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Colloquium Paper

This paper serves as an introduction to the following papers, which were presented at a colloquium entitled "Physics: The Opening to Complexity," organized by Philip W. Anderson, held June 26 and 27, 1994, at the National Academy of Sciences, in Irvine, CA.

Physics: The opening to complexity

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In the minds of the lay public, or even of scientists from unrelated fields, physics is mainly associated with extremes: big bangs and big bucks; the cosmic and the subnucleonic scales; matter in its most rarified form such as single trapped atoms; or measurements of extraordinary precision to detect phenomena—dark matter, proton decay, neutrino masses—which may well not be there at all.

The intellectual basis for this kind of science has been expounded by Victor Weisskopf, Leon Lederman, Stephen Hawking, and particularly Steven Weinberg, in his book *Dreams of a Final Theory*. The buzzword is "reductionism," the idea that the goal of physics is solely or mostly to discover the "fundamental" laws which all phenomena involving matter and energy must obey and that ignorance about these laws persists only on the extreme scales of the very small, the very cosmic, or the very weak and subtle.

The glamorous image of physics that this preoccupation projects is not necessarily all good: with the end of the Cold War and of expansionist public spending, physics is seen by all too many policymakers as too expensive for its practical return or simply too big for its boots. Some pundits have called the past half-century "The Age of Physics" and suggested that this age is coming to an end.

This pessimistic view may or may not be true even of Big Science physics. It seems to me that cosmic physics, at least, is in the midst of a very fertile period, not near collapse. But what it ignores is the fact that most physics and most physicists are not involved in this type of work at all. Eighty percent or so of research physicists do not classify themselves as cosmic or elementary particle physicists and are not much concerned with testing the fundamental laws. Admittedly, some portion of this 80% are concerned with applications of physics to various practical problems, as for example prospecting geophysicists or electronic device designers. But another large fraction are engaged in an entirely different type of fundamental research: research into phenomena that are too complex to be analyzed straightforwardly by simple application of the fundamental laws. These physicists are working at another frontier between the mysterious and the understood: the frontier of complexity.

At this frontier, the watchword is not reductionism but emergence. Emergent complex phenomena are by no means in violation of the microscopic laws, but they do not appear as logically consequent on these laws. That this is the case can be illustrated by two examples which show that a complex phenomenon can follow laws independently of the detailed substrate in which it is expressed.

(*i*) The "Bardeen–Cooper–Schrieffer (BCS)" phenomenon of broken gauge symmetry in dense Fermion liquids has at least three expressions: electrons in metals, of course, where it is called "superconductivity"; ^{3}He atoms, which become a pair superfluid when liquid ^{3}He is cooled below 1–3 $\times$ 10^{-3} K; and nucleons both in ordinary nuclei (the pairing phenomenon explained by Bohr, Mottelson, and Pines) and in neutron stars, on a giant scale, where superfluidity is responsible for the "glitch" phenomenon. All of these different physical embodiments obey the general laws of broken symmetry that are the canonical example of emergence in physics.

(*ii*) One may make a digital computer using electrical relays, vacuum tubes, transistors, or neurons; the latter are capable of behaviors more complex than simple computation but are certainly capable of that; we do not know whether the other examples are capable of "mental" phenomena or not. But the rules governing computation do not vary depending on the physical substrate in which they are expressed; hence, they are logically independent of the physical laws governing that substrate.

This principle of emergence is as pervasive a philosophical foundation of the viewpoint of modern science as is reductionism. It underlies, for example, all of biology, as emphasized especially by Ernst Mayr, and much of geology. It represents an open frontier for the physicist, a frontier which has no practical barriers in terms of expense or feasibility, merely intellectual ones. It is this frontier that this colloquium was destined to showcase. A typical (but incomplete) selection of the papers given at the colloquium are reproduced here.

The subfields of complexity which we chose to represent are only a fraction of the available material. This frontier of complexity is by far the most active growth point of physics. Physicists are also finding themselves, more and more, working side by side with other scientists in interdisciplinary collaborations at this frontier. The flavor of many of the talks was interdisciplinary.

We chose four areas under which to group the talks. These highlighted four kinds of physics. A brief description of each follows.

(*i*) Conventional solid state physics is really the quantum physics of materials, and as such deals mainly with electronic properties. There has been a resurgence of interest in this area because of several new and startling discoveries of new types of materials: We called this "The New Physics of Crystalline Materials."

(*ii*) Noncrystalline materials such as glasses and polymers have become increasingly subjects of interest in physics, so we included a section on "The New Physics of Noncrystalline Materials." Some of the deepest problems in theoretical physics still surround the dynamics of glasses. It is slightly unsuitable to include biophysical materials under this heading since biophysics is an important and growing frontier in itself but in order not to subdivide the sessions infinitely this was done.

(*iii*) Physicists are increasingly moving into realms very far from equilibrium, studying processes which form many of the natural objects we encounter as well as describing the highly nonequilibrium behavior we see all around us in turbulent convective flow (weather) and the non-

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equilibrium states we see in our geological surroundings. The phenomenology of this sort of phenomenon ("fractals," chaos, pattern formation) far outstrips our theoretical apparatus for dealing with it. The emphasis is on the "search for generalizations."

(*iv*) Finally, there is a field that has grown up around the new statistical physics developed for some fascinating materials problems of disordered dynamical systems, which has overlapped into problems of computational algorithms for complex problems and into the theory of neural networks. This is a development which promises to allow us to deal with true complexity with physical rigor and needed to be presented: "New Theories of Complexity."

A fifth topic was omitted because of overlap with a recent colloquium: complexity in astrophysics, and I am sure those interested in complexity will have their own candidates. But, in the end, this program is what we had room for and the attendees seemed to have enjoyed the program as presented.