CHAPTER 2

ENTROPY AND DISORDER

2.1 The relation between energy and order: a classic example

The concept of entropy was introduced by Clausius in connection with his formulation of the Second Law of Thermodynamics, as previously noted. In its original use it referred to used-up energy, and this use remains current in various sciences. By the middle of the 20th century, a broader understanding had developed associating entropy with randomness and disorder.[1] Although seemingly disparate upon first consideration, these two ways of conceiving entropy are basically equivalent. To see why, we need to consider the relation between order and usable energy.

A standard illustration of this relation is that of a container of gas divided into two compartments. As long as gas molecules pass freely between compartments, their average speed will be the same in both. Since heat is directly proportional to average molecular speed, the two compartments will also be at the same heat level.

If the molecules were distributed so that one compartment contains a significantly larger proportion of fast-moving molecules than the other, however, there would be an appreciable difference in heat level between the two compartments. If this difference is sufficiently great (say, enough to boil water), the chamber will contain heat energy capable of doing work. Energy in this form could be used to produce electricity (steam turbines), for example, or to power machinery (steam locomotives) for transporting goods.

The work potential of the gas chamber in this illustration can be described in two equivalent fashions. On one hand, the temperature difference between the two compartments constitutes such-and-such an amount of usable thermal energy. On the other, the degree of order in the arrangement of molecules in the two compartments is sufficiently great to produce such and such an amount of work as the order is dissipated (i.e., as the average speeds of the molecules in the two compartments return to parity). For the molecules to be distributed with a certain degree of order is tantamount to the chamber's containing a certain amount of thermal energy.

2.2 Order and energy: other common examples

Similar illustrations are provided by other energy sources. Electrical energy is available from a socket only as long as a difference in charge is maintained between opposing terminals. In the standard way of thinking about electrical current, a terminal is negatively charged when its individual ions are aligned to induce a flow of electrons toward a positive terminal (in a closed circuit), and a terminal is positively charged when its ions are ordered to attract that flow.

Alignment of this sort among ions in a conductor is highly unlikely to occur on a random basis. In a random state, the particles are orientated without regard to polarity, which means that they are disordered in that respect. It is only when connected with an electrical generator of some sort that conductors become ordered on the molecular level in a manner making energy available at an electrical outlet. Energy again makes an appearance as a correlate of order, and disorder as an absence of usable energy.

Another illustrative example comes with the fuel cells currently being developed as a replacement for fossil fuels. In a typical fuel cell arrangement, hydrogen entering the cell is broken down into electrons and protons on the atomic level. The electrons then are diverted into an external circuit as a flow of electricity, while the protons remain within the cell to be recombined with returning electrons in the presence of oxygen. The main outputs of the process are usable electricity (from the flow of electrons), water (from the combination of hydrogen and oxygen), and low-grade heat (which escapes into the atmosphere).

In this process, the atomic structure of the two elements is manipulated to produce usable energy in the form of electricity. The order present at the atomic level is the source of energy made available for everyday use.

Radiational energy also fits into this picture. Because of its highly ordered wave-structure, solar radiation in the mid-frequency-range serves as a medium conveying solar energy directly to chlorophyll-bearing plants, where it is converted into biomass providing food for other organisms. The structure of the highly-directional incoming radiation, as it were, is transformed into energy for use by the rest of the biosphere. The low-grade heat energy that results, on the other hand, exists at wave-lengths lacking structure for further work. When this useless energy is emitted from the surface of the earth, it spreads randomly (non-directionally) through surrounding space.

Examples like this show that usable energy and order go hand-in-hand. The flip side of this relation is that degradation of energy is tantamount to degradation of order. Expended energy and disorder are equivalent forms of entropy.

2.3 Gradations of structure correlated with gradations of energy

As might be gathered from observations like these, change in structure is directly involved in transformations among forms of energy. Insofar as structure is an orderly arrangement among parts of a system, changes in order are involved in such transformations.

