Research Management

Phase transitions and cooperative phenomena in solid state science have analogies in management.

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The phase transitions and cooperative phenomena observed in solid state science are analogous to phenomena observed in the management of scientific research and in other organized human activities. Here I compare several kinds of dynamic, interacting systems, some microscopic, some human, to increase our understanding of them.

Cooperative Phenomena and Nucleation Centers

When a very pure liquid is slowly cooled a few degrees below its freezing point, it may remain in a supercooled liquid state for a long time. Once the change of phase from a liquid to a solid is initiated, however, it spreads rapidly through the material. The effect is cooperative; it is dependent on the interactions of many particles.

When a magnetic field is applied to a permanent magnet in such a direction as to tend to reverse the magnetization, the magnetization will not reverse unless the field exceeds a certain value called the coercive field (a marvelously anthropomorphic term which I hesitate to borrow for management science), even though the reverse polarization state is the one of lowest energy and is therefore the truly stable state. In other words, an individual magnetic moment is restrained from reversing its direction by the cooperative effect of all the other moments. Once the coercive field is exceeded, the polarization reversal proceeds quickly, particularly after some domains of reverse polarization are formed. Like the liquid-solid phase change, this switching is a cooperative phenomenon.

In large measure, phase changes and switches of emphasis in industrial research may also be thought of and dealt with as cooperative phenomena. To a scientist viewing the large industrial laboratories from the outside, it is often amazing to see the speed and apparent harmony with which large programs are dropped and new ones initiated. (Seen from the inside, the speed and harmony are sometimes less apparent.) What are the factors that either speed or block change?

First, scientific research is, indeed, a cooperative phenomenon. New breakthroughs in research generate excitement, which spreads through the community and attracts eager scientists into the new field. In phase transition terminology, the new research and the breakthrough researcher are nucleation centers for the program's phase change. In research programs, as in materials, phase changes are very difficult to accomplish without nucleation centers, even if a substantial external force (management pressure) is applied.

For a truly new direction of research —new to the world—program initiation is almost always a phase change unforced by management direction. It is facilitated only by recognizing individuals as actual or potential nucleation centers and by affording them the opportunity to generate new research. Often, however, management will wish to initiate in its laboratory new research lines that have appeared in other laboratories. The cooperative nature of research will motivate some of the scientists of the nucleation type to enter the new field, even though they did not start it. In magnetic or ferroelectric terminology, domains (another anthropomorphic term) of the new program will then form about these nucleating individuals, and a carefully applied managerial force will encourage these domains to grow. Even if only very limited monitoring is desired, this positive applied force is important since, in the process of cluster formation (preceding domain formation) about a nucleating center, the cluster must grow to a certain critical size or it will not be stable.

Of course, not all new fields of research are appropriate to the area of interest of a particular laboratory. If nucleating centers of unwanted activity spring up in the laboratory, an opposing managerial force will discourage the formation of domains. The creative nucleating individuals will be expected to adapt their interest to a more appropriate field, but they do not always do so. One objective of intelligent scientific management is to determine the optimum density of nucleating centers in a laboratory; another is to determine when some or most of these centers should be subject to almost no external forces (freedom of research) and when positive or negative forces should be applied to encourage or discourage the growth of particular research fields.

Managerial Phases and Phase Reversals

The managerial phase transitions are motivated either by technological development or by changing philosophies of management. It is not unusual to find reversals of earlier management phases in both situations.

In the 1950's industry had a phase of interest in ferroelectric phenomena, which was partly motivated by the potential usefulness of ferroelectrics as reversible memories for computers. Recording a binary one or zero corresponds to switching between two stable polarization states of the material. Industry initiated research programs in fundamental materials and investigations of exploratory devices aimed at achieving useful memories. The physical phenomena proved less useful for these applications than their magnetic counterparts, however, and most of these programs were dropped by 1960. Coincidentally, in 1960 a new development, the laser, provided strong motivation for achieving rapid modulation of light. It was soon realized that ferroelectric materials had a property that differed from but was related to their reversible switching characteristics —namely, their large electrooptic coefficients—and that this property made

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them promising for use as laser modulators. Related useful interactions of light with transparent ferroelectric and piezoelectric materials were also found. Thus new fundamental research in ferroelectric materials and the exploratory device programs began in the decade of the sixties.

