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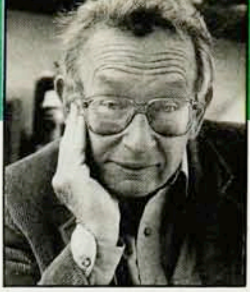

SPIN GLASS VII: SPIN GLASS AS PARADIGM

Philip W. Anderson

In my last column on spin glasses (September 1989, page 9) I tried to show you that the exact solutions of a particular spin glass problem, by Giorgio Parisi and Gérard Toulouse, gave us great insight into the theory of complex optimization problems, as well as an algorithm for solving some of them. One such problem, which has been exhaustively studied by methods of spin glass theory, is the graph partition problem. This is the question of how to divide an arbitrary graph into two pieces, cutting the fewest possible bonds. My student Yao-Tian Fu (now at Washington University, St. Louis) initiated the study of the graph partition problem by replica theory. This classic problem of complexity theory was difficult to solve for sparse graphs by those methods, but another of my students, Wuwell Liao, seems to have done it.

Even more interesting than these applications to complexity theory is the way apparently unrelated areas of science have been stimulated into parallel growth by the spin glass work. John Hopfield (Caltech), who was instrumental in bringing me to Princeton in 1975, became interested in models for neural networks and brain function about 1979–80. It was natural for him to realize that complex, interconnected systems of simple units could have the "rugged landscape," multistable properties of spin glasses. Using, very ingeniously, an *ad hoc* and apparently unrealistic assumption of symmetric coupling between neurons, John got the following results:

- For a given set of coupling synapses (interactions) J_{ij} between neurons (spins) i and j, the conventional McCulloch–Pitts model of neuronal interactions maps onto a "greedy" algorithm for finding the *local* ground state of a corresponding spin glass. ("Greedy" is the computer scientists' self-evident jargon term for jumping directly to the lowest local energy for each spin.)
- Modifying the couplings, or choosing the J_{ij}, in such a way as to form the so-called Hebb synapses makes the neural network into a model for "content addressable" memory: a memory like our own, which can reproduce full detail from fragmentary information. A system of N neurons connected by $N(N-1)/2$ symmetric synapses can remember about $N/6$ N-bit messages in the form of locally stable "spin" (that is, neuron firing rate) configurations. (John made this conjecture about the capacity of a neural network on the basis of simulations, but it later turned out to agree with exact analytic theory.) Thus, in exchange for a capacity reduction of a factor of 3 relative to the information-theoretic maximum, one gets the content-addressable feature.
- Finally, several other brain functions, such as pattern recognition, could be modeled with the spin glass type of neural network.

Many of you may be aware of the gigantic growth of neural network science in recent years. In 1979, however, when I tried to whip up interest in John's ideas among computer scientists at Bell Labs, there was little response; and he, Alan Gelperin and John Connor got nearly equally short shrift among neuroscientists. Nowadays the neuroscientists and computer scientists like to point to prior claims for each component of John's achievements. I can hardly believe, however, that such further developments in neural networks as the revival of the perceptron would have occurred except as a response to John's beautiful demonstrations that, after all, *one* such system—the Hopfield neural network—does work and has a rigorous, mathematically respectable basis. In particular, John's work has generated a very healthy trend toward rigorous mathematical demonstrations of limits on capacity, accuracy and so on in neural networks and perceptron-like models, using the statistical mechanics methods provided by Toulouse, Haim Somopolinsky, Miguel Virasoro, John Hertz, Richard Palmer (who was John's associate at Princeton in 1975–78) and many others. It turns out that statistical mechanics can be applied to realistic, asymmetric networks as well, and that there is no real difference between the capabilities of symmetric and asymmetric networks.

I promised I would close my series on spin glasses with this column, so it must be descriptive, not detailed. But I must also mention how the "rugged landscape" of spin glasses relates to theories of biological evolution. In 1981 I visited John Hopfield at Caltech and helped with the course on "physics of information" that he, Richard Feynman and Carver Mead were giving. Stimulated by John's work on neural nets, I came back to Princeton with the realization that I could put my own rugged-landscape ideas into a theory of prebiotic evolution that Daniel Stein (now at the University of Arizona) and I were already working on. The genome of an organism can be thought of as a set of Ising spins—two for each base in the DNA because there are four types of bases and the Ising spin has two possible values. The fitness, or reproductive capacity, of the genome can be modeled by a frustrated, quenched random function of this list of spins, and the simplest random function that satisfies the requisite plus–minus symmetry is a spin glass Hamiltonian function. (The plus–minus symmetry is imposed by the complementarity of base pairing.) With a senior thesis student, Dan Rokhsar, Stein and I made a simple model of primitive evolutionary processes using this idea.

Related ideas, but without the statistical mechanics insights, had already occurred to Gérard Weisbuch at the Ecole Normale in Paris and to Stu Kauffman at the University of Pennsylvania. Nonetheless the extra understanding those insights provide has encouraged us, and especially Stu, to go on and attack all kinds of evolutionary—and other—problems with spin-glass-like random, rugged-landscape models. This approach has become an important part of the program at the Santa Fe Institute, of

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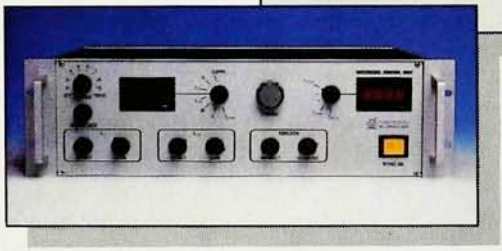

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which Stu and I are members. Unfortunately I cannot discuss here the many other ramifications of this way of thinking. From my point of view, its attractiveness lies in that it allows us to explain simultaneously the contradictory aspects of variety and stability of certain special forms and patterns. Life exhibits these contradictory aspects: Among the countless possible mutations, many lead to stable species. In the language of spin glass theory, there are many "basins of attraction," but each is stable (or at least metastable). It is also clear, as Gérard Weisbuch first pointed out, that evolution in such a landscape will exhibit "punctuated equilibrium," or sudden changes from one deep maximum of fitness to another, a feature that has been emphasized recently as characteristic of much of evolution.

I realize that I never returned to "real" spin glasses, even though it was studies of the low-temperature properties of those dilute magnetic alloys that led to the theoretical ideas I have been discussing. There is a reason: In spite of much beautiful experimental, computational and theoretical work, a complete and consistent understanding of those materials is not yet at hand. Helène Bouchiat and Pierre Monod, among others such as Laurent Levy, have beautifully demonstrated that real spin glasses have divergent nonlinear magnetic susceptibility at T_{SG}, verifying that there is a real phase transition, albeit one without a visible specific heat singularity. Spectacular simulations carried out on special purpose machines by Peter Young (University of California, Santa Cruz) and Andrew Ogielski (AT&T Bell Labs) have also verified the existence of a phase transition in three dimensions. Daniel Fisher (Princeton) and David Huse (Bell Labs), among others, speculate, however, that real spin glasses are really *not* ultrametric or replica-symmetry breaking. The theory is still under development. Some of it was explored in the December 1988 PHYSICS TODAY special issue on disordered solids.

For further information on random landscapes and evolution, Stu Kauffman's forthcoming book *Origins of Order: Self-Organization and Selection in Evolution* (Oxford U. P., New York) is perhaps the best source. John Hopfield has written (with David W. Tank) a *Scientific American* article on his neural network ideas (December 1987, page 104). An article on neural networks by Haim Sompolinsky appeared in the December 1988 PHYSICS TODAY (page 70). ■

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