By way of illustration, consider the conversion of (1) solar energy to (2) electricity (by photovoltaic receptors), and then to (3) high-grade heat (in a stove burner), which in turn produces (4) kinetic energy (in boiling water) and (5) low-grade heat (in the surrounding air). Correlated with each energy source ((1) – (4)) in this series, there is a characteristic structure that accounts for its capacity for doing useful work. Usable energy in case (1) is conveyed by a highly ordered configuration of wave oscillations, in case (2) by an orderly arrangement of charged particles within the conductor, and in case (3) by a nonrandom pattern of molecular activity within the stove burner. Usable energy is still available with the water-turbulence of (4), although this does not figure in the illustration. When the low-grade thermal energy of (5) has been dissipated in the air, however, it no longer contains potential for useful work.

At each stage of this process, structure is expended in making energy available for work. The wave structure of the solar radiation, for instance, is spent producing electrical energy, and the orderly arrangement of the conductor's ions is spent in producing high-grade heat energy.

At each stage, moreover, energy made available by the expenditure of structure is used in establishing additional structure at a following stage. Solar energy is used to increase the orderly arrangement of ions in the conductor, electrical energy is used to induce nonrandom agitation of molecules in the burner, and so forth. The net effect is that, at each stage of the series, structure is expended in making energy available for work, which then is used to augment structure at a subsequent stage.

What happens in the conversion from (1) solar to (2) electrical to (3) thermal to (4) kinetic energy, accordingly, is a series of transactions in which one kind of structure is exchanged for another. The stage-wise progression of energy-forms can also be viewed at a stage-wise progression involving different kinds of structure—the wave-structure of the solar radiation, the arrangement of changed particles in the conductor, and so on.

Furthermore, just as there is a rank-ordering of progressive degradation in the series of energy-forms (1) through (5), there is a sense as well in which the associated structures exhibit decreasing gradations of order. Intuitively, the wave-structure of solar radiation represents a greater departure from randomness than the molecular activity of the stove burner, and that in turn a greater degree of nonranndomness than the heated molecules of the air above the stove.

Intuitions aside, we need a characterization of order—that is, of departure from randomness—that make comparisons like this possible on an objective basis. The groundwork for such a characterization is laid out in the following two sections.

2.4 Randomness and order

Order and disorder are comparative states, which means that both can be present in varying degrees. Things may be well ordered in one comparison and disordered in another. A deck of cards segregated by color only (say, spades and clubs coming first, with hearts and diamonds following), for example, exhibits more order than a deck that has been thoroughly shuffled, but is relatively disordered in comparison with a brand-new deck (where each suit is arranged internally by rank).

In most contexts, nonetheless, there will be arrangements in which disorder is maximal, and others in which order reaches a peak. Maximum disorder occurs in a deck of cards when the sequence within the deck is entirely random (a state approximated by repeated shuffling), whereas maximum order is present when each card is located both by rank (i.e., "taking order," 10 over 9, Jack over 10, etc.) and by strength of suit (spades over hearts, etc.).

Other commonplace examples are easy to find. A row of spice containers in a kitchen cabinet is maximally ordered when arranged alphabetically by names of contents (e.g., anise, basil, coriander, dill), and maximally disordered when their arrangement is random. A set of socket-wrench heads is completely ordered when each is placed in its container according to size, and completely disordered when scattered haphazardly across the garage floor. A set of professional journals is shelved in perfect order when arranged uniformly in sequence of publication dates, and so forth.

Speaking generally, we may say that maximum disorder is a state of completely random distribution, and that maximum order is a maximal departure from an entirely random state. What we need next is a working grasp of comparative degrees of order that fall between these two extremes.

2.5 Factors determining degrees of order

Given this understanding of maximal disorder as a state of complete randomness, it is natural to think of degrees of order as degrees of departure from a completely random state. When departure from randomness is complete, of course, the degree of order is maximal, as noted previously.

To clarify the sense of which departure from randomness admits degrees, we need a working definition of randomness. As a first approximation, randomness is equivalent to statistical independence. Two events are statistically independent if the occurrence of one does not affect the probability of the other's occurrence. A set of events thus is completely random when the occurrence of one has no bearing on the occurrence of any other.