The possible relevance of superconducting phenomena to computer memory and logic has also gone through two phases. The first phase was initiated by Dudley Buck's invention of the cryotron. Buck's cryotron was a computer memory element based on switching superconducting currents between alternate paths; it was reversible and free from dissipation. Developmental activities stopped, however, when the device speeds were found to be relatively slow (of microsecond rather than nanosecond magnitudes). Also, the technological problems of reliable fabrication and operation remained unsolved. More recently, the discovery of Josephson tunneling produced a faster version of the cryotron, which introduced a different (perhaps more difficult) set of technological problems that have initiated new research programs and reawakened interest in development programs.

The reversals in phases of scientific management activity just described resulted from technological developments. I have also referred to changes in management philosophy, by which I mean, for instance, changes in emphasis from basic to applied research or from applied to basic. We are currently going through a national phase of increased emphasis on applied "mission oriented" research (perhaps more accurately described as decreased emphasis on basic research) in both government and industry. More generally, however, emphasis in particular laboratories or in particular fields shifts from time to time from research to development, from development to research. To some extent, the technologically motivated phase changes discussed above were accompanied by such philosophical phase changes.

Another example is the long history of basic research in magnetic phenomena and materials, paralleled by an equally long history of practical applications. Often there have been tenuous and indirect links between the two streams of activity. In the fifties, however, intense development and application activities began after the discovery of the importance of a class of magnetic insulators, the ferrites, in the application of computer memories. (These materials are the ones that prevailed over ferroelectric memories.) With the maturing of this field, there has ensued a renewed period of searching and exploring into other properties of magnetic materials. Of current interest, for instance, are combined magnetic and optical phenomena analogous to the electrooptical resurgence of ferroelectrics, or combined magnetic and electrical transport phenomena (magnetic semiconductors). If research efforts in these fields achieve sufficient success, a new wave of developmental activity may be expected and, indeed, is to some extent already under way in magnetooptic phenomena. These examples are chosen as counterexamples to the idea that change either is or should be always unidirectional. The forward march of technological progress is always accompanied by changes in emphasis that reach back into the past to accomplishments and philosophies that may have been temporarily abandoned or forgotten.

Let us consider again some solid state analogies. In growing single crystals of complex composition by cooling from a melt, minority phase inclusions are often incorporated within the majority phase. Usually these are deleterious to the desired properties of the material, and great care is taken to eliminate them. A related phenomenon is the retention of reverse polarization phases in the switching of ferroelectric and ferromagnetic materials. Here there is a more subtle balance between desirable and undesirable effects. The physical effect utilized, the permanent moment of the material, is indeed diminished by these reverse domains. On the other hand, the speed of the switching process is increased, and the work done in the phase reversal is diminished by the inclusion of these reverse domains. Without them, higher coercive fields would be required to initiate domain formation at nucleation centers, and it would be necessary to wait for the formation of the domains. (In the absence of nucleation centers the reversal process would be even more difficult.)

The analogy to be drawn in management science is that, in circumstances where some phase reversals are expected and are desirable, it is best to maintain an environment that encourages the retention of some inclusions of the old phase or the reversed domains. (In other words, our thoughts should not all be polarized in the same direction.) This retention is particularly important in reversals of management philosophy, which can be anticipated with greater certainty than reversals of emphasis on particular technological fields. After all, some fields attain a fairly permanent maturity or decline, and domains of research cannot be retained in all potential fields of interest. For potential developments it is adequate to rely on nucleation centers. Indeed, a careful analysis of some of the technological research fields already cited would probably reveal an intermediate situation in which the domains of new research programs in once abandoned fields were formed about new nucleation centers. In these instances, however, the scientific and managerial climate retained much local knowledge of the old field and therefore reduced the activation energy of the domain formation. It can thus be seen that laboratories that are large enough to maintain some fields in research and others in advanced development phases have an advantage. The appropriate management philosophies can also coexist and can grow or diminish in specific fields by sidewise domain wall motion, a phase equally descriptive of solid state and some managerial phenomena.

Dynamics of Switching Phenomena

It is well known that in reversible ferromagnetic or ferroelectric switching processes a definite amount of work is done in each switching process and that twice this work is done each time one returns to the original state of the system, even though the system is not then in a different state than before the expenditure of this work. In this solid state example, the material may produce a useful output only when switched, or it may produce an output while in each of its switched states. The information on a magnetic tape, for instance, may be read many times before new information is recorded by applying new switching forces.

The management science situation is more subtle. There a phase change is initiated because the research or development activity of a particular group is observed to be or predicted to become less useful to the company's objectives than is expected for the new phase of research. Such changes are necessary; the question we are exploring is the optimum frequency of these changes. The estimate of this optimum frequency should include a balance of the expected advantages of specific changes (which we cannot explore here) with the *irreversible losses* that accompany the switching process as a result of dissipation in the generation of unproductive heat and friction.

