Materials Science and Applied Science

Focusing on interaction between multiple scientific disciplines is the key to uniqueness.

William A. Tiller

I belong to that group of people who believe that "philosophy should be the precursor to action." Thus, when I had an opportunity to become involved in the management function of the materials science department at Stanford University, I saw it as an opportunity to seriously think about the character and uniqueness of materials science, its origins, its limitations, and its future capabilities. This article contains my initial thoughts on the subject. The philosophy presented applies very generally to the total field of applied science, of which materials science is a part. Thus, although I emphasize materials science as a pertinent example, the concepts and notions discussed in that frame of reference are readily transferable to the broader field.

My purpose in writing this article is to try to articulate in an orderly framework what many of my colleagues have felt intuitively for years. Not for the teacher or student alone have I set down these ideas, but for the general applied scientist, the metallurgist, and the materials scientist, in the hope that he may come to know himself better and have a greater awareness of his talents and of the characteristics that make him "special."

Since metallurgy is the parent of materials science, it seems relevant, before considering the latter, to discuss metallurgy relative to the more basic fields of science. Going back one step further, I begin by examining the purpose, goal, and methods of scientific investigation.

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Patterns of Science

Why are we concerned with science at all? The answer is fairly simple: man wants to understand the milieu in which he find himself. He wants to engineer and control as much of his environment as possible in order to sustain and enrich his life. Science and engineering appear to have complementary goals: that of science is the reliable prediction of behavior as a function of ever-changing environment; that of engineering is the generation of materials, devices, attitudes, moralities, philosophies, and so on, for producing order and expanding human potentialities in this environment. (These are personal definitions rather than generally accepted ones.)

As to the patterns of science, the time-honored method of inquiry treats a phenomenon under study (which may be the result of a single event or of an ensemble of interacting events) as a black box whose internal characteristics are unknown but are amenable to probing and analysis. Such a situation is illustrated in Fig. 1a: we apply some input stimulus (I.S.) to the box and determine some output response (O.R.). By correlating the output response with the input stimulus, we deduce information about the most probable behavior of the box for this degree of variation of the stimulus. We then speculate on models that would reproduce such a spectrum of responses and design critical tests for discriminating between acceptable models. With time, man has learned to recognize clustered phenomena and to dissociate them so that isolated phenomena can be probed and modeled in great detail. This discrimination into isolated phenomena has led to the disciplines of physics, chemistry, mathematics, and so on.

Our first steps toward determining the behavior of the black box of Fig. 1 is to characterize it in the following form:

$$\frac{\text{O.R.}}{\text{I.S.}} = f(\epsilon_1,\epsilon_2,\ldots\epsilon_i\ldots\ldots\epsilon_n;\ X_1,X_2,\ldots X_i,\ldots\ldots X_n) \qquad (1a)$$

$$\approx f'(\epsilon_1\ldots\epsilon_j;\ X_1,\ldots X_k);\quad \epsilon_j^{*} \lesssim \epsilon_j \lesssim \epsilon_j^{**},\quad X_k^{*} \lesssim X_k \lesssim X_k^{**} \qquad (1b)$$

for all indices, $j,k = 1,2\ldots m$.

In Eq. 1a, f represents the true functional relationship between all the possible material parameters ε_i and the variables X_i of the system, where unlimited range is allowed for these parameters and variables. In Eq. 1b, the observed functional relationship f' between a limited but seemingly sufficient number of the parameters and variables is indicated for bounded ranges of the parameters and variables. For the disciplines of mathematics, physics, and chemistry, j and k are generally small, and f' is determinable to a high degree of accuracy. With the passage of time, our sensing capacity increases, so that j and k tend to increase and the bounded ranges of the parameters and variables increase ($\varepsilon_i^{**} - \varepsilon_i^{*}$ increases; $X_i^{**} - X_i^{*}$ increases). One tends to forget that the entire fabric of nature is represented by Eq. 1a and that man has restricted his view to conform to Eq. 1b in order to make a manageable assessment of a part of the fabric; that is, he focuses his attention on one thread of the fabric in order to find reproducibility and thus reliable behavior in this restricted domain. This generates *knowledge* of the thread, which is different from *understanding* of the fabric. Some individuals recognize this difference; many do not.

In a large number of the real situations that we encounter in life, the events that we wish to understand and control involve the treatment of clustered phenomena which interact strongly with each other and must be considered in association. Such events—in metallurgy, medicine, technology, business, politics, history, and so on—may be treated as events conforming to Eqs. 1a and 1b; however, we find that j and k tend to be extremely large, many important ε_n and X_n must be neglected, and f' is poorly defined, even for very

Table 1. Crystallization variables and parameters.

