

# 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 few brief moments. Imagine such a movie skipping forward past the growing period to the point where leaves and pedals begin their quick descent to the ground. Our present concern is illustrated by this latter part of the movie.

Take the case in particular 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 the bulk of their leaves in a brief golden shower. Having brought a camcorder to the scene at the opportune moment, we capture the motion of the leaves as they fall to the ground. By speeding up the display we can watch the tree shed its leaves in what appears to be just a matter of seconds.

Let us consider the distribution of leaves before and after their fall. During the summer months the leaves were distributed in an orderly manner along the tree's branches. After their fall they are spread randomly around the base of its trunk. In filming their transit from the branches to the ground, we have recoded a progression from order to relative disorder.

Once this progression has been recorded, of course, we can view it in reverse by running the display backwards. A backward viewing of the falling leaves would show them streaming upward to rejoin their branches. Seen in rapid sequence, this backward flow of leaves would be dramatically opposed to the way things work in the ordinary world. In the ordinary world, order generally gives way to disorder. Change in the other direction runs distinctly contrary to the observable course of nature.

Next imagine that we are viewing 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 observed a series of transformations brought about by a massive discharge of energy. The force of the erupting magma imparts kinetic energy to the rocks being lofted outward from the peak. At the height of their trajectory this energy receives a gravitational boost before their energy is dissipated in the destruction of the trees. Similarly, the high-grade thermal energy of the lava sends up columns of glowing particles and smoke until finally giving way to low-grade heat. What we see, from the perspective of energy transformation, is a process of energy being dissipated as these effects are accomplished.

Our display of these events could also be reversed in the manner of the movie of the falling leaves. One point of doing this 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 moving energetically up the face of the mountain and rocks springing upward to form a new peak. When the sequences forward and backward are compared, we have no trouble telling which corresponds to the ways of nature. Energy normally is expended as time advances; any reversal of this process appears unnatural.

The transformations we have been talking about thus far are correlated with the progression of time from past to future. On one hand, the forward progression of time is marked by a progressive slide from order to disorder. Other examples of order degrading into disorder are weeds taking over gardens, machines breaking down, and dust accumulating on bedroom floors. On the other hand, temporal progression is marked as

well by a progressive expenditure of energy. Other examples of energy depletion, albeit less dramatic than an exploding volcano, are flashlight batteries running down, heated rooms becoming cold, and runners becoming fatigued in the course of a race.

As we shall see presently, indeed, the degradation of order and the degradation of energy are equivalent processes.<sup>1</sup> In this study, degraded energy is energy that has undergone a diminution in its ability to produce work. As further elaborated in section 1.3, entropy is the work capacity expended in the process. With these provisions in mind, we can think of entropy as a measure of energy degradation – or as degraded energy for short. The concept of degraded order will be clarified in Chapter 2. This equivalence follows from the fact that high-grade order and high-grade energy are mutually convertible. To prepare ourselves for understanding why this is so, we must first become familiar in general terms with what happens when energy becomes degraded. Let us begin with a brief look at the scientific underpinnings of such commonplace events as batteries running down and rooms in winter losing heat.

## **1.2 The First and Second Laws of Thermodynamics**

Illustrations of progressive energy degradation like these 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<sup>2</sup> 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

producing work<sup>3</sup> 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 capable of producing work (free energy) in a closed system 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 producing work is lost. A quantity of energy within a given system might lose this capacity either by being wasted or by being expended as the system actually accomplishes work. This loss typically occurs through a series of changing system states during which the work potential of the system becomes increasingly degraded (recall 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 lose its ability to produce work with the passage of time. An equivalent statement is that the amount of degraded energy (i.e. lost work potential) 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 few practical applications.

Application to open systems is assured by an important consequence of the two laws taken together. The First Law says that the total amount of energy in the universe remains constant. The Second Law says that energy in the universe tends to be degraded

in use. The consequence is that degraded energy remains part of the universe. Energy once used does not just “go away,” but continues to exist 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 stem from 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 some sort of work. 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. Clausius'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 heat,<sup>4</sup> 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 physics and chemistry. By the mid-20<sup>th</sup> Century, various biological and social sciences had also adopted the term, as had the burgeoning discipline of information theory.

As a result of this considerable diversity in use, the term 'entropy' has been defined in several different ways.<sup>5</sup> It may be assumed 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 lost work potential, or (in the sense previously specified) for degraded energy. Its use as a designation for degraded structure (disorder) is 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 examples should help make this point clear. Electricity can be used to pump water uphill, and water running downhill through turbines 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-driven generators.

But most processes of energy transformation in 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 there are more than one at the top, each will be convertible into the others as well.

