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A principal component of the contract has been the development of the renormalization group, with specific emphasis on applications to percolation and random materials. The main accomplishment is summarized in a series of several papers. One of these was identified by the *Science Citation Index* as being among the 100 most-cited physics papers during 1980-1981. This paper dealt with the problem of how the Wilson renormalization

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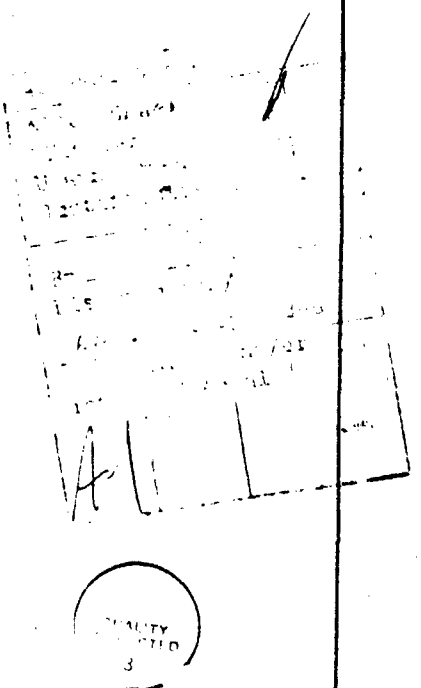
group could be applied to random systems in a fashion that yielded specific numbers that could be compared with real systems. The approach developed rests on the essential idea of percolation, that elements must connect across a macroscopic distance.

This approach was extended to continuum percolation shortly thereafter, confirming that results first obtained for lattice systems also hold when there is no lattice.

Other random systems, like linear and branched polymers, were found to be made tractable by the suitable modifications of our original approach. Keywords: Clusters; Nucleation; Metastable States;



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FINAL TECHNICAL REPORT

U.S. ARMY RESEARCH OFFICE

PERCOLATION AND LOW DENSITY MATERIALS: THEORY AND APPLICATIONS

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ABSTRACT

We have focussed attention on the many applications of percolation to low density materials of practical concern. To make progress, we have developed new concepts—such as directed percolation—and new mathematical analysis techniques—such as renormalization group. Two articles were among the 100 most-cited articles of the year.

Part I: Renormalization Group

A principal component of the ARO contract has been the development of the renormalization group, with specific emphasis on applications to percolation and random materials. Our main accomplishment is summarized in a series of several papers. One of these was identified by the *Science Citation Index* as being among the 100 most-cited physics papers during 1980-1981.[1] This paper dealt with the problem of how the Wilson renormalization group could be applied to random systems in a fashion that yielded specific numbers that could be compared with real systems. The approach developed rests on the essential idea of percolation, that elements must connect across a macroscopic distance.

This approach was extended to continuum percolation shortly thereafter,[2] confirming that results first obtained for lattice systems also hold when there is no lattice.

Other random systems, like linear and branched polymers, were found to be made tractable by the suitable modifications of our original approach.[3] Eventually the researchers involved in this project were invited to summarize both the fundamental method and it many applications in a review article which appeared as a chapter in a book on renormalization group.[4]

More recently, considerable emphasis has been placed on electrical and mechanical breakdown phenomena. It has come to be appreciated that a wide range of such phenomena can be described by the Witten-Sander model of DIFFUSION LIMITED AGGREGATION (DLA). The problem with studying DLA is that many of the traditional methods of investigation will not work. In particular, there was originally no renormalization group approach that gave realistic approximations to the actual properties of DLA. Accordingly, an effort was initiated along these lines under the auspices of this ARO contract.

The resulting paper, published in 1983, was recently identified by *Science Citation Index* as being among the 100 most-cited physics papers during 1983-1984.

In summary, the ARO contract contributed in a substantial way to a very active segment of research into the nature of random materials. This research was widely recognized by the scientific community, as evidenced by two of the papers having appeared on the lists of most-cited physics papers compiled by the *Science Citation Index*.