Areas of study	Boundary-value problems	Material parameters*	Interface variables*	Macroscopic variables*	Constraints
Phase equilibria		ΔH, T_o, k, m_L		$T_L(C_\infty)$	
Nucleation		N, ΔT^+		t	
Solute partitioning	Diffusion Eq. (C)	D_S, D_L k_i	C_i, T_L (C_i) V, S		
Fluid motion	Hydrodynamic Eq. (u)	ν	δ_i	u_∞	C_∞
Excess solid free energy		γ, ΔS, $\sum_n \gamma_n^F$, $\sum_n N_n^F$	T_e		$\dot{T}$
Interface attachment kinetics		β_1, β_2			
Heat transport	Heat Eq. (T)	K_S, K_L α_S, α_L	T_i	T_∞	
Interface morphology	Perturbation response and coupling Eqs.				
Defect generation	Stress Eq.				

* ΔH, latent heat of fusion; T_o, melting temperature of solvent; k, solute distribution coefficient; m_L, liquidus slope; N, parameter related to area of nucleation-catalyst surface; ΔT^+, parameter related to potency of nucleation catalyst; k_i, interface partition coefficient; D, solute diffusivity; ν, kinematic viscosity; γ, solid-liquid interfacial energy; ΔS, entropy of fusion; γ_n^F, fault energy; N_n^F, number of faults of type n; β, parameter related to interface attachment kinetics; K, thermal conductivity; α, heat diffusivity; δ, boundary-layer thickness; T, temperature; t, time; C, concentration of solute; u, fluid velocity; V, freezing velocity; S, shape of crystal. The subscripts S, L, i, ∞, and e are, respectively, solid, liquid, interface, far-field liquid, and equilibrium.

restricted bounds of ε_i and X_i. Thus we are confined to a "recipe" or "art" mode of operation in these fields. A better way of characterizing such events is represented schematically in Fig. 1b, and mathematically in the following equations:

$$\frac{\text{O.R.}}{\text{I.S.}} = g[f_1, \ldots f_n] \qquad (2a)$$

$$\approx g'[f_1', \ldots . f_j'] \qquad (2b)$$

where the f_i and the f_i' are of the form represented by Eqs. 1a and 1b and where g and g' represent, respectively, the exact and the observed functional relationships between the various f_i and f_i'. For such association phenomena, in the analysis or representation, the f_i' can be treated as elemental parts or subsets in the overall system or ensemble, and, although the f_i may be well characterized for certain disciplines, we must expect the initial reliability of g to be fairly poor.

In order to develop a science of events that conforms to Eqs. 2a and 2b for a considerable range of variation of the ε_i and X_i, we must develop methods of systems analysis for analyzing the events. The steps to be taken appear to be (i) identifying the critical and individual phenomena included in the single black box that encompasses the associated event (that is, identifying the f_i in Eqs. 2a and 2b—boxes A through E of Fig. 1; (ii) gaining an understanding of the f_i in isolation, so that a quantitative response spectrum can be determined for a quantitative input stimulus; (iii) gaining an understanding of the f_i as they interact with various of the other f_j in pairs, triplets, and so on; and (iv) partitioning the total potential for the associated event into the potentials consumed by the various elemental f_i as they interact with each other, and evaluating the spectra of these potentials. The use of mathematical tools is essential for such a science.

As an example, suppose we want to predict the structure (grain size, shape, degree of macro- and microsegregation, and so on) of a volume v of binary alloy liquid having a solute content C_∞, that is held at some superheating temperature T_o at time $t = 0$ and is then cooled at its outer surface at a given cooling rate $\dot{T}$ per unit area of surface. To make this prediction it is necessary to discriminate at least nine separate f_i, indicated in Table 1 (*1*); moreover, at least 20 material parameters, at least 7 interface variables which control the processes going on at the interface between the crystals and the liquid, and at least 5 major field equations must be considered. If one relied solely on the philosophy represented in Eqs. 1a and 1b, it would be relatively impossible to predict the behavior of one system on the basis of the performance of another, since the variation of any one of the parameters or variables leads to large variability in the morphology of the growing crystals and thus in the resulting structure of the solid. When one uses the approach of Eqs. 2a and 2b the problem becomes manageable and one can partition the total excess free energy driving the total reaction at any time into the partial excess free energies consumed by the various elemental f_i in the system as a function of time (*1*). It is only by using the approach of Eqs. 2a and 2b rather than that of Eqs. 1a and 1b that this basic metallurgical problem has become manageable; that is, we have reduced it to the simultaneous solution of nine interrelated physics problems.