Candidates for top ranking include gravitational and orbital energy, which (when not producing work) do not invariably degrade with time.<sup>6</sup>

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 (following 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 intermediate 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.<sup>7</sup>

Abstract as it may be 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 us pull these concepts together. The model is based on a series of bar graphs ordered along a horizontal baseline, as follows.

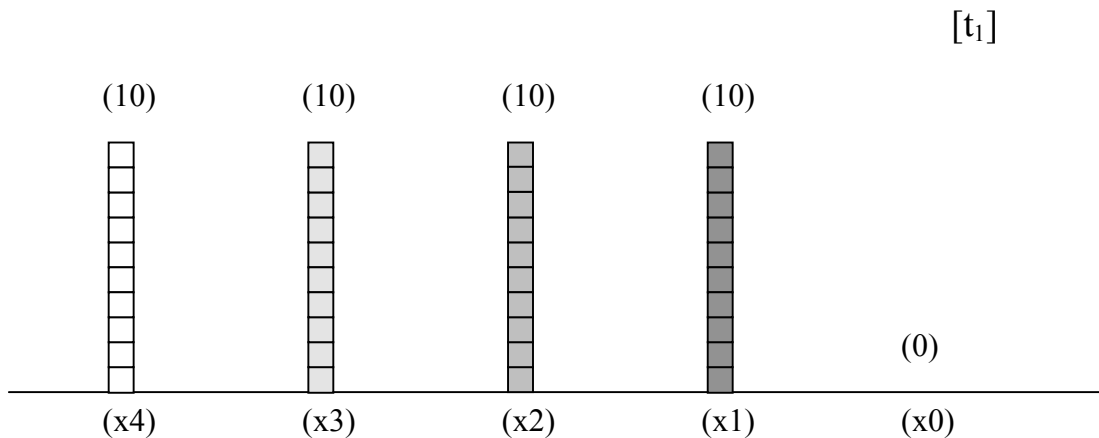


Figure 1.1: Energy rankings (1)

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 rankings 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 abstract 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.<sup>8</sup>

Each bar graph in this figure is divided into ten packets, as indicated by the number above it. The leftmost column thus contains (10 x 4 =) 40 units of usable energy.

Taking all four columns into account, we see that the bar graph as it stands has  $(40 + 30 + 20 + 10 =) 100$  units of work-capacity overall. The place to the right marked '(x0)' is reserved for a bar representing energy with no work potential to be added in the following figures.

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

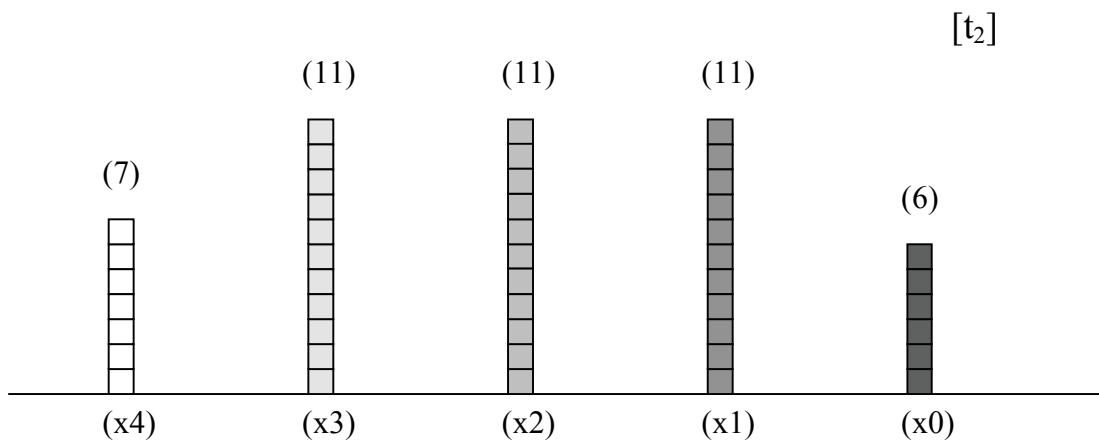


Figure 1.2: Energy rankings (2)

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  $(3 \times 4)$  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 of graphs in question still has 100 units of energy overall, of which  $(7 \times 4 + 11 \times 3 + 11 \times 2 + 11 \times 1 =)$  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.

