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CERAMIC EDUCATION
Do a Few Courses More or Less Make Much Difference in the Long Run?

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Discussing ceramic education with an international audience of renowned Academicians is rather a daunting task. First, there are substantial differences in different national systems of education. Doctoral candidates in ceramic science are expected to do quite different things than undergraduate and M.S. applied scientists and engineers. Then, the whole field of ceramics and other advanced materials is undergoing rapid change. Finally, there's nothing I can say about engineering education that hasn't been said many times before. This presentation is mostly aimed at stimulating discussion rather than presenting solutions.

I believe there are three essential skills required for a successful and satisfying career in science and engineering, technology management and most other endeavors. First, one must be able to find, identify, define, classify and characterize problems and opportunities. Second, one must be able to select an appropriate problem on which to exert one's efforts. Finally, heuristic skills are necessary to come up with a satisfactory solution. This pattern - finding problems, selecting a problem, solving a problem - is central to science and engineering. The core requirement of university education is to provide the intellectual tool kit, insights, and judgments required for performing these tasks.

The nature of science problems and engineering problems is different. The central objective of science is discovery - discovering new facts, discovering new explanations. The central objective of engineering is to design, develop and put into place processes, products and systems that provide improved and satisfactory performance. Engineers have more complex tasks than scientists.

Find a problem. As all faculty know from the wide range of topics that students select for term papers, there are an enormous number of problems available in every field of endeavor. All arise from the same source - a mismatch between expectations and experience, an anomaly. In science we have observations without a theoretical explanation, theories without experimental observations, theories and observations in conflict; we also have needs for incremental modifications of theory and experiment. In engineering we have expectations without performance, performance beyond or below expectation, performance contrary to expectation; we also have continuing needs for incremental modifications of designs, processes and products. One educational requirement is to provide a basis of facts, techniques, insights and experience useful for judging whether the plethora of apparent anomalies all around us are real or ethereal. And practice in using this intellectual tool kit.

Selecting a problem. Derek D.S. Price thought it "the most precious art of the scientist to develop almost a sixth sense...that can tell him which researches are likely to be most promising" (p. 73 in *Science Since Babylon,* Yale Univ. Press, New Haven, 1961). Michael Polonyi said that the most important achievement is to discover and recognize a problem "that is ripe for solution by your own powers exerted to the full, and worth the expenditure of this effort" (p. 630 in *Fifty Years of X-ray Diffraction*, P.P.

Ewald, Ed., Intl. Union of Crystallography, 1961). Thomas P. Hughes has commented on Sperry's and other successful inventors' gift for recognizing the "reverse salient" in a technological *system*. Sperry said, "I tried to discern the weakest point...". (p. 293 in T.P. Hughes, *Elmer Sperry: Inventor and Engineer*, Johns Hopkins Press, 1971). Selecting a problem requires some vision of the structure of a field or system and how it can or might be changed.

Envisioning a field or system first of all requires a few facts. It requires the ability to place a problem in context within a system or a field of endeavor; it requires good instincts, judgment and practice. Even more so, anticipating change in a system requires that we have in mind a model of the way change occurs. In science, William Whewell, Michael Polanyi, Peter Medawar, Derek Price, Thomas Kuhn and others have contributed models of how change occurs. In engineering, Lewis Mumford, Thomas Hughes, George Basalla, Walter Vincenti and others have elaborated on technological change. No one model is perfect. However, as a guide to one's professional career every university graduate must begin to develop his or her own vision of how innovation and change take place.

Solving a problem. George Polya has given an incomparable guide to heuristic in his classic *How to Solve It* (2nd ed., Princeton Univ. Press, 1985). First of all, one must place a problem in context and see similarities with previous experience. A collection of facts, techniques and experiences is required. Experience teaches us that solving important or persistent problems often requires a wide expanse of applicable facts and experience. Second, one must devise a plan. Third, carry out the plan. For different fields different intellectual kits of methods, facts and techniques must be available or learned. Finally, every problem solution must be creatively examined to evaluate its consequences and implications. Every university student needs a lot of practice solving problems.

One group of university graduates is Ph.D. candidates focusing on ceramic science who are expected to enter academic, government or industrial research careers. There are significant national differences but for the most part Western education is aimed at producing rather narrowly focused specialists.[1] The apprentice program of doctoral and post-doctoral study is as good as the professors in charge. The system is often excellent at producing clones of the master, but not necessarily broadly educated or highly innovative scientists and engineers. A critical question is whether cloning academic faculty is appropriate in a period of rapid change.