As a second example to illustrate the interaction between the disciplines of matter transport and thermodynamics, let us suppose that we have a liquid containing several chemical species of average concentration $\overline{C}_1, \overline{C}_2, \ldots . \overline{C}_i, \overline{C}_j$ and that we wish to find the time-dependent concentration C_i of the constituent i at a particular point in space, (x,y,z), as a function of an applied electric field E. Using Eqs. 1a and 1b we obtain

$$\frac{C_i}{\overline{C}_i} = f_i[x,y,z,t,M_1 \ldots . M_j, \overline{C}_1 \ldots . \overline{C}_j, T, \nu, \rho, E, \sigma, \ldots .]$$

where M_j is the atomic mobility of the j species in the liquid, T is temperature, ν is kinematic viscosity, ρ is density, and σ is electrical conductivity; some other parameters have probably been neglected. Using the approach of Eqs. 2a and 2b, one would first say that C_i is given by a solution of the transport equation

$$\nabla(J_i + uC_i) + Q_i = \frac{\partial C_i}{\partial t} \qquad (3a)$$

where u is the convective velocity of the fluid which arises as a result of density differences caused by temperature variations and as a result of electromagnetic forces, Q is a source term to take account of any generation of species i in a unit of volume, and ∇ is the differential operator, and where the diffusive flux J_i is given by

$$J_i = \sum_k L_{ik} F_k \qquad (3b)$$

Here the L_{ik} are coefficients and the F_k are the forces present in the system. For example,

$$L_{ii} = M_i$$

and

$$F_i = -T \, \nabla \left(\frac{\mu_i}{T}\right)$$

where μ_i is the electrochemical potential of i, which is given by

$$\mu_i = \mu_i^0 + RT \ln \gamma_i X_i + \sum_j \mathcal{E}_j^i \quad (3c)$$

In Eq. 3c, μ_i^0 is the standard-state chemical potential, R is the gas constant, X_i is the mole fraction of i, γ_i is the activity coefficient of i, and $\mathcal{E}_j^i$ is the interaction energy of i with the various fields in the material—that is, electrostatic field, stress field, and so on. Again, from thermodynamics, we can evaluate γ_i as

$$\ln \gamma_i = \ln \gamma_i^0 + \sum_j \varepsilon_{ij} X_j + \ldots . \quad (3d)$$

where ε_{ij} is an interaction coefficient between the jth and the ith species.

We should note that, although Eqs. 3a, 3b, and 3c and the relevant additional equations appear to be somewhat complicated, they allow us to completely specify the problem (provided we specify the electrodynamic, heat, and hydrodynamic equations) and to see the interactions between its subsets. Using analytical procedures or a computer, we may obtain the desired information.

I am not proposing that the successful description of some multiple-associated event in science or of some piece of technology should be derived by such pencil-and-paper procedures. Nor am I implying a weakness of the basic philosophy or analytic procedures. Rather, I am trying to be realistic about a fundamental characteristic of man that makes him interested in events that challenge his imagination and stretch his limitations. Stated another way, man generally seeks a successful systems solution with knowledge of only a fraction of the pertinent information. If he knows all the facts needed for such a systems analysis, he is generally no longer vitally interested in the solution. Because of this characteristic, the total path to gaining a successful solution to such systems problems consists of two segments: (i) a scientific trajectory based upon the available information and (ii) an empirical study of the system. Both segments are of vital importance to the success of the endeavor.

Figure 2 illustrates the ratio O.R./I.S. for the system in some hyperspace where the coordinate axes are the independent variables $\varepsilon_1, \ldots . \varepsilon_j, X_1, \ldots . X_k$; for purposes of illustration I use a "three-dimensional" representation, in which O.R./I.S. forms some surface with ε_i and X_i. Let our starting position for some state of the system be at point A, and let one of the possible "success" locations be centered at B (the others are not shown in Fig. 2). The question we now ask ourselves is, Starting at A, how do we find B? We note that our scientific trajectory takes us to point C, which is located somewhere in a volume increment ΔV, of this hyperspace, which includes B. The size of ΔV depends upon the accuracy of our scientific analysis and the reliability of the input data. With point C as center, we make an empirical study of the surrounding volume V of the hyperspace, that just includes B. Let us call this the "domain of credibility" for finding the success point with a reasonable expenditure of time and effort. We may think of this volume V as a hypercube of side d and may want to make experimental investigations at some average grid-spacing λ. The number of experiments, Q, needed to map the behavior of this hypercube is given by

