement that energy degraded by use in an open system remain within the system where it was used. The requirement is that energy degraded by use in an open system remains somewhere in existence, whether or not in the system where the degradation occurred.

This consequence plays a crucial role in the discussion that follows. At various points in discussing the ecosystem, for example, we will be concerned with the effects of degraded energy that remains within the system. And in discussing problems arising from excessive use of energy by industrial technology, we shall see why these problems hinge upon the inability of the biosphere to ride itself of all the energy degraded within it.

1.3 Entropy

The term 'entropy' (from the Greek ἐντρέπω, meaning "to alter") was coined (c. 1865) by Rudolf Clausius, the originator of thermodynamics, in connection with his work on problems of heat exchange. In line with the general principle that heat passes spontaneously only from hotter to colder bodies, Clausius conjectured that the transmission of heat in the opposite direction (e.g., when bodies are heated by friction) requires work of some sort. The Second Law emerged with his observation that this work can be accomplished only at the expense of some irreversible alteration in the surrounding environment. The alteration produced by work is an increase in what he called entropy. Clausius's expression of the Second Law was the simple statement that the entropy of the universe tends always to increase.

What Clausius observed, in effect, is that the natural flow of heat from hotter to colder bodies can be reversed only by the expenditure of energy (e.g., rubbing cold metals together to make them warm). The term 'entropy' designated the change undergone by the source of this energy. Put in terms introduced above, this change amounts to a degradation of the energy involved. Claudius's statement that entropy in the universe tends always to increase thus converges with our expression of the Second Law in the previous section, to the effect that the amount of degraded energy tends to increase with time.

Whereas Clausius's original use of the term 'entropy' applied specifically to contexts involving the exchange of thermal heat,[2] its use soon became standard in other contexts as well. It was not long before it had become an important part of the conceptual apparatus of both physical and chemistry. By the mid-20th Century, various biological and social sciences had also adopted the term, as had the burgeoning discipline of communication theory.

As a result of this considerable diversity in use, there are several different ways in which the term 'entropy' has been defined.[3] It is safe to assume that for the most part these definitions are mutually compatible. For present purposes, the term will be used only in ways that have been explicitly introduced as the discussion progresses. In the present section, the term has been introduced as a designation for degraded energy. Its use as a designation for degrade structure (disorder) will be explained in the following chapter.

1.4 How energy degrades

Energy is analogous in some ways to monetary value. The value of an ounce of gold can be converted into currency, which then can be used to purchase a valuable commodity. But there is an important disanalogy as well. Whereas under favorable circumstances the commodity (say a blue-chip stock) can be exchanged back for currency, which can be used to buy gold in turn, not all forms of energy are mutually interchangeable. Solar energy, for example, can produce electricity; but electricity, regardless of the amounts involved, cannot be reconverted into solar energy.

Other example should help make this point clear. Electricity can be used to pump water uphill, and water running downhill through generators can produce electricity. Thus electrical and mechanical energy are mutually convertible. Electrical and kinetic energy likewise are mutually convertible, as shown by electric fans and wind-drive turbines.

But most processes of energy transformation in our everyday experience involve forms of energy that are convertible in one direction only. The chemical energy produced in plants by photosynthesis cannot be transformed back into solar energy. The rotational and gravitational energies (on the part of the earth and the moon, respectively) involved in the production of tidal energy cannot be generated out of tidal energy in turn. And the thermal energy put out by a common space heater cannot be recovered to energize further cycles of space heating.

Energy for the most part is degraded in use, which means that it cannot be reconverted to its previous form. This is the manner of energy degradation featured in the Second Law.

Even in transformations between mutually convertible forms of energy, some energy is always degraded to forms not reconvertible to the original. In conversions between electrical and mechanical, for instance, some energy is always degraded to the form of low-grade heat. Thus all transformations producing work involve some manner of energy degradation, which is to say that energy expenditures producing work are never 100 percent efficient. Processes that are reversible without loss of usable energy (if in fact there are any) by definition are not productive of work.

1.5 Degrees of degradation

Forms of energy can be ranked with respect to convertibility. At the top will be forms convertible into every other form. If there is only one such (perhaps the energy of the “Big Bang” thought to have originated the universe), it alone will have top ranking. If more than one at the top, each will be convertible into the others as well. Candidates include gravitational, rotational, and orbital energy, which do not invariably degrade with time.[4]

At the very bottom of the ranking fall forms of energy incapable of being converted into any other form at all. In current thinking, one such form is the cosmic background radiation into which (according to the Second Law) all energy ultimately will be converted. Inasmuch as work typically involves conversion to different forms of energy, this lowest form is incapable of doing work.

