Entropy Anyone?

To judge from the writings of C. P. Snow, entropy and the second law of thermodynamics were once indelicate subjects. Now things have changed, and on the cocktail party circuit we hear of entropy in art, entropy in economics, entropy in urban decay, and other erudite-sounding applications. A most difficult concept in physics is being applied to confused areas in the social sciences, with the impression being conveyed that this increases our comprehension. Clearly, such a situation should send us scurrying back to the first principles of physics to clarify the issues.

Thermodynamics, the science of heat and work, was firmly established in the mid-1800s. Its development paralleled the Industrial Revolution, an era characterized by the application of heat engines in manufacture and transport. Studying the efficiency of these machines was the task of science, although generations of aspiring engineers have repeated the adage that the "steam engine has done more for thermodynamics than thermodynamics ever did for the steam engine." During the decade from 1840 to 1850, two physicians, Mayer and Helmholtz, developed a full understanding of the concept of energy and derived the conservation law. The principle that energy can be changed from

one form to another but can never be created or destroyed has been an enduring cornerstone of physics.

Using this new knowledge, Rudolf Clausius began his studies of the efficiency with which heat could be transformed into work. He set down the second law of thermodynamics in the form "heat cannot of itself pass from a colder to a hotter body." From this experimental generalization and the work of Lord Kelvin he was able to deduce that engines could not be 100% efficient; it was impossible to transform all the heat into work. In seeking a formal measure of the energy unavailable as work, Clausius, in 1865, introduced the word *entropie*, derived from the Greek root *tropie*, or "transformation." This parameter, in classical theory, permits a determination of the amount of energy that cannot be recovered as mechanical work.

The precise Clausius definition of entropy was abstract, mathematical, and formulated in terms of differential calculus. It provides an excellent way of carrying out calculations but yields very little in terms of intuitive notions. In this branch of physics we use such quantities as pressure, volume, and temperature, which can easily be related to everyday experience. Other parameters, such as work, heat, and energy, are harder to conceptualize but make contact with familiar ideas. Finally, we have quantities, such as entropy, that are almost entirely dependent on abstractions and therefore are the most difficult to understand.

In developing their science, the founders of thermodynamics also introduced and stressed the concept of equilibrium to provide reference states upon which a comprehensible theory could be based. A system at equilibrium must have aged for a long time in isolation from active processes. This was done by immersing the system of interest in a heat bath or placing it in a rigid insulated box; under these conditions, it exchanges neither materials nor energy with the rest of the universe. Such collections of matter are basically dead and uninteresting. They can be investigated in the laboratory but rarely exist in the real world. Equilibrium is an idealization that has enabled scientists to gain a deep and percep-

tive insight into many natural processes; however, such measures as entropy, which have a precise meaning only at equilibrium, must be used very cautiously in the far-from-equilibrium everyday world. Using these ideas, Clausius and Lord Kelvin recast the second law of thermodynamics in the statement that for spontaneous processes entropy always increases. This was widely interpreted as meaning that the universe was running downhill toward a "heat death." It was assumed that physical processes always led to the most disordered states.

Nineteenth-century biologists, fresh from the triumphs of the theory of evolution, were baffled by the seeming contradiction between the degradative thrust of the second law and the progressive direction of evolution toward higher organization. They wondered if life, with all its anabolic processes, was a violation of the known principles of physics. The seeming paradox was first resolved by the perceptive Ludwig Boltzmann, who pointed out that the surface of the earth and the biosphere were kept far from equilibrium respectively by the constant flow of sunlight and by continuing photosynthesis. Such systems under an energy flow were not constrained to undergo an increase in entropy but could indeed experience a decrease to more ordered states. Life was fully consistent with the laws of thermodynamics.

During the following period an elaborate structure of thermal physics and chemistry emerged and helped to provide an understanding of our world. Boltzmann, Gibbs, and Einstein demonstrated that laws of thermodynamics are exact because ordinary measurements are averages over huge numbers of atomic and molecular events. Although the individual behavior of these fundamental entities is very hard to predict, their statistical properties can be precisely accounted for.

In the years from 1880 to 1915 the atomic theory became universally accepted by the scientific community. One necessary characteristic of all matter is the constant random motion of atoms and molecules when viewed on their own size scale. The glass of water serenely sitting on my desk consists of 10^{24} molecules, which are constantly moving about, dissociating into hydrogen

and hydroxyl ions and then reassociating, forming and unforming microcrystals, and colliding with the walls of the container. Because the individual molecules are so small, we see only averages over vast numbers of particles and hence the illusion of great regularity.

Underlying this external impression of order is a real molecular chaos that has been studied by statistical mechanics and kinetic theory. One of the major triumphs of those disciplines has been a development of the entropy function as a quantitative measure of that submicroscopic disorder. The reason why some of the heat energy is unavailable for work is that it is randomly distributed among molecular modes and cannot be extracted in any coherent way by large-scale devices. This gives added insight to Clausius's finding. With the advent of information theory came the realization that entropy relates to disorder by providing a measure of our residual ignorance about the molecular details of a system after we have acquired all the necessary quantitative data at the size range of ordinary instruments.

Returning to the modern popularizers of entropy as a universal explanatory, I have before me a letter from Jeremy Rifkin, author of *Entropy: A New World View*. His communication states that "entropy helps explain why we have runaway inflation, soaring unemployment, bloated bureaucracies, a widely escalating energy crisis, and worsening pollution." That sentence is an archetypical example of the patent intellectual nonsense being offered in applying physics to the social sciences. Entropy, a deep and hard-to-penetrate physical construct, is being indiscriminately applied to situations in which it is devoid of physical meaning. No hint is given that the far-from-equilibrium world in which we live is governed by different laws than the thermodynamics learned in an introductory physics course. Boltzmann's work of a hundred years ago is ignored, as are numerous works of modern science showing the antientropic character of energy flow processes. In short, entropy is being made a code word to explain every political idea Rifkin wishes to propound. This is a dangerous misuse of science, because it may fool the scientifically untrained into be-

lieving that certain conclusions come from natural laws, when in fact they do not. Fooling the public with "sciencese" decreases our society's ability to make rational judgments.

The popular purveyors of entropy pap should be reminded of the words of Pope:

> *A little learning is a dangerous thing;*
> *Drink deep, or taste not the Pierian spring;*
> *There shallow draughts intoxicate the brain.*
> *And drinking largely sobers us again.*

In the meantime, what of the notion of entropy? This elegant quantity is a precisely defined construct of physics; it can be rigorously measured for equilibrium systems and can be given meaning for near-to-equilibrium considerations. The second law, when formulated in terms of entropy, gives powerful insights into a wide variety of problems. It seems a shame to take such a beautiful and exact idea and blur its meaning by indiscriminately applying it to all sorts of areas that have nothing to do with equilibrium thermodynamics. Such a procedure might disorder our thoughts about other disciplines that are already difficult enough.