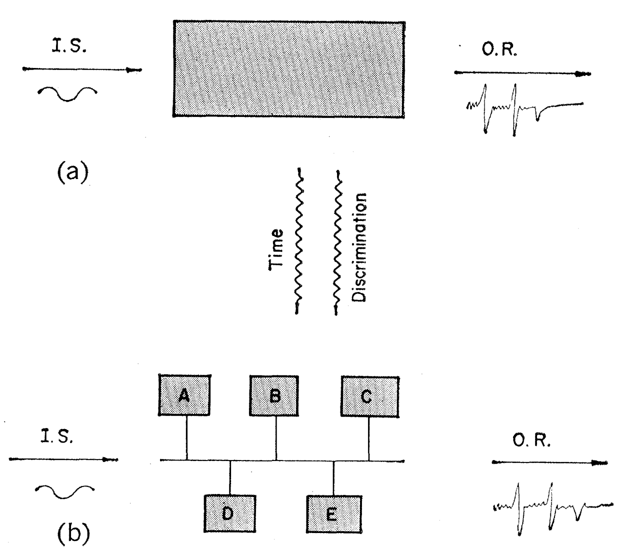
$$Q = \left(\frac{d}{\lambda}\right)^p \quad (4)$$

where p is the total number of parameters and variables chosen as coordinates of this hyperspace (we have conveniently neglected the uncertainty of C and the volume of relative success surrounding B). If the average time per experiment is τ_o man-days, the total time τ for the empirical study is given by

$$\tau = \tau_o Q \quad (5)$$

The cost of the empirical study will be proportional to τ (to a first approximation).

To illustrate the importance of Eq. 5, let us suppose we are considering



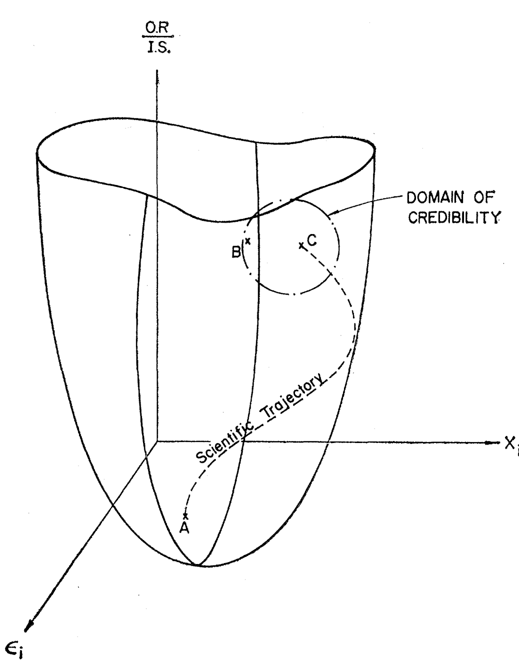


Fig. 1 (left). Schematic representation of (a) the "black-box" approach and (b) the "system" approach for studying nature; I.S., input stimulus; O.R., output response. Fig. 2 (right). "Three-dimensional" representation of O.R./I.S. correlation as a function of two of the natural system variables, ε_i and X_i, illustrating the complete path needed to proceed the "success" location B from the starting state A.

an elementary event where $p \simeq 3$, and let us choose $\tau_0 \simeq 1$ man-day; that is, we are considering a typical physics problem. Let us suppose that we can afford only 3 man-years for the study—the typical duration of work for the Ph.D. Then, from Eqs. 4 and 5, we find that $d/\lambda \simeq 10$, and we can thus develop and test fairly detailed models. For this example, a fairly reliable pattern of behavior can be mapped and real scientific understanding generated. As p increases to about 10, as we find to be the case in a typical engineering problem, d/λ decreases to about 2 for the same τ/τ_0 ratio, so only a very coarse grid of experimental points has been staked out in our hypercube of side d, and only the crudest of models can be tested with this number of data. Such a limited study is, at best, only able to provide a rational explanation of behavior; it does not fulfill the requirements imposed by my definition of science (by using dimensionless grouping of variables, p can be significantly reduced). As p increases to about 20 to 30, as it does in many real events encountered in metallurgy, d/λ is only slightly larger than unity, and only a narrow band of behavior is charted in our hypercube with this number of data. If, by chance, the success point B is intersected by this band, the result is a single path or trail through the unknown surroundings (that is, a recipe).

At this point we begin to see why metallurgy has been largely an art up to the present, whereas physics has been a science for a few hundred years. Moreover, if it has taken this long to begin to transform metallurgy into a science, we begin to realize how long it will be before medicine and sociology (for example) can be reliably classified as sciences. Both these fields are characterized by multiparameter, multivariable interaction events with large p. In the case of medicine, each of the parameters is a function of the condition of the body. In the case of sociology, the parameters are a function both of the environment and of the evolutionary history of the environment (that is, of long-time constant phenomena). One might guess that transformation from an art to a science might take several hundred years for medicine and perhaps thousands of years for sociology, if the philosophy represented in Eqs. 1a and 1b is followed for these systems of thought and practice.

