

## 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 (previously noted in section 1.3). In its original use it referred to used-up energy, and this use remains prevalent in various sciences. By the middle of the 20<sup>th</sup> century, a broader understanding had developed associating entropy with randomness and disorder.<sup>1</sup> Although seemingly disparate upon first consideration, these two conceptions of entropy are closely interconnected.<sup>2</sup> To see why, we need to consider the relation between order and usable energy.

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

If the molecules are distributed so that one compartment contains a significantly larger proportion of fast-moving molecules than the other, however, there will be an appreciable difference in heat level between the two compartments. If the difference is sufficiently great (say, enough to boil water), the system 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 present in the distribution of high- and low-energy molecules between 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 kinetic energies 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 usable 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 when it is connected to a power source with opposing polarities (+ and -). The negative pole of a power source is the terminal characterized by a concentration of negatively charged atoms, while the atoms of the positive pole are predominantly positive. When the circuit is closed (e.g., by switching on an appliance), the positive pole attracts electrons and the negative pole repels them (by Coulomb's Law). The resulting movement of electrons constitutes a flow of electrical current.

The opposing concentrations of charged atoms at the terminals of a power source constitute a departure from purely random arrangements. In as much as atoms arranged randomly with respect to polarity are incapable of inducing an electrical current, the flow of power between terminals is enabled by this departure from randomness. Usable energy shows up again 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. The electrons then are diverted into an external circuit as a flow of electricity, while the protons remain within the cell to be combined with returning electrons to reconstitute hydrogen 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 gases is manipulated to produce usable energy in the form of electricity. The order induced on the atomic level is the source of energy made available for everyday use.

Radiational energy also fits into this picture. Solar radiation is highly ordered insofar as it is (1) directional and (2) characterized by a relatively high number of oscillations per unit distance.<sup>3</sup> 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 plant-eating organisms. The low-grade heat energy that results, on the other hand, exists at wave-lengths lacking sufficient structure for further work. When this useless energy is emitted from the surface of the earth, it spreads randomly (non-directionally) through surrounding space.

Structure is an orderly arrangement of parts within a system. What examples like these show, accordingly, is 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 correlative forms of entropy.

### **2.3 Gradations of structure correlated with gradations of energy**

Transformations among energy forms proceed according to rankings with respect to convertibility (section 1.5). It follows that the structures implicated in energy transformations are subject to ranking as well. In general, transformation from a higher to a lower form of energy is accompanied by change from a higher to a lower degree of structure.

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 accomplishing useful work. Usable energy in case (1) is conveyed by a highly ordered configuration of wave oscillations, in case (2) by an orderly movement of electrons through the conductor, and in case (3) by a nonrandom pattern of molecular activity within the stove burner. Usable energy is still available with the structural turbulence of the water in (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 accomplishing 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 flow of electrons through the conductor is spent in producing high-grade heat.

At each stage, moreover, energy made available by the expenditure of structure is used in establishing further structure at a subsequent stage. Solar energy is used to induce the orderly flow of electrons 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 generate structure at a later stage.

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

Moreover, just as there is a rank-ordering of progressive degradation in the series of energy-transformations (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 the latter in turn a greater degree of nonrandomness than the molecules in the hot air above the stove.

Intuitions aside, we need a characterization of order that makes comparisons like this possible on an objective basis. The groundwork for such a characterization is laid out in the following two sections, which examine the reciprocal relation between randomness and order.

## **2.4 Degrees of 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 relatively disordered in another. A deck of cards segregated by color only (spades and clubs coming first, say, with hearts and diamonds following), for example, exhibits more order than a deck that has been thoroughly shuffled. But the former is relatively disordered in comparison with a brand-new deck in which 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 by 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 itself and for the sequence resulting when cards are dealt off the top of the deck.

In the case of a newly opened pack (arranged in maximal 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, there will of course be many intermediate degrees of order. Generally speaking, we may say that degree of order varies directly with degree of interdependence among members of the sequence. But degree 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 it includes. 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 (excluding 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 deck in proper sequence represents a greater departure from randomness than does a smaller series also in proper sequence.

Think of it in terms of a mathematical analogy. There are  $(3 \times 2 \times 1 =) 6$  ways in which the first three cardinal numbers can be arranged,  $(4 \times 3 \times 2 \times 1 =) 24$  for the first four,  $(5 \times 4 \times 3 \times 2 \times 1 =) 120$  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 all 52 exhibits a higher degree of order than the arrangement of only 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.

