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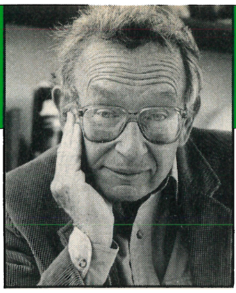
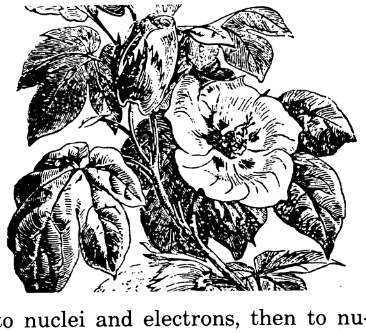


IS COMPLEXITY PHYSICS? IS IT SCIENCE? WHAT IS IT?

Philip W. Anderson

Questions like the ones posed in the title of this column are being asked nowadays by faculty members in university departments of physics—and many other disciplines as well. They find themselves having to assess graduate work or applicants for jobs or tenure in strange fields like neural networks, self-organized criticality applied to earthquakes or landforms, learning systems, self-organization and even such older fields as nonlinear dynamics or spin glasses. The easy way out in these decisions is to give the nod to more orthodox and traditional work. So it is a matter of some urgency to decide whether "complexity" is a part of physics—or even vice versa.

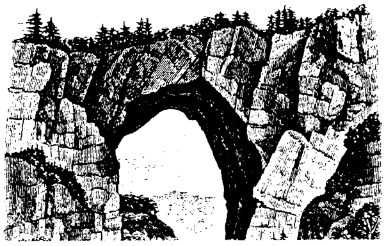
For most of its history, and for its most well-known practitioners, physics has been the ultimate reductionist subject. Physicists reduce matter first to molecules, then to atoms, then



to nuclei and electrons, then to nucleons and so on—always attempting to reduce complexity to simplicity. We found there were, in all of physics, only four forces, which then were reduced to three; now string theorists tell us all three boil down to a single quantum gravitational, supersymmetric, utterly featureless earliest universe. In condensed matter physics, the diversity of the world of solid matter seemed to be reducible to a universal band theory of electronic structure plus a few elementary defects such as donors, acceptors, grain boundaries and dislocations.

With the maturation of physics, a new and different set of paradigms began to develop that pointed the other way, toward developing complexity out of simplicity. I happen to have written one of the early manifestos for this infinitely quiet revolution, a Regents' Lecture (given at the University of California, San Diego, in 1967) and magazine article called "More Is Different" (*Science* **177**, 393, 1972). I emphasized the concept of "broken symmetry," the ability of a large collection of simple objects to abandon its own symmetry as well as the symmetries of the forces governing it and to exhibit the "emergent property" of a new symmetry. ("Emergent" is a philosophical term going back to 19th-century debates about evolution, implying properties that do not preexist in a system or substrate. Life and consciousness, in this view, are emergent properties.) The canonical example was the Bardeen–Cooper–Schrieffer theory of superconductivity, which could be described as broken gauge symmetry. The elementary-particle theorists Yoichiro Nambu, Geoffrey Goldstone, Peter Higgs, and eventually John Ward, Abdus Salam and Steven Weinberg used a BCS-like theory to unify particles and forces, but one could just as justifiably look at broken symmetry as a scheme for getting complex behavior from simple origins. (A primer of broken symmetry is to be found in my book *Basic Notions of Condensed Matter Physics* [Benjamin–Cummings, 1984], in the second chapter and especially among the reprints.) More recently, the study of defects of broken-symmetry systems by Gérard Toulouse, G. E. Volovik and others has opened a whole new realm of complexity.

John Hammersley's theory of percolation and my ideas of localization set a second kind of pattern for developing complex behavior, namely, the idea that randomness and disorder could result in generic properties that are utterly different from those of merely somewhat impure



regular materials. For instance, they result in new types of transport theory. The spin glass is in a way the ultimate illustration of this situation: It requires a whole new version of statistical mechanics. Glass itself remains one of the deepest puzzles in all of physics.

More recently, dynamical instabilities and deterministic chaos have been brought to our attention. Yet another group of developments involves spontaneous pattern formation, fractals and the beginning of self-organization. The whole ball of wax has been jumbled together by the remarkable idea of Per Bak, Kurt Wiesenfeld and Chao Tang that many of the phenomena of nature exhibit scaling laws determined by self-organized behavior like that at critical points of phase transitions. (See the Reference Frame column by Leo Kadanoff, March, page 9.)

As one probes deeper into the origin of the universe or the interior of the quark, it will never be questioned that one is doing physics. By contrast, the traditional, reductionist physicist and, for sure, the funding agencies can be left vaguely disturbed or hostile as new fields lead us *up* the hierarchy of complexity toward sciences such as geology, developmental biology, computer sci-

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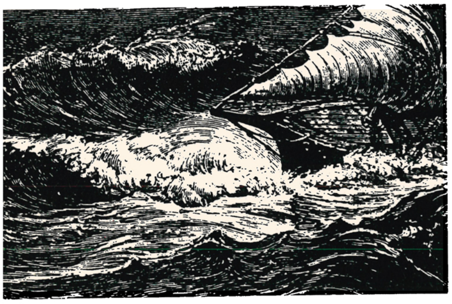
ence, artificial intelligence or even economics. There can be a somewhat surprising lack of understanding of what those of us working in these new fields are doing. It is still possible, for instance, to find Marvin L. Goldberger and Wolfgang Panofsky, who are relatively enlightened physicists, saying, in an op-ed piece for *The New York Times*: "Other branches of physics [than particle physics] . . . are interesting, challeng-



ing, and of great importance. . . . The objectives are *not a search for fundamental laws as such* [my italics], these having been known . . . since the 1920s. Rather, they are the application of these laws." If broken symmetry, localization, fractals and strange attractors are not "fundamental," what are they?

A movement is under way toward joining together into a general subject all the various ideas about ways new properties emerge. We call this subject the science of complexity. Within this topic, ideas equal in depth and interest to those in physics come from some of the other sciences. This movement is overdue and healthy. On the other hand, one may well be apprehensive—or at least I am—that such an enterprise might go the way of General Semantics, General Systems Theory and other well-meant but premature and intellectually lightweight attempts at building an overall structure. We complexity enthusiasts (perish the thought that we be called complexity scientists!) are talking, at least for the most part, about specific, testable schemes and specific mechanisms and concepts. Occasionally we find that these schemes and concepts bridge subjects, but if we value our integrity, we do not attempt to force the integration.

A number of institutions have grown up to foster this kind of work, and in a future column I'd like to write about one of them, the Santa Fe Institute. Meanwhile, let me give my own answers to my opening questions: Complexity, as defined in the preceding paragraph, is often physics. It is the leading edge of science. And it is surely exhilarating. ■