One can also begin to understand

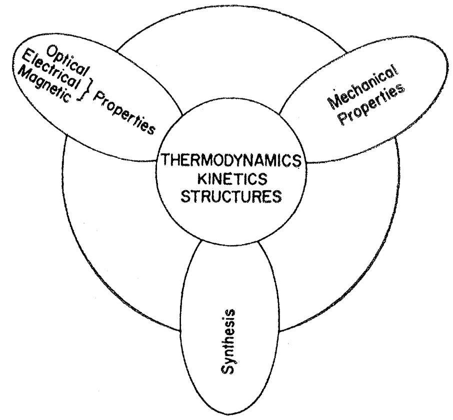


Fig. 3. Schematic representation of the basic activities of Stanford University's materials science department (see text).

why metallurgists make good managers, businessmen, and politicians. It is because they have, either intuitively or consciously, learned to accept and handle the problem of multiparameter, multivariable interaction events. They tend naturally to seek a balance between a seemingly large number of forces or options which gives the best compromise among the properties desired in the material or the process (the system). In this respect their closest counterparts are the chemical engineers.

It is important to emphasize the fact that *both* the scientific-trajectory component and the empirical component are necessary parts of the path to understanding and achievement in these areas of endeavor. As the complexity of the system increases (that is, as p increases), the accuracy of the scientific trajectory must be increased because the size of the "domain of credibility"—the size of the area that can be surveyed with a given number of man-years of effort—is decreasing.

Many people have hypothesized that, as our scientific knowledge increases, the delay time between scientific discovery and technological innovation should decrease. This is certainly true if p is held constant. However, as time passes and our scientific understanding grows, so also does the demand to control, within narrower limits, more variables and parameters in the systems event. Thus, p tends to increase also, and thus the required time from discovery to innovation (and the cost) does not generally decrease as our scientific knowledge increases. In fact, it may significantly increase.

In the future, we will probably need to develop techniques other than orderly empirical investigation of the region of hyperspace between C and B in Fig. 2. One of these techniques will probably be trained intuition. Anyone who has played charades with a group where men compete against women knows about the reality and the power of intuition. Men generally approach the game logically and proceed to the answer in an orderly and clear fashion, with each clue built upon the framework suggested by the other clues. The women, on the other hand, seem to start out in a random fashion in the wrong direction and suddenly leap to the immediate vicinity of the answer. In my experience, they always defeat the men! Can one doubt, with such a display, the usefulness and reality of intuition? This is a technique that can probably be taught and learned, and it is probably the method used unknowingly by many of our best development people to reduce the empirical work involved in technical innovation.

Materials Science

Finally, we come to the topic of materials science. Today there appear to be two states of mind concerning the essential character of this science. To some people it is solid-state physics applied to all materials; that is, it is a discipline. To me, materials science means metallurgy grown up to the stage where interest and experimentation are extended to all materials and, furthermore, where an attempt is made to quantitatively evaluate the multivariable, multiparameter problems encountered with these materials. Thus, materials science is not a discipline in its own right but is an area where disciplines converge to give balanced understanding about real problems; that is, it deals with an ensemble of interacting phenomena, where the important characteristics of the event are associated with the interactions.

Because its ancestor is metallurgy, the core of materials science's uniqueness lies in its special concern with thermodynamics, phase transformations, and the defect structure of solids. Materials science interacts with its technical environment largely through understanding of the behavior of materials and their structure and also through the ability to manipulate the defect structure by controlled synthesis in such a way as to generate desirable properties. Materials science may be likened to the three-bladed propeller of Fig. 3. One blade represents research concerned with mechanical properties—the historical domain of the metallurgist. Here we have considerable technological knowledge, but the field is in need of more basic science. The second blade represents work concerned with the electrical, optical, and magnetic properties of materials—the historical domain of the solid-state physicist. This area is rich in basic science but is in need of more technological understanding. The blade labeled "synthesis" represents activities concerned with the controlled preparation of a material in a certain state of aggregation to give optimum properties. This area is only now becoming enough of a science so that predictable and fine-gauge control of properties is possible.

It seems likely that university departments of materials science will extend their interest to polymeric materials, and then to biological materials. One can readily imagine the day when such departments might consider the synthesis of a particular hormone by a suitable controlled reaction between primary molecules on a catalytic substrate that is made electrically active by specific optical pumping. These departments will probably enter such areas of endeavor because of two factors: their interests are sufficiently broad to encompass all the technical aspects of the problem, and (more important) their state of mind is such that they do not boggle at the seeming complexity of such events.