In between are forms of energy that can be converted into forms with lower (or equal) rankings, but not into forms above them on the scale. Fairly high within this mediate range will appear the internal heat of stars, which (in the case of the sun) is convertible into solar radiation but not vice versa. Lower will be forms of energy into which solar radiation is convertible, such as electrical, mechanical, and kinetic, but which are not convertible to solar radiation in turn. Lower yet will be waste heat of terrestrial origin, which is emitted from the earth in the form of black-body radiation.[5]

Abstract as it may seem in general outline, this ranking establishes a complex network of paths along which energy can be expended in doing the world's work. Apart from a few that can be traveled in either direction (e.g., that between electrical and kinetic energy), these paths are mostly unidirectional.

One might think of it this way. The lines of energy-flow by which the world's work is accomplished lead inexorably "downward," with an excursion now and then in a "horizontal" direction. This downward trend is a consequence of the Second Law of Thermodynamics: the amount of energy available for work inevitably diminishes with time.

1.6 A graphic model

A simple model might help pull these concepts together. The model is based on a series of bar graphs ordered along a horizontal baseline, as follows.

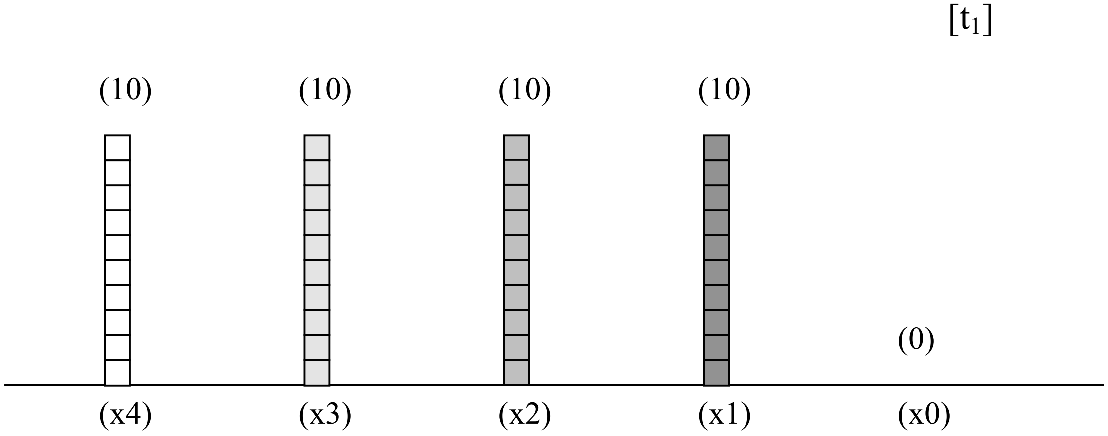

Figure 1.1

Each bar graph represents a particular (here unspecified) form of energy (solar, electrical, mechanical, etc.), and the bar graphs are ordered left to right according to the convertibility ranking discussed above. For example, inasmuch as solar energy is convertible into electrical energy but not vice versa, a bar graph representing the former would appear to the left of one representing the latter.

In keeping with the requirement that work-capacity is always lost in transformations among energy forms, the bar graphs are broken down into segments so conceived that more usable energy is contained in segments of bar graphs to the left than in comparable segments to the right. These segments will be called "usable-energy packets." Due to the general character of the model, no empirically significant values are assigned to comparable segments. Difference in usable-energy content is represented instead by "multipliers" ((x4), (x3), etc.) specified below the bar graphs. The sense of the (x4) multiplier, for instance, is that each segment (packet) in its column contains four units of usable energy. These units are for comparison only, and have no specific value in terms of standard measures like watts and joules.

Each bar graph in this figure is divided into ten packets, as indicated by the number at its side. The leftmost column thus contains (10 x 4 =) 40 units of usable energy. Taking all four columns into account, we see that a system represented by the model as it stands has (40 + 30 + 20 + 10 =) 100 units of work-capacity overall. The place marked '(x0)' is reserved for a bar graph representing unusable energy to be added in the following figures.

As it stands, Figure 1.1 is static, showing that state of the system at its initial moment only (time t_1 at the upper right). Progression in time is represented by a series of ordered bar graphs, each step in the series showing a change in at least one column involved. Figure 1.2 represents a possible second stage (t_2) in a series beginning with Figure 1.1.

