CC/NUMBER 37
SEPTEMBER 16, 1985

This Week's Citation Classic®

Edwards S F & Anderson P W. Theory of spin glasses.
J. Phys.—F—Metal Phys. 5:965-74, 1975.
[Cavendish Laboratory, Cambridge, England]

When magnetic atoms are dispersed in a nonmagnetic metallic matrix, the forces between their magnetic moments depend on separation and are sometimes of ferromagnetic type and sometimes antiferromagnetic. The net experimental observation is thermodynamic, not magnetic, and shows a phase change at low temperatures. Both phases are nonmagnetic and apparently completely disordered. This paper invents a new order parameter that is the correlation of an atom's spin at one time with the value at a much later time. This opens a vista onto many new problems in statistical physics. [The *SCI*® indicates that this paper has been cited in over 1,015 publications since 1975.]

Sam Edwards
Cavendish Laboratory
University of Cambridge
Cambridge CB3 OHE
England

July 17, 1985

This paper has an interesting history. In 1974 I was chairman of the (UK) Science Research Council (the National Science Foundation of the UK) and commuted each day to London. On Saturdays, Phil Anderson and I would meet and discuss what we had been thinking about during the week.

One Saturday, Phil explained to me the problem of spin glasses. They apparently had a phase change, but both states were completely disordered and showed no magnetism. How could one find a method to describe such a system? I had not worked in magnetism, but had studied molecular networks in rubbers. In these, too, there was complete randomness but the permanent crosslinks between the polymers made rubbers solid. I had found the theory of rubbers very unsatisfactory and reformulated it in a precise but rather abstract way: a particular method of evaluating the thermodynamic properties of rubbers involved averaging log H. I did this by averaging H^n and letting $n \to 0$ $H^n = 1 + n \log H + \ldots$. Now H^n represents n versions of the rubber, and correlations between these "replicas" represent the solid nature of the rubber. I thought this might work for spin glasses, too, and tried it out on Phil. He pointed out many problems in what was admittedly a weak analogy and also specified a set of criteria that would have to be met. We then broke up and met the next Saturday. Commuting to London in comfortable, not-too-fast trains gave me two hours of peace each day and enabled me to try runs of quite complex algebra. Phil did the same in more leisurely surroundings, and we soon put together a theory of spin glasses that resulted in this paper.

It was the opening of Pandora's box. At long last, there was an "order" parameter to characterize disordered systems. The mathematics were optimistic to say the least, and many authors[1] have improved upon the original to the point that some cases have been solved exactly. It is surprising, however, that the experiments still seem to bear out some of our original results. However, real, three-dimensional cases remain completely beyond mathematical treatment.

There is another odd citation feature. The original paper used this "replica" method, but it is clear that, if the dynamics of the spins are adequately solved, there is no need for the replica method. In fact, in an early section, we began this process; and in a second paper,[2] we did just this and also noted the significance of the highly degenerate (near) ground states of the system. This paper seems very little read, and, although this line of research has been widely developed (as was that of the first paper), it is rarely cited.

1. **Parisi G.** An introduction to the statistical mechanics of amorphous systems. (Zuber J B & Stora R, eds.) *Développements récents en théorie des champs et mécanique statistique/Recent advances in field theory and statistical mechanics.* Amsterdam: North-Holland, 1984. p. 473-523.
2. **Edwards S F & Anderson P W.** Theory of spin glasses: II. *J. Phys.—F—Metal Phys.* 6:1927-37, 1976. (Cited 95 times.)

 ©1985 by ISI® CURRENT CONTENTS®