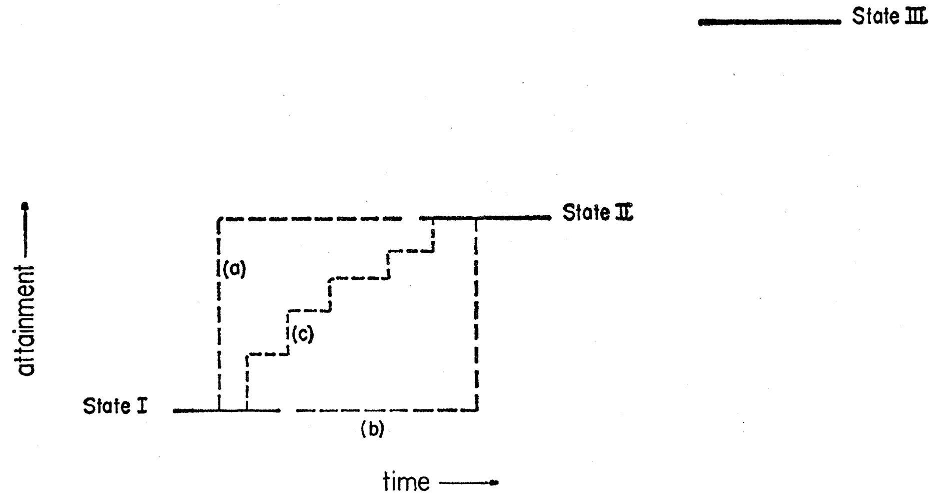


Fig. 4. Representation of the evolutionary transition (*c*) relative to the revolutionary transition (*a* or *b*) between the levels of attainment (states I, II, and III).

Strengthening of Student Perceptions

At the moment there seems to be insufficient appreciation, on the part of most students and some faculty, of the total system, from specific phenomenon-oriented understanding to the ultimate application of knowledge. Thus, perspective on, and attunement to, the larger picture is needed, and an intellectual awareness of the important subroutines must be generated. Just as one knows that the failure of only one component in a space probe is often sufficient to abort the entire mission, the student must learn that reliable prediction for the system requires reliable prediction for ever single one of the subroutines and their interactions.

In the distant past, students treated their problem areas in the manner of Fig. 1a. More recently, the discrimination process of Fig. 1b became operative, and students began to dig into the particular subroutines of the system with "laser-like" concentration, to the exclusion of concern with the total system. This has been a very natural development, psychologically, and it is important that a particular student develop expertise in one of these subroutines. However, the exclusiveness of this penetration or specialization threatens to decouple the system, and students of materials science are in some danger of losing their prime function—that of competently handling systems problems. It is time they progressed to the next stage of the evolutionary process represented in Fig. 1b—that is, while maintaining expertise in one of the subsets of the system, to understand, work with, and appreciate the other subsets, their interaction, and the overall function of the system. Thus they will come to know the ultimate value and relevance of their work to the immediate as well as the long-range goals.

At the moment, many students in the area of materials science show inadequacies in their awareness of mathematics and in their mathematical skills. On the average, students in this area do not use mathematics as a comfortable and trusted tool to increase their understanding. This is a pity because we can recognize three distinct paths to knowledge: (i) totally experimental, (ii) theoretical and analytical, based on idealized models and variable parameters, and (iii) theoretical and numerical, based upon much more exact models with specific parameters. As pointed out above, one needs to deduce the locations of certain "domains of credibility" wherein states of success lie; for this, we need the second and third paths. To gain the final success point, we need the first path. Although the interactions between the subsets of our system are often sufficiently complex that analytic solutions must relate to a model too idealized to be exactly relevant, the differential equations that govern the time-space change of our variables are well specified. Further, the boundary conditions are generally also well specified over the contours of the domain that contains our problem; thus, a computer solution is definitely possible and will, I feel, become the most effective path to the "domain of credibility" once the students have learned to use such a solution creatively.

Because of a present lack of awareness of the uniqueness of this technical area, the application of knowledge is insufficiently appreciated.

We must ask ourselves why many American companies are seeking employees from graduates with B.S. and M.S. degrees, rather than from those with the Ph.D. They say it is because the former can be of more use to them. This means that our total educational system is out of balance: the more education you receive past a given point, the less valuable you become. I'm sure the fault lies with both the student and the company. In the minds of many students, the application of knowledge to technological problems appears to have lost intellectual status. Is this because we are breeding an intellectually sterile group of students, or is it because the students have been taught great skills without having been taught how to use these skills with assurance and pride to solve practical problems? I prefer to think that it is the latter, and that the systems viewpoint, on the part of both student and management, will make it possible to state a practical problem in such a way that a student can continue to grow as he generates the solution. I fear that the present problem-solving procedure in some industries makes the student stagnate rather than grow, and that he tends to avoid this procedure like the plague. We have educated him too much to have him go back and solve real problems in the "old" way—that is, in the way shown in Fig. 1a; rather, we must complete his education so that he can solve these real problems in the "new" way (that of Fig. 1b).