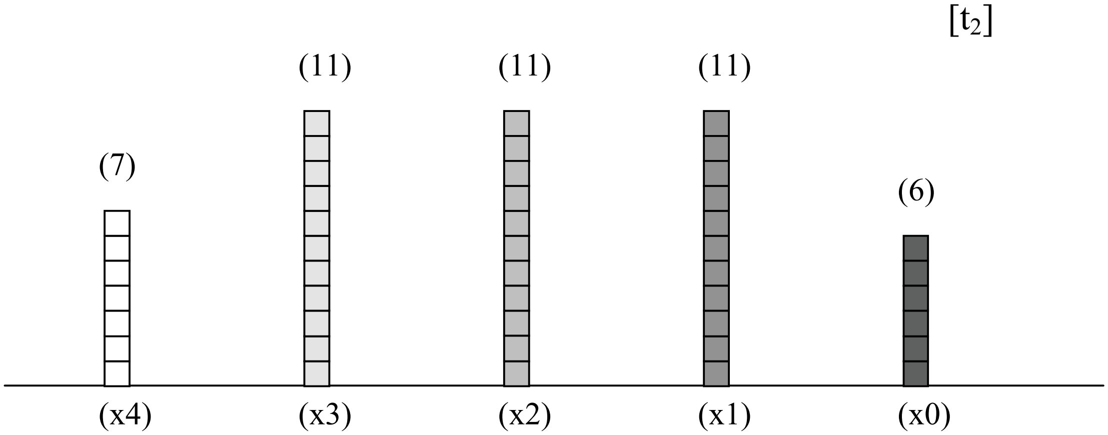

Figure 1.2

In comparison with Figure 1.1, this figure shows a decrease of three packets in the (x4) column (12 units of usable energy), an increase of one packet in each of the (x3), (x2), and (x1) columns, and a new column in the (x0) position measuring 6 increments high. This latter column is heavily shaded to indicate that it contains no usable energy, in accord with the significance of the (x0) multiplier explained previously.

These changes are to be interpreted as follows. Twelve (3 x 4) units of usable energy have been expended from the supply of the (x4) column. Of these, 3 units (one (x3) packet) have been converted to the (x3) column, 2 units to the (x2) column, and one unit to the (x1) column. Each of these three columns, accordingly, is one packet higher. This accounts for 6 of the 12 units removed from the (x4) column. The remaining 6 have lost all potential for useful work, and hence show up in the (x0) column. All of the 12 units removed from the leftmost column have been degraded; but while 6 still retain work capacity, the remaining six are incapable of further work. At the stage represented by Figure 1.2, the system in question still has 100 units of energy overall, of which (7x4 + 11x3 + 11x2 + 11x1 =) 94 remain available for work.

To continue the demonstration, consider that during the next stage of operation (t_3) additional work is done involving the conversion of one packet of (x3) energy into a single packet of (x1) energy and 2 units of (x0) energy, while one packet of (x2) energy is "wasted" (no work accomplished) by conversion into (x0) energy directly.

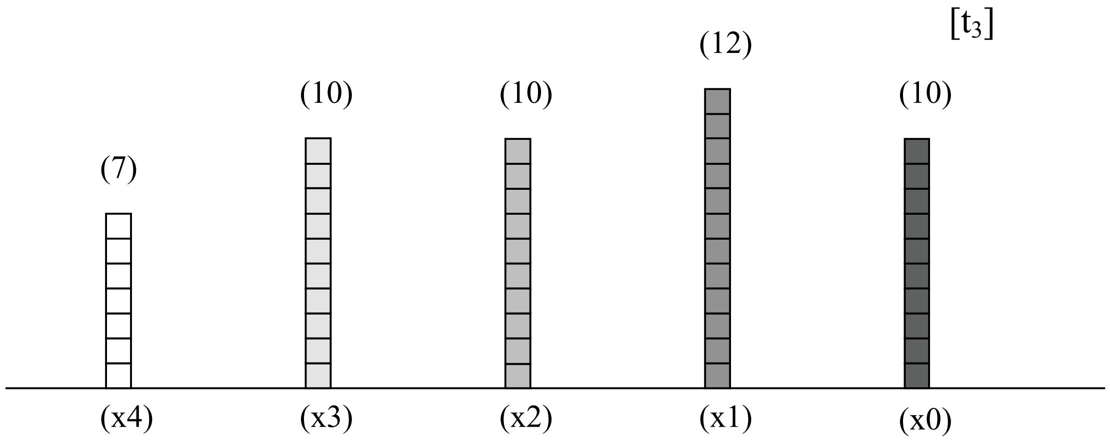

Figure 1.3

As a result of these latest transactions, both the (x3) and the (x2) columns have been diminished one packet, the (x1) column has gained another packet, and the (x0) column has been increased an additional four increments. At this stage, the model represents a system with 90 units of usable energy (7x4 + 10x3 + 10x2 + 12x1) and 10 units of energy without work capacity. As with stages t_1 and t_2, however, 100 units of energy remain within the system overall.

Insofar as the total amount of energy remains constant, the model thus far corresponds to a thermodynamically closed system. As system operation progresses, more and more energy will end up in the (x0) column. Its final stage of operation would be reached when all 100 units of energy initially within the system have reached this final column, indicating that it is capable of no further work.