[Technical addendum.<sup>3</sup> Our concern with order and disorder for the remainder of this study will have to do mainly with operating systems, in contrast with decks of cards and number sequences. As defined in Chapter 1, an operating system is an open system of physical variables interacting through time. Of primary concern in what follows will be systems constituting biological organisms (Chapter 3) and ecosystems in which various species of organisms interact (Chapter 4).

In the case of ecosystems and of individual organisms alike, order is created and maintained by a steady flow of high-grade energy into the system. This energy is put to work in building biomass (e.g., plants in ecosystems, tissue in organisms) and in running the metabolisms of the organisms involved. In both kinds of system, likewise, entropy resulting from this work is discharged back into the surrounding environment. As with operating system generally, some of this entropy will take the form of low-grade heat. Some also will take the form of degraded structure, such as dead plant mass and animal excreta.

Entropy in the form of low-grade heat (degraded energy) typically can be quantified in measures applicable to the higher-grade forms of energy consumed in producing it. A standard measure of entropy in chemistry, for instance, is joules per kelvin. As matters stand, however, there is no comparable measure of entropy in the form of degraded structure or disorder. The reason for this lack is not that degrees of structure are inherently unmeasurable. At very least, a given degree of structure can be quantified with reference to the amount of energy required to raise it to a higher degree.

The reason there is no standard measure of structure *per se*, rather, must be that no need has been perceived to define such a measure independently of the amount of energy necessary to produce it in the first place. Need now arises with the present project of comparing degraded (expended) energy and degraded structure (disorder) as separate but interacting forms of entropy. Meeting this need does not require finding a measure of structure that is applicable in fieldwork or in the laboratory. This is a separate project.<sup>5</sup> For present purposes, we must be content with a demonstration showing how different degrees of order can be quantitatively distinguished.

A mathematical (thus quantitative) measure of order in operating systems is explained in the Appendix to this chapter. Its purpose, as already indicated, is to show that entropy in the form of degraded structure or disorder is subject to quantitative measurement no less than entropy in the form of degraded energy. Readers not concerned with this matter may pass over the Appendix without losing track of the continuing discussion.]

## **2.6 Entropy and randomness**

Discussion of entropy in Chapter 1 was confined to expended energy, which is energy no longer capable of work. Work is done when physical occurrences are brought about by other physical occurrences rather than occurring randomly (section 1.2). A standard example of energy incapable of further work is the low-grade heat expended by metabolic activity (e.g., the body heat of living animals).

Another conception of entropy was introduced into the discussion at the beginning of the present chapter. This second conception equates entropy with disorder. In photosynthesis, solar energy is expended in creating biomass which provides chemical energy to plant-eating organisms. This highly ordered wave structure of sunlight is converted into chemical structure, which then is further degraded into the waste products of metabolic activity. This process of increasing degradation culminates in the nondirectional wave structure of black-body radiation by which fully expended energy from the sun is eventually returned to space.

The conceptions of entropy as expended energy and as structural disorder can be further integrated in terms of a third conception equating entropy with randomness. This conception was implied in our discussion of orderliness in the preceding section, but needs to be more explicitly articulated. On one hand, random events are events the occurrence of which exhibits no particular order. The entropy present in disorder thus is equivalent to that present in random occurrences.

On the other hand, random occurrences are incapable of doing work. This follows from the definition of work as a physical alteration that occurs on a nonrandom basis (section 1.2). Random events do not bring about nonrandom occurrences. Also by definition, usable energy is energy with work potential, which entails that occurrences incapable of work are devoid of usable energy. The joint consequence is that random occurrences ipso facto are devoid of work potential. Randomness and absence of energy capable of work are equivalent forms of entropy.

In connection with operating systems particularly, increased disorder is equivalent to increased randomness and increased randomness is equivalent to increased amount of energy unavailable for work. The upshot, thermodynamically speaking, is that (i) expended energy, (ii) randomness, and (iii) disorder are equivalent forms of entropy. Different forms may come into play in different contexts. Our main concern in the present study will be with forms (i) and (iii).

## **2.7 Negentropy**

Let us summarize and simplify. One way of conceiving entropy (i) equates it with expended energy. This conception occupied center stage in Chapter 1. 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 (ii) equates it with random occurrences, which by definition are incapable of producing work. This sense was laid out in the preceding section. The opposite of entropy thus understood is departure from randomness which, if sufficiently extensive, amounts to potential for doing work.