If we look at the solid-state electronics industry, we see that, in fact, may Ph.D.'s are happily and gainfully employed in practical pursuits. I feel that this is because the technology in this industry is so sophisticated that management cannot merely give lip service to the scientific method—the system event is so large (the value for p is so high) that getting even remotely close to a domain of credibility requires scientific guidance. Perhaps, if we get our psychology and our intellectual capabilities in balance, we can even utilize graduates with a Ph.D. degree to run our foundries (as is common practice in Europe), and to do so effectively and happily.

In general, all students need to understand that changes occur by evolution rather than by revolution, and that everyone has his own optimum learning curve. The intellectual skills of the student of today are impressive; however, he seems to have an inadequate perception of himself as an evolving element of an evolving system, dependent on other elements as they are on him, and to be insufficiently aware that the subsets and the total system must follow different learning curves because of differences in their states of evolution and in the totality of their constraints. Figure 4 represents certain evolutionary goals (states I, II, and III) for an individual or a system; although it is the individual's will that provides the driving force for the transition from one state to another, it is his optimum learning curve that determines the path. Paths a and b are likely to be destructive and unattainable. Path c is determined to be the optimum one, which is likely to be somewhat different for the various subelements of the system; it must be the one that gives growth accompanied by continued confidence and by regeneration of spirit. It is only through acceptance of this simple viewpoint that either a subelement or a total system can put itself on a path of conscious development without the catastrophe of ultimate discouragement. Also, we should remember that our sensing of our changing environment is somewhat analogous to the action of a pendulum—we recognize the position of stability only when we have passed it.

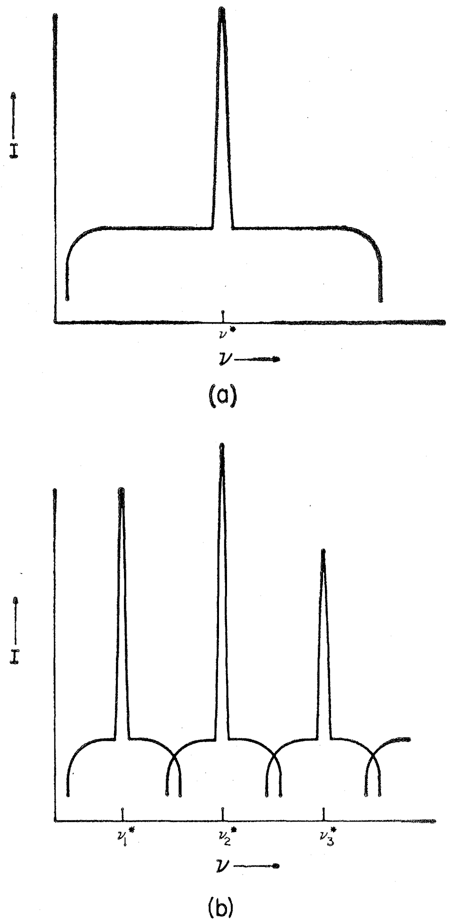


Fig. 5. Schematic representation of the output intensity I of students as a function of an "effective" frequency of technical (and nontechnical) competence. (a) First goal; (b) second goal.

Furthermore, there is insufficient awareness of the simple truth that devotion to science *can be* and *should be* part of a larger devotion to life—to a life that is more abundant and more satisfying for all mankind. Science can and should provide a wealth of understanding that enriches the individual's own life and the lives of those around him. Students need to take the time to see how their views of science relate to the subroutines of their personal lives, and to see how these subroutines can be induced to interact with aspects of their professional lives in such a way that the local system grows. This requires time, reflection, and patience. Students have set their feet on a path that continues for a lifetime; they need to condition themselves to take the time and develop the patience. They will then find the stroll more exciting and satisfying. I know that our present educational system seems geared to the ingestion of facts, and that there seems little time for carrying out this suggestion. However, this is a problem that must be worked on, in particular because it relates to the faculty too. Many faculty members have perceptions that can be of great value to the students, but communication of these insights requires quiet and leisure. I feel that these insights are perhaps the professor's most important potential contribution to the student—the one that can do most to help the student grow. It is to be hoped that our universities can evolve in a way that encourages such communication.