Two different but related changes are occurring that need to be addressed. One is the emerging importance of research beyond the boundaries of existing specialties. The present culture of academia calls for outstanding accomplishment in a rather limited field of excellence. University departmental structures, tenure arrangements, and reward systems are built around the concept of narrowly defined peer review prior to research funding, publication, promotion and tenure. In a way we are fortunate: Materials Science and Engineering has not yet become a discipline (and may never do so). However, it is unlikely that a mechanical properties specialist would be considered capable of judging the professional competence of a colleague concerned with sol-gel powder preparation - an anthropology professor on a ceramic peer review committee is unthinkable. Yet, cutting edge research and the tendency of research funding is increasingly aimed at questions and

[1]In Japan much more research training occurs on the job and most Ph.D.s are based on post-university scholarship.

problems that call for more than single-field competence. The blurring of disciplinary boundaries is occurring across the board; nowhere more rapidly than in materials science and engineering.

Second, beginning in the 1950's materials science and engineering has undergone an unprecedented expansion of knowledge that has transformed its very nature. The number of scholarly MS&E journals has increased exponentially as has the number of books and monographs. The number of University programs in ceramics has expanded, as has the number of small and large firms for which ceramics are critical components in a wide range of products. Competition in applying new knowledge to commercial products is intense and the time constraints on obtaining knowledge and applying it are tight. There has been a proliferation of products for a wide audience of customers who are tailoring materials selection of compositions and forms to increasingly special applications. High-value-added ceramics are no longer generic high-volume commodities.

The standard model of materials advance is the replacement of one material with an improved material having lower cost or improved properties. In our new technological environment improved systems performance is the primary basis for expanded use of new advanced materials and components. As one example, the development of optical wave guides is much more than a replacement of copper with glass; rather the whole telecommunications system is changing. This transformation in the way in which high-value-added ceramics are designed and used requires an equally large modification of our intellectual kit. Understanding molecular structure and microstructure must be accompanied by understanding how ceramics fit into and contribute to the performance of complex mechanical, electrical, optical and electronic systems. Design and processing must be closely tailored to performance. This is analogous to the widely accepted requirement that firms fully understand and respond to customer needs. New University structures need to be developed to educate students for the 90's.

For applied scientists and engineers at the SB & MS level entering industry, the situation is equally challenging. On graduation these students will be entering materials development and use careers which are part of a complex *socio-technological*

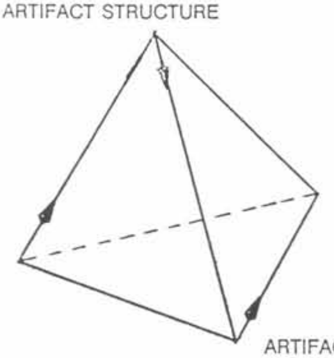

Figure 1. The basic paradigm of ceramic science and engineering is that production activities give rise to structure and properties that determine performance.

activity. The paradigm of ceramic technology is that materials synthesis, selection, processing, shaping, firing and finishing lead to an object with a particular structure, composition and properties giving rise to acceptable performance in a number of possible functions and uses (Fig. 1). This paradigm mixes apples and oranges. The structure, composition and properties of a product are inanimate attributes capable of precise measurement, characterization, modification and evaluation. In contrast, processing and performance are socio-technical activities involving human perceptions, human behavior, social organization, economics, politics, legal systems and national and corporate cultures. These social components are as important as strictly "technical" factors in determining technological and engineering success. A ceramic product standing alone is remarkably uninteresting. Its importance arises as a result of performance in a device, product or system much more complex than the product itself. There are utilitarian, social and symbolic functions associated with performance success. This concept of ceramic science and engineering as technological *activities* embodied in a socio-technological system has been mostly ignored in developing ceramic curricula.

We have discussed how the field of ceramics and other cutting edge technologies are undergoing rapid change. At university few students are told that the facts and techniques they are learning will soon and inevitably become outdated. As engineers move through a career, it is essential that they continuously renew their learning and stay current if they are going to be effective participants. There are three ways of doing this. The easiest is to lower the need for further *technical* learning by moving into management, sales or some non-technical function. This is the original intent of many engineering students and the direction taken by most engineers. A second approach, pictured as the most popular method of staying current, is to attend formal continuing education courses. Industry acknowledges that continuing education is necessary and everyone says it is supported. Nevertheless, there is often little real time allowed engineers for education or anything else not central to performance. At performance evaluation time little credit is obtained for attending an outside course. The third approach to maintaining continuing currency is self-learning. This involves reading technical books and journals, attending professional meetings and having networks of associates who are able to provide continuing support. This seems to be the course of our most successful scientists and engineers. The habit of self-learning should be acquired at university.

The accelerating changes in the nature and content of ceramic engineering and technology means that the educational process must become less concerned with the transmittal of current knowledge and more focused on *learning how to learn.* Professional education should concentrate on (1) learning how to accumulate facts and techniques, (2) learning how to develop insight and judgment and (3) learning how to apply new facts and techniques to old problems as well as old facts and techniques to new problems. Every class, every course, must be judged on this criterion - how does it contribute to learning how to learn? This is not to say that the accumulation of facts and techniques, methods and theories is unimportant. Indeed, it is essential at all stages of cognitive, athletic and social learning. When we encounter a new problem, we must first situate it in our accumulated experience. But let me cite an example: there are hundreds of oxide crystal structures of some interest for ceramics. All of these are derivatives of only a few basic arrangements. Almost all are described in one or two reference texts. With a relatively small data base, appreciation of the principles of derivative structures, a minimal knowledge of the literature, and practice, students should be able to accumulate their knowledge of crystal structures as needed rather than receiving the whole set as stored knowledge.