Unproductive work is particularly evident in cyclical situations where the new laboratory phase coincides with an earlier one. As already noted, these cyclical changes are normal and to a certain extent predictable in management philosophy (research versus development), even though they are unpredictable in specific technological fields. The more frequent the phase reversals, the more unproductive the work done; the power dissipated is the product of the work done per cycle times the frequency of the reversals.

The problem is even more serious, however. Switching processes take time. The growing domains involved have walls that have physical limits to their speed of motion. Often this limit can be characterized by a mobility, so that the velocity of motion is a product of the effective applied field multiplied by the mobility. Rapid switching can be achieved only by applying a high driving field that increases the work expended during the switching process. (The effective field is enhanced or diminished by the cooperative effects already alluded to.)

If the rapidity of attempted phase (polarization) reversals becomes too great, only partial phase transitions are accomplished or, indeed, none at all for too high a forcing frequency. Thus, if analogies to management situations are valid, the dangers of seeking to impose too frequent cyclic changes of direction are not only that unproductive work may be expended but also that the desired changes may not be accomplished in time to be in phase (in the electrical circuit theory sense) with the applied managerial force. Indeed, phase lags are well known in alternating current theory and become 180° out of phase with (that is, diametrically opposed to) the driving force if the forcing frequency greatly exceeds the pertinent resonant frequency of the system.

These thoughts lead to two related management philosophy questions: What are the natural human "resonant frequencies" or "domain wall mobilities" that limit the response frequency of human systems? Once these natural frequencies are known, what is the optimum driving frequency of managerial change? These questions are not trivial, nor do they have obvious answers. For instance, in the electrical analogs it is often desirable to drive the system at or near its resonant frequency because, even though the dissipated work is greatest there, the useful work done is also greatest. Sometimes, however, the wear and tear on the material is excessive under these circumstances, and the driving frequency must be lowered to a more tolerable level. (Dissipation is also lowered by imposing a driving frequency higher than the resonant one. However, as we have seen, the system simply lags behind the driving force and no useful work is accomplished.)

The technical reader will note a mixing of analogies between resonant linear systems and nonresonant nonlinear systems in the preceding comments. In both systems, however, excessively high driving frequencies are nonproductive of useful end results, and excessive dissipation, heat, and general wear and tear may occur at driving frequencies that might seem optimum from simple systems analysis. There are, in other words, problems of lifetime and reliability in the components. At very low driving frequencies a shelf-life deterioration problem takes over. Similarly, people in a nonproductive environment cannot be stockpiled or their performance will deteriorate. These considerations indicate the complexity of the problems involved in optimum timing of managerial change and also indicate the necessity of avoiding the extremes of working at very high, very low, or resonant frequencies.

Continuity versus Discontinuity in Phase Changes

In thermodynamics, phase changes are characterized as being of first or second order, depending on whether certain properties of the two phases change gradually and continuously at the phase boundary or whether they experience a discontinuous mismatch. For instance, the polarization of a material goes gradually to zero in a second-order transition, whereas it drops discontinuously from a finite value to zero at a first-order transition. Dimensional changes, either gradual or discontinuous, accompany these polarization changes. The resulting strains sometimes shatter a material whose polarization is changed by a first-order phase transition. On the other hand, a material whose polarization can be changed by a gradual second-order transition is less susceptible to damage. In the jargon of lattice dynamics and ferroelectricity, the phase transition is accomplished by means of a soft mode, one whose resonant frequency goes to zero at the phase transition, so that the phase change is accomplished gradually, with time for the material to adjust to the new phase.

There are also hard and soft modes of accomplishing managerial phase transitions. Change effected by a hard mode may be a shattering experience, whereas a soft mode may accomplish the change almost unnoticed.

Conclusion

Although solid state science and management of scientific research are very different subjects, the similarity in terminology results from real similarities observed by the humans who coined the terminology for both subjects. Of the two fields, scientific mangement is surely the more complex. Its very complexity leads to a drive for simplistic solutions that can be made comprehensible to the nonscientist. Indeed, there is a need for as simple and communicable a philosophy as possible in this subject.

The analogies in this article will remind us that no solution will be effective if it does not make full use of the talented individual (the nucleation center). The examples in nature of cooperative phenomena influenced by applied forces will suggest to individual scientists that their work assumes significance only in the broad context of its influence on other scientists. Their work in turn will reflect the influence of others and will also reflect the environmental forces under which the research is conducted.