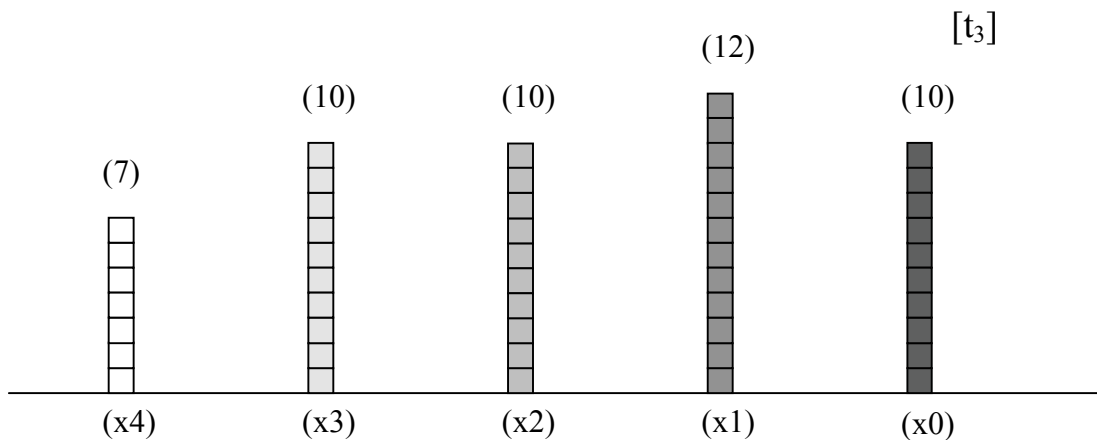


Figure 1.3: Energy rankings (3)

As a result of these latest transactions, both the (x3) and the (x2) columns have been diminished one packet from Figure 1.2, the (x1) column has gained another packet, and the (x0) column has been increased an additional four increments. At this stage, the system represents 90 units of usable energy  $(7 \times 4 + 10 \times 3 + 10 \times 2 + 12 \times 1)$  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.

### 1.7 The model applied to open systems

Given that its total amount of energy remains constant, the model thus far corresponds to a thermodynamically closed physical system. As operation of a corresponding physical system progresses, more and more energy will end up in the state represented by the (x0) column. Its final stage of operation would be reached when all energy initially within the system has reached this final state, indicating that the system is incapable of further work.

The model can be altered to illustrate 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 additional energy being brought into the corresponding physical 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 outside source.

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 indicates that usable energy is being exported to another system. When the decrease occurs in the (x0) column, this indicates that the corresponding physical system is getting rid of 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 in physical systems 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 corresponding depleted energy is still present elsewhere in the physical system's environment.

### **1.8 The “heat-death” of the universe**

Energy which has lost all its work potential 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 still 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.<sup>9</sup> 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.

### **1.9 Entropy confined to earth**

The earth itself, of course, is an open system. It receives a constant stream of high-grade energy from the sun, and emits a corresponding stream of low-grade energy back into space by black-body radiation. Since the first appearance of life on earth

(roughly three and one-half billion years ago) up to the present era, the amount of depleted energy leaving the earth has roughly matched that of the high-grade energy entering from the sun. During the past two or three centuries, however, changes in the earth's atmosphere have impeded the normal flow of low-grade energy back into space. This has led to substantial amounts of depleted energy being retained within the atmosphere, a phenomenon currently known as global warming.

Global warming is the result of entropy being prevented from leaving the earth's surface via its normal channels of black-body radiation. For reasons soon to be examined in detail, abnormal amounts of entropy are accumulating on and about the earth's surface in the form of degraded structure as well. To understand how degraded structure (disorder) ties in with degraded energy, we need to take a careful look at the relation between order and energy in their undegraded forms. This sets the task for the following chapter.

#### Notes

1. In this study, degraded energy is energy that has undergone a diminution in its ability to produce work. As further elaborated in section 1.3, entropy is the work capacity expended in the process. With these provisions in mind, we can think of entropy as a measure of energy degradation – or as degraded energy for short. The concept of degraded order will be clarified in Chapter 2.
2. 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. Such systems will also be referred to as operating systems. Living organisms are examples of operating 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 (or fully isolated) 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 system are retained within the system.

3. In thermodynamics, energy capable of producing work is commonly referred to as “free energy.”

4. 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.

5. An often-cited comment by John von Neumann (a pioneer in computing theory and the theory of games) to Claude Shannon (the founder 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.

6. See Freeman Dyson, “Energy in the Universe,” *Scientific American*, September 1971.

7. 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 determined by that temperature. This definition is elaborated in the notes of Chapter 5.

8. It must be emphasized that this model is not a depiction of actual energy transformations. Nor is it a model of actual systems in which energy is used to produce work. A consequence is that it has no significance in terms of actual physical processes studied in thermodynamics. Its purpose is merely to help the non-technical reader to conceptualize the transformation of energy from one form to another and to understand in a general manner how work involves the production of entropy (i.e. expanded work capacity).

9. 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. The cosmic space occupied by this background radiation has a temperature of about 3° Kelvin (which is actually quite chilly). See Steven Weinberg, *The First Three Minutes* (Basic Books, New York, 1988), esp. p. 70.