Departure from randomness occurs when the occurrence of certain events begins to influence the likelihood that certain other events will occur as well. The more extensive this influence among events within the set, the more extensive their departure from a completely random state. The greater this departure, in turn, the more the events are statistically interdependent. The degree of order of a given set of events is directly correlated with the degree of interdependence among the events themselves.

By way of illustration, let us return to the example of the playing cards. To simplify matters, we may stipulate that the arrangement of cards in a series is entirely random if the identity of any given card is independent of its place in the series. This holds both for the arrangement of the deck and for the sequence resulting when cards are dealt off the deck.

In the case of a newly opened pack (arranged in proper order at the factory), a series of cards dealt off the top will exhibit complete regularity as the sequence unfolds. The sequence accordingly is completely nonrandom. The identity of each card is maximally interdependent with the identities of adjacent cards in the unfolding sequence.

In the case of a sequence dealt from a thoroughly shuffled deck, by contrast, there will be no appreciable interaction among successive members. The purpose of shuffling is to arrange the cards randomly, which is intended to ensure that each card's identity is independent of its place in the series. Randomness in arrangement of the deck goes hand in hand with a card's independence from its neighbors in the sequence dealt.

Between the maximal order of a new deck and the randomness induced by shuffling, of course, there will be many intermediate degree of order. Generally speaking, we may say that degree of order varies directly with degree of interdependence among members of the sequence. But degrees of interdependence varies inversely with degree of randomness in their arrangement. One variable affecting degree of order, accordingly, is degree of randomness. As the latter increases, the former decreases.

Another factor affecting an arrangement's degree of order is the number of items participating in it. To get a feel for this, compare a series of six cards dealt from a newly opened deck with a series that continues until all 52 cards (ignoring jokers) have been dealt. Under assumptions laid out previously, numbers of both series are entirely regular in sequence. Nonetheless it appears natural to think that the series of 52 is more highly ordered than the series of six. An entire desk is proper sequence represents a greater departure from randomness that does a smaller series also in proper sequence.

Think of it in terms of a mathematical analogy. There are (3 x 2 x 1 =) 6 ways in which the first three cardinal numbers can be arranged, (4 x 3 x 2 x 1 =) 24 for the first four, (5 x 4 x 3 x 2 x 1 =) 120 for the first five, and so forth. This means that the probability of a correct ordinal sequence (1, 2, 3) for the first three is 1/6, that for the first four is 1/24, and that for the first five 1/120. But the lower the probability of a given occurrence, the less likely that it would happen on a strictly random basis. The occurrence of five numbers in correct ordinal sequence (1, 2, 3, 4, 5) thus is a greater departure from randomness than in the case of three or four.

Similarly, an arrangement of 52 cards all in proper order is a greater departure from randomness than a proper arrangement of a smaller number. Given the relationship between randomness and order, it follows that the regular arrangement of 52 exhibits a higher degree of order than the arrangement of 6.

These considerations enable a working definition of orderliness (degree of order). An arrangement's degree of order is tied to its incidence of nonrandom occurrences. In upshot, an arrangement's degree of order (1) varies directly with the number of its featured members, and (2) varies inversely with the degree of randomness (independence) among these members.

Our concern with order and disorder for the remainder of this study will pertain mostly to the configurations of operating systems. An operating system is an open system of physical variables interacting through time. A mathematical measure of order in operating systems is explained in the appendix to this chapter. Its purpose is to show that entropy in the form of disorder is subject to quantitative measurement no less than entropy in the form of depleted energy to which it is thermodynamically equivalent. Readers not concerned with this topic may pass directly from the end of this chapter to the beginning of chapter 3.

2.6 Entropy and disorder

As already noted, the term 'entropy' was first used in reference to used-up energy, which is energy incapable of doing work. In the general sense explained in Chapter 1, work results in a physical occurrence being bought about by another physical occurrence rather than occurring randomly. A standard example of energy incapable of work is the black-body radiation emitted from the earth's surface into space. Unlike incoming solar energy, black-body radiation lacks directionality (a form of order), and hence lacks the intensity needed to accomplish work.