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Part II: Directed Percolation

Directed percolation is a generalization of the percolation problem in which a lattice may be randomly occupied by one-way bonds (diodes) instead of the two-way bonds (resistors) of the classical model.[1,2] There are several compelling physical reasons to investigate models of this type. For example, in strong-field hopping conduction processes, electrons are extremely unlikely to hop between impurity sites against the sense of the external electric field. This situation can be conveniently modelled by a random electrical network in which the sites are connected by diodes.[3] In addition, the temporal evolution of a number of simple chemical systems (described by Schlögl models) in d space dimensions, can be viewed as a directed percolation process in $d+1$ dimensions, in which the bias direction in the diode network plays the role of a time axis.[4]

In directed percolation, the salient feature is the existence of a global orientational constraint on all the diodes. For such a model, we have obtained a number of noteworthy results.[5,6] First, the percolation transition is fundamentally anisotropic in nature, in which two independent diverging correlation lengths, are needed to describe the geometry of the network near the percolation threshold. One length describes the mean extension of clusters along the bias, while the second describes the transverse spread of the clusters. Corresponding to the anisotropic nature of the percolation transition, we have shown that the upper critical dimension, d_c, for directed percolation equals 5, in contrast to $d_c = 6$ in isotropic percolation. We have also developed an anisotropic version of finite-size scaling[7] that has proved to be a powerful method for treating the geometrical features of directed systems.

We have also performed analog experiments[8] and numerical simulations[7] for the conductivity in directed peorcolation. From the experiments, we have elucidated the rather dramatic effect that the directionality constraint imposes on the current-carrying paths. Due to the very non-local topological nature of the conduction pathways, disconnecting just one bond in the network leads to surprisingly large perturbations at the network level. We have shown how to exploit this extreme correlation between the geometry of the network and the current flowing through it in order to obtain excellent quantitative estimates for the critical behavior of directed conductivity, with experiments and simulations of a relatively modest scale.

We have also introduced a much more general and rich model in which the orientation of the diodes may be random.[9,10] Such a model represents a logical extension of bond

percolation to incorporate degrees of freedom of an orientational nature. We have derived both exact duality relations, and exact topological relations that have facilitated a complete investigation of the percolation phenomena in this general network. As an example, we have unravelled the mysteries of "random Manhattan", a fully-occupied square lattice in which each bond is a randomly-oriented one-way path. We have demonstrated that this system is precisely at its percolation threshold, and that many of the geometric features of this network can be described exactly. There are a proliferation of new percolation transitions associated with this very general model, which are mediated by either concentration or orientational driving fields. The former influence underlies the conventional percolation transition, but the latter gives rise to rich multicritical behavior which we have elucidated in a complete fashion through the use of renormalization-group techniques.

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Part III: Clusters and Nucleation

One of the most interesting results to come out of percolation studies is the ability to characterize thermal systems in terms of percolation models.This has led to an increased understanding of critical phenomena as well as a significant advance in our understanding of metastability and nucleation.

Specifically we have shown for magnetic systems and fluids that critical points can be mapped onto percolation transitions[1] This allows us to give a geometric definition to critical fluctuations which for example allows us to assign to them a fractal dimension.

In a related development we have investigated metastable systems undergoing deep quenches. This is accomplished with systems in which particles interact with long range potentials.[2] Such systems are quite important in several materials applications since various lead alloys, Hydrogen in metals and systems with dipolar forces(most notably water) belong to this catagory. We found that classical nucleation theory as formulated by Becker and Doering is not valid in such deep quenches. The proper characterization of the nucleating droplet is in terms of percolation clusters.[3–5] The percolation models which are essential for the description of the nucleating droplet were developed wiyh ARO support.

Research projects which will be of practical importance to the ARO that will use these developments are at present focussing on the application of these concepts to heterogeneous nucleation in cloud and fog formation and cloud seeding.

We have also made some progress in understanding the modification of the nucleation process in super cooled liquids and have found that the spinodal which exists in liquids with long range potentials[6] and also in infinite dimensions[7] also significantly changes[8] the nucleation process from what one expects from the classical theory.[9]

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SUMMARY

YEAR	PAPERS	PHYS REV LETT / NATURE / PNAS CITATIONS
1976	1	0
1977	5	0
1978	4	1
1979	10	1
1980	21	0
1981	31	3
1982	44	6
1983	48	9
1984	49	9