Implementation of Needed Changes

The most difficult task is the introduction of changes into the daily operating conditions of our departmental activity so that the student gains, in a very natural way, the enhanced understanding that is needed. Two conventional methods are (i) the addition of appropriate courses and (ii) periodic reemphasis, by the faculty, of the visualized goal and the needed attitudinal changes. The generation of courses which stress the synthesis of knowledge, the techniques of decision-making, and the development of applied mathematics, with examples chosen primarily from the area of materials science, would be most helpful. This is not sufficient, however, and there exists in the minds of many the idea that bringing technological problems into the university to be worked on by students and professors in cooperation with some specific industrial effort will probably satisfy this need.

On the surface, this would seem to be an ideal solution. However, there seems to be a basic incompatibility of goals. The purpose of the student's research is to help him unfold and know his strengths and weaknesses; the locus of the work should be dictated by the student's needs. On the other hand, the goal of the technological study is a very specific thing: to proceed directly and steadily toward a well-defined solution in phase with some cooperative industrial effort. These goals can be made more compatible provided the bulk of the technological effort is borne by postdoctoral candidates, with the students having only peripheral involvement in the technological development but detailed involvement in the scientific aspects of some of the "subroutines."

An alternative or complementary path that promises to be very useful is the development of a Computer Simulation Laboratory course, which all students would take. Systems-event problems would be programmed for the computer; the student would put all the relevant physics into the various subelements of the system and couple them together in the appropriate fashion. By varying certain parameters in various subroutines, he could study the output spectrum of the total system. In this fashion he could gain vicarious experience concerning the systems event. Not only would he learn the techniques of dealing with this kind of problem but, more importantly, he would realize the subtle interplay of forces in real problems and should find the confidence to face and resolve problems of this class in his personal and professional life.

Future Trends

At one time I felt that, as the field of materials science became more quantitative and more scientifically oriented, the undergraduate population in this field would tend to disappear and materials science would become totally a graduate department. Detailed knowledge in the primary disciplines would become more important, and these could be taught by the appropriate departments more effectively than by the materials science department. Only when the field is treated as an art (Eq. 1a) does it function like a discipline and thus have uniqueness of content. I felt that in graduate school one could meaningfully begin the systems approach on an intellectual level and learn the associations needed for problem solving in this area. However, a little thought leads one to realize that it is one's "state of mind" that lets him clearly perceive on a systems basis, and that the time constant for this particular portion of the human learning curve is long. Thus, provided one centers his attention on the system and on seeing that it operates in the most advantageous way possible, a viable and important basis exists for having an undergraduate department. Unfortunately, the undergraduate student may not have, until he is a senior, sufficiently precise knowledge of the important subroutines in the system to perform meaningful system studies.

If materials science departments such as ours at Stanford are able to carry out a program, and conform to a philosophy, of the type outlined here, I feel that in about 5 years we will begin to graduate what can be called the "new materials scientist" (*2*). Not only will he be in tune with the systems frame of reference for perceiving his environment but he will have the mathematical capabilities to analyze systems events and will present to society a spectrum of capabilities such as is indicated in Fig. 5a. His "capabilities spectrum" will exhibit a good background intensity I of ability over a very wide spectral range ν of scientific (plus nontechnical) content; this is his "generalist" component. Further, it will exhibit at least one extremely high spectral peak at some specific frequency ν^* relating to the position of one of the activities represented in Fig. 2; this is his "specialist" component. The specialist component identifies him as an authority in his field and allows him to be uniquely useful. The generalist component allows him to join with other specialists in his environment in a meaningful and cooperative way that will both deepen his insights pertaining to his ν^*-mode activities and enable him to effectively treat large systems-event problems.

One dilemma that remains to be faced is the dichotomy of (i) the continuous expansion of knowledge and the continuous growth in sophistication of our society, which necessitates more specialization, and (ii) the continuous growth of p with time (Eqs. 4 and 5) in the systems-event problems with which we must deal; that is, the need for a broader bandwidth of capabilities. Obviously (since the duration of study for the Ph.D. should have practical limits), such a situation can be resolved only through having overlapping groups of cooperating scientists working in teams, as illustrated in Fig. 5b. This situation will require the sociologist's special abilities to teach (i) effective cooperation with other specialists and (ii) perception transfer from one portion of the spectral range represented by one individual to remote but equally important regions represented by other individuals. I myself will be pleased when we have satisfactorily evolved to the state represented by Fig. 5a, and am willing to leave the challenge implied by Fig. 5b until a later date.

Reference and Note

1. W. A. Tiller, in *Proceedings O.A.R. [Office of Aerospace Research] Research Applications Conference, Washington, D.C., March 1967* (1967), p. 109.
2. To some degree this is now being done.