An equivalent conception equates entropy with random occurrences. Inasmuch as work amounts to physical alteration brought about on a nonrandom basis, randomly occurring events are incapable of doing work. The fact that random occurrences cannot produce work shows the equivalence between these two forms of entropy (useless energy and randomness).

This brings to hand another conception of entropy which equates it to disorder. In the preceding section we saw a direct link between a system's degree of order and the incidence of nonrandom occurrences within it. As a system's incidence of *nonrandom* occurrences decreases, however, its incidence of *random* occurrences tends to increase correspondingly. An increase in randomness thus is tantamount to a decrease in order, which is to say a higher degree of disorder.

As a system's incidence of random occurrences increases, accordingly, there is a corresponding increase in its degree of disorder and hence in its degree of entropy. In effect, to conceive entropy in terms of random occurrences is equivalent to conceiving it in terms of system disorder.

2.7 Negentropy

Let us summarize and simplify. One way of conceiving entropy (discussed in chapter 1) equates it with used-up energy. The opposite of entropy thus conceived is usable energy, which is to say energy capable of being used for work.

Another way of conceiving entropy equates it with random occurrences, which by definition are incapable of producing work (that is, incapable of producing change on a nonrandom basis). The opposite of entropy thus understood is departure from randomness in a system's occurrences, which amounts to potential for doing work.

Yet another conception equates entropy with disorder, the opposite of which is structure or order. Along with each conception of entropy goes a distinct way of understanding its opposite—first, unable energy, second, nonrandom occurrences, and third, structure and order.

As scientists concerned with these matters have found, it is convenient to have a single term covering the opposite of entropy in these several senses. Schroedinger chose the expression 'negative entropy'.[2] Others have opted for the condensed version 'negentropy'.[3] Thus understood, the term 'negentropy' can be used to refer to usable energy, nonrandomness, and order, indifferently.

2.8 Other formulations of the Second Law

In Chapter 1, dealing with the two laws of thermodynamics, the Second Law was formulated as saying that the amount of usable energy in the universe tends to decrease with time. An obviously equivalent formulation also mentioned is that the amount of used-up (degraded) energy in the universe tend always to increase. The First Law states that the amount of energy in the universe (usable or not) remains constant through time. A joint consequence of these two laws, however expressed, is that the energy consumed in doing work does not simply go away, but rather remains in a form no longer capable of work.

After sections 2.6 and 2.7, other formulations of the Second Law now are available. One is that events in the universe tend to occur on an increasingly random basis. An alternative in terms of randomness is that the incidence of nonrandom occurrences tends always to decrease. Another is that the disorder present in the universe tends to increase with time. In terms of order and disorder, an alternative is that the incidence of order in the universe tends always to decrease. In these terms, the so-called "heat death" of the universe (see section 1.7) is a state of total disorder.

Since expended energy, randomness, and disorder are all forms of entropy (section 2.7), a more comprehensive formulation of the Second Law is to the effect that the amount of entropy in the universe tends to increase with time. An equivalently comprehensive formulation is that the amount of negentropy in the universe tends always to decrease. This formulation will take center stage when we begin in Chapter 3 to consider the implications of the Second Law for living organisms.

Notes

1. Treatments associating entropy with randomness or disorder are standard today not only in branches of mathematical and social science, but also in the physical sciences where the concept was first employed. For examples in physics and chemistry, see E. Schroedinger, *What is Life*?, and P. Bridgman, *The Nature of Thermodynamics*. For chemistry, see H. A. Bent, *The Second Law*; for ecology, H. T. Odum, *Environment, Power, and Society*; and for economics, N. Georgescu-Roegen, *The Entropy Law and the Economic Process*. For computer science, see J. Rothstein, "Generalized Entropy, Boundary Conditions, and Biology," in R. Levine and Myron Tribus (eds.), *The Maxim Entropy Formalism*. For communication theory and ergodic theory

(both mathematical disciplines), respectively, see L. Brillouin, *Science and Information Theory*, and Karl Petersen, *Ergodic Theory*.

2. By this, Schroedinger said he meant entropy with a negation sign. See the work cited in the previous footnote.

3. Prominent examples are Brillouin and Georgescu-Roegen, op. cit.