Yet another conception (iii) equates entropy with disorder. Entropy in this sense has been the primary focus of the present chapter. The opposite of entropy in this sense is orderly structure. Orderly structure constitute a departure from randomness, which in suitable forms provides energy capable of doing work (section 2.3).

Along with each conception of entropy goes a specific way of understanding its opposite. The opposite of (i) is energy capable of work. The opposite of (ii) is nonrandom occurrences, and that of (iii) is orderly structure. Under certain circumstances, as we have seen, both nonrandom occurrences and orderly structure provide potential for doing work.

Scientists concerned with these matters have found it convenient to have a single term covering the opposite of entropy in these several senses. Schroedinger chose the expression 'negative entropy'.<sup>5</sup> Others have opted for the truncated version 'negentropy'.<sup>6</sup> Thus understood, the term 'negentropy' can be used to refer to usable energy, nonrandomness, and order or structure 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 energy in the universe capable of work tends to decrease with time. An obviously equivalent formulation also mentioned there is that the amount of expended (degraded) energy in the universe tends 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 expended in doing work does not simply go away but rather remains in a form no longer capable of doing work.

At this point in the discussion, other formulations of the Second Law are also available. An alternative formulation in terms of randomness is that the incidence of nonrandom occurrences tends always to decrease.

Put in terms of order and disorder, the Second Law states that the disorder present in the universe tends always to increase while the incidence of order constantly decreases with time. In these terms, the so-called “heat death” of the universe (section 1.7) is a state of complete disorder. A consequence is that all happenings in the universe at this conjectured point occur on a strictly random basis.

Since expended energy, randomness, and disorder are all forms of entropy, 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 equivalent formulation is that the amount of negentropy in the universe tends always to decrease. This latter formulation will play a central role in Chapter 3 when we begin to consider the implications of the Second Law for living creatures.

### 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, see E. Schroedinger, *What is Life?*, and P. Bridgman, *The Nature of Thermodynamics*. For chemistry, see [A Dictionary of Chemistry](#) (Oxford University Press, 2004); 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. There is a movement among recent authors of chemistry textbooks to avoid illustrations that introduce entropy in terms of disorder, on the grounds that ordinary connotations of the term ‘disorder’ tend to mislead beginning students (e.g., see

[http://www.entropysite.com/cracked\\_crutch.html](http://www.entropysite.com/cracked_crutch.html)). A case in point is a bowl of cracked ice which subsequently melts into water. This illustration can be misleading insofar as the jagged ice appears visually to be less orderly than the homogeneous volume of clear water, suggesting erroneously that melting results in a change from disorder to relative order. As any advanced student of thermodynamics should realize, however, the molecules in a piece of ice are more highly ordered than the same molecules in the form of liquid water. For the instructor to point this out would seem to be an appropriate exercise in a standard first year chemistry course. At any rate, the present reader should be forewarned that the concepts of entropy as degraded energy and as disorder (degraded order) are interconnected only when disorder is understood in an appropriate sense. An appropriate sense introduced later in this chapter is disorder as randomness, correlative with order as departure from randomness.

3. By way of analogy with the second factor, consider a number of birds perched on a power line. One hundred birds evenly spaced (say one foot apart) constitute a higher degree of order (further departure from randomness) than a mere 5 or 6 also evenly spaced but further (maybe 20 feet) apart. This factor is examined more fully in section 2.5.

4. This label is used for passages containing technical material relevant to the main text but not necessary for following the overall argument. These passages are included for the benefit of the

readers who, for whatever reason, might be interested in more background than the main text provides

5. Significant work has already been done in measuring the flow of energy through ecosystems.

See section 4.6 and associated endnotes. Measuring the objective structure brought about by those energy flows is another matter.

6. By this, Schroedinger said he meant entropy with a negation sign. See the work cited in the note 1.5.

7. Prominent examples are Brillouin and Georgescu-Roegen, *op. cit.* The present author adopted the term in *Cybernetics and the Philosophy of Mind* (Routledge and Kegan Paul, London, 1976).

See also my more recent “Cybernetics,” ch. 9 in Stuart Shanker (ed.) *Routledge History of Philosophy*, Vol. IX, *Philosophy of Science, Logic and Mathematics in the Twentieth Century* (Routledge, London, 1996).