The model can be made to represent an open system with two additional provisions. First, any given column can increase without a corresponding decrease in any column to its left. Such increases would represent energy being brought into the system. When the increase is in one of the columns with positive multipliers, the imported energy contains capacity for work. When an increase is in the (x0) column, however, it represents energy whose work capacity has previously been exhausted. The significance of this latter case is that useless energy has been "dumped" into the system from some source outside.

The second provision is that any column can decrease without a corresponding increase in any column to its right. When the decrease occurs in one of the columns with a positive multiplier, this means that usable energy is being exported to another system. When the decrease occurs in the (x0) column, this means that the present system is getting rid of its useless energy.

Addition of these provisions does not change the basic requirement of the model that energy conversions occur exclusively in the rightward direction. This requirement signifies the fact that energy conversions always involve some degree of degradation, regardless of whether the system in which they occur is open or closed. Nor do these provisions affect the basic physical fact that used-up energy does not simply go away.

While (x0) units may disappear from the model, the depleted energy they represent is still present elsewhere in the physical system’s environment.

1.7 The “heat-death” of the universe

Energy from which all work potential has been exhausted constitutes low-grade heat. In its terrestrial form, low-grade heat is exemplified by the body temperature of a living animal or the warmth of an operating engine. In its cosmic form, it is exemplified by the black-body radiation by which terrestrial heat leaves the surface of the earth.

High-grade thermal energy, on the other hand, is capable of doing work. Energy present in boiling water, for example, is capable of driving steam engines, and intense heat generated by electricity can be used to melt metals. But heat emitted from the earth by black-body radiation is too far degraded to retain capacity for further work.

The so-called “heat death” of the universe is the state at which all energy in the universe has been degraded to a form no longer capable of doing work. One way of conceptualizing this state is to think of it as a condition in which all energy in the universe has been reduced to a form thermodynamically equivalent to the energy emitted from the earth’s surface into space.[6] In this state, all temperature differences capable of work have been exhausted and the universe at large has become thermally inert.

So the “heat death” of the universe is not a state at which the universe has become “too hot” to survive. It is a state at which the universe has become “dead” in the sense of containing no heat capable of doing work. At this state all energy has been degraded to useless entropy, and the universe has reached the end intimated by the Second Law.

Notes

1. The following characterization of a closed system will suffice for our purposes. Broadly conceived, a system is an assemblage of variables (physical or otherwise) that interact in a nonrandom fashion. Euclidean geometry is an example of a nonphysical

system. A physical system is one with physical variables that undergo change with time. Physical systems are either open or closed. An open system is one that can influence or be influenced by factors outside itself. The defining feature of open systems thermodynamically is that they can import energy to accomplish work and can export the resulting residues. Living organisms are examples of open systems; as elaborated in Chapter 3, they must draw in energy to remain alive and must rid themselves of wastes produced by their metabolic activity. A closed system, by contrast, is one that cannot interact with anything outside itself. A thermodynamic consequence is that a closed system can neither import energy for work nor rid itself of the resulting by-products. All residues of work accomplished by a thermodynamically closed must remain within the system.

2. In Clausius's original sense pertaining to heat exchange specifically, increase in entropy equals the amount of thermal energy exchanged divided by the absolute temperature (Kelvin) at which the exchange takes place.

3. An often-cited comment by John von Neumann (a pioneer in computing theory and the theory of games) to Claude Shannon (the founded of communication theory) is that Shannon ought to call his newly formulated measure of information 'entropy', for the reasons (1) that the term was already used for a similar function in thermodynamics, and (2) that "most people don't know what entropy really is, and if you use the term 'entropy' in an argument you will win every time." The quotation is from Myron Tribus, who heard it from Shannon directly. See R.D. Levins and M. Tribus (eds.), *The Maximum Entropy Formalism* (The M.I.T. Press, Cambridge, 1979), p. 3.

4. See Freeman Dyson, "Energy in the Universe," *Scientific American*, September 1971.

5. This is radiation characteristic of a body that absorbs all energy it receives, heats up to a certain temperature, and then reradiates its energy with an energy/wavelength

correlation defined by that temperature. This definition is elaborated in the notes of Chapter 5.

6. As noted previously, energy leaves the earth's surface by black-body radiation. By current scientific consensus, this black-body radiation shares characteristic features with the non-directional cosmic background radiation predicted in "big-bang" theory and empirically discovered in the 1960s. This background radiation has a temperature of about 3° Kelvin (which actually is quite chilly). See Steven Weinberg, *The First Three Minutes* (Basic Books, New York, 1988), esp. p. 70.