

THERMODYNAMICS, KINETICS, AND BIOLOGY

by Barry B. Edelstein

I think the purpose of this session is to try to draw some guidelines for ethics and sociopolitics which are motivated by scientific theory. The anticipated progression is by a hierarchy from the theories of physics to those peculiarities and modifications necessary for biological systems, and then, by analogy, from biological systems to ethics and politics. There are two steps in the transition. I shall not comment on the second, except to point out the danger of selecting a favorite ecological or ethical consideration and then constructing a transition from physical to biological theory that will lead to the appropriate ethical interpretation.

There is a long history of attempts to characterize living systems by peculiarities of physical law. Among the attempts are the purely thermodynamic characterization and the thermodynamic and kinetic characterization. To make this distinction clear, it should be recalled that thermodynamics is a purely static theory in which all transformations are quasi-static and at equilibrium. Once we are concerned with kinetic changes, which occur only in systems not at equilibrium, we can consider the kinetics of the change, including nonequilibrium thermodynamics. Thus a thermodynamic characterization uses names such as entropy, order, and disorder, while a kinetic characterization uses names such as entropy production, stability, and cybernetics.

The initial thermodynamic characterization was independently due to Schrödinger,¹ Delbrück,² and Wiener.³ They originated the idea of negentropy. This concept, that the entropy of living systems is sub-maximal, follows from the truism that living systems are not at equilibrium but are open systems "feeding" on the negative entropy of the environment.

It is from the association of entropy with disorder that the conjectured biological importance of order or disorder arises. That this association is inexact can be realized by considering a crystal. Although crystals are among the most ordered structures, they are at

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equilibrium and hence have a maximum entropy for the constraints. The apparent contradiction arises because entropy is a function of the $6N$ coordinates of phase space, while we are looking at the crystal in the $3N$ coordinates of physical space.

The books of Schrödinger⁴ and Wiener⁵ stimulated a large production of papers in the attempt to calculate a biologically significant quantity of negentropy. It became clear that such attempts were fruitless. This is seen by considering cells in the living state and after they have been minimally disrupted, say, in a Waring blender. The change in physical entropy is infinitesimal, and yet the cells are no longer living.

The difficulty the homogenized cell raises for the relevance of negentropy to living systems is countered by the concept of levels of order or levels of stability. This concept has recently been discussed by Bronowski⁶ and by Bohm.⁷ In our example, it implies that the structural integrity has great importance, which in some way must be included in the calculation of negentropy. This concept has been extrapolated to the many levels of stability in evolution or in a multicellular organism.

It is theoretically possible to calculate a negentropy in which levels of order are properly included. The calculation just requires choosing (or constructing) the proper variable and probability space and then using the prescriptions of information theory. However, since we will not be using equal a priori probability in phase space, the connection with thermodynamics will be tenuous. The negentropy will be a uniquely biological quantity, and the major achievement will be finding the biologically significant probability spaces.

The search for biological relevance in kinetics is a new and exciting field. Kinetics not only includes some problems of cybernetics, but that class of phenomena associated with multiple, possible states in open, nonlinear systems. I must recommend the remarkable paper by Turing, "The Chemical Basis of Morphogenesis,"⁸ for anybody interested in the biological implications of kinetic order.

The physical reasons for the origin, because of an energy flux, of new stable states far from equilibrium—where hitherto only one had existed near equilibrium—are too intricate to be succinctly discussed. Accept the fact that, as Katchalsky⁹ has already told us, certain nonlinear chemical reactions with diffusion, in open systems, can have new stable states.

The importance of such new states arises from their apparent freedom from some of the restrictions of near-equilibrium thermodynamics. In an isotropic system with symmetric boundary conditions, the

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Onsager reciprocity relations, which are applicable near equilibrium, require that the chemical concentrations be time independent and homogeneous in the stable state. Moreover, this stable state is unique, and all deviations return to it monotonically. However, with the same symmetric starting conditions, these new stable states can be inhomogeneous and hence introduce asymmetries. The inhomogeneities can be time dependent; or periodic behavior, such as limit cycles, can occur homogeneously. Finally, multiple time-independent homogeneous states, with or without hysteresis, have been predicted.

This new class of kinetic order is the more remarkable because the states are stable. This means that, if the system deviates by a sufficiently small amount from the stable state, it will return to the stable state by itself. Not only is this an ideal homeostatic mechanism, but this shows that the observed effects of such kinetic order do not require the strict accounting, in terms of negentropy, that the near-equilibrium order, without stability, appears to require.

NOTES

1. Erwin Schrödinger, *What Is Life?* (New York: Cambridge University Press, 1944).
2. Max Delbrück, "A Physicist Looks at Biology," *Transactions of the Connecticut Academy of Arts and Sciences* 38 (1949): 173-90.
3. Norbert Wiener, *Cybernetics* (Cambridge, Mass.: M.I.T. Press, 1948).
4. See n. 1 above.
5. See n. 3 above.
6. J. Bronowski, "New Concepts in the Evolution of Complexity: Stratified Stability and Unbounded Plans," *Zygon* 5 (1970): 18-35.
7. D. Bohm, "Some Remarks on the Notion of Order," in *Towards a Theoretical Biology*, ed. C. H. Waddington (Chicago: Aldine Publishing Co., 1969), 2:18-40.
8. A. M. Turing, "The Chemical Basis of Morphogenesis," *Philosophical Transactions of the Royal Society of London* B237 (1952): 37-72.
9. A. Katchalsky, "Thermodynamics of Flow and Biological Organization," *Zygon* 6 (1971): 99-125.