One extreme of the education process might aim to optimize the accumulation of a sufficient quantity of well structured facts and techniques. Another extreme model would optimize learning how to learn with minimal accumulation of facts and techniques on which to operate. As in most things, some golden mean is to be aimed at. Nevertheless, missing a few facts and techniques at university seems a very good thing. Then, what are the areas in which ceramics students should aim to accumulate facts, techniques, insight and judgment? I think they're adequately shown in the paradigm illustrated as Fig. 1. The technological activities of materials synthesis and selection, product design, manufacturing, processing and firing which create objects having a particular set of composition, structure and properties must be included. Increasingly important are technological activities associated with performance, function and use in particular applications. By and large, ceramic curricula now focus on the inanimate structure, composition and properties of inorganic nonmetallic materials. More time needs to be spent on processing; more time needs to be focussed on performance. Little attention is now given to either processing or performance as socio-technological activities.

Learning how to learn requires practice in recognizing and defining the anomalies that are the source of science and engineering problems. Students of ceramic science and engineering need to practice planning for innovation (engineering) and for discovery (science). This requires that students develop some kind of model for the essential content of their field and how changes come about. This has to be continuously refined through a university career and beyond since it requires a growing context of facts and techniques as well as developing insights and judgements. It is hard to see how this can be done without some historical background, some understanding of the socio-technical processes of technological innovation, and an appreciation of the relationships between processes, objects and performance. Students need to develop heuristic skills in finding solutions. This requires an intellectual tool kit that can devise a plan; it requires skills in manipulating data to carry out the plan and find an acceptable solution. This aspect of science and engineering skills is the part of the curricula which is best developed and most effective. Even so, most students and teachers would benefit from a better acquaintance with more explicit discussion of heuristic skills.

Part of the reluctance to approach engineering as a socio-technological activity is the deeply embedded cultural belief in a standard linear view of science and technology. A myth has developed that the support of basic science leads automatically to effective applied science, technology, manufacturing and an improvement in the quality of life. In corporate planning this has led to a similar linear model of innovation in which research leads to development which leads to production which leads to marketing. The inadequacy of these linear models has long been recognized by historians of technology. More recently Kodama has said that a "consensus among science policy researchers is the inadequacy of the linear model in explaining the parameters of innovation. Researchers all over the world think the traditional innovation model needs overall reconsideration" (Fumio Kodama, *Analyzing Japanese High Technologies: The Techno-Paradigm Shift,* Pinter Publishers, London and New York, 1991, p. 172). More realistic models involve a more complex relationship between engineering knowledge, scientific knowledge and a wide range of feedback loops between users, designers and manufacturers. One result of this myth (which is widely believed by ordinary people, legislators, chief executives and faculty) is the very structure of engineering undergraduate education, a clone of the linear model. Programs are set up to begin with "basic" science, progress to applied science and only then come to technology and engineering and sometimes manufacturing. Different faculty teach these different topics and the feedback between them is often absent, a particular fault of American education. Engineering education is a socio-technical activity and a much wider range of feedback loops needs to be encouraged.

Science seen as isolated from real materials and from engineering turns off many beginning students. Arguments that basic science _as_ basic science provides the fundamental foundation for long time ceramic careers is unsubstantiated by any logic or empirical data. These sciences are rapidly changing in the same way that engineering is changing. Ceramic engineering students should begin and continue their education with a focus on the design of processes and products, bringing in chemistry, economics, social and behavioral sciences, physics, on a just-in-time as-needed basis in concert with a strong foundation in mathematics. Integration of physics, chemistry and mathematics into the ceramic curricula will mean better physics, better chemistry, better mathematics, better ceramics and better engineering.

In understanding technology as activities involving social organization and human behavior one path has been to leave those aspects of engineering education to experiences at the fraternity or sorority house and on the playing field. I think not, but there is a problem. Social scientists have not developed methods and theory of social organizations and human behavior appropriate to an engineering context. Historians of technology, sociologists of technology and anthropologists of technology are all relatively insecure in the esteem of their larger peer groups. For the moment (this may be changing) their efforts are mostly aimed at an audience consisting of their own peer groups. There have been few studies of applied science and engineering as _activities_ on a behavioral basis in a way directly useful to faculty or students of engineering. Scholars in these fields have rarely worked synergistically with engineers on a joint basis to develop behavioral analyses helpful for engineers learning how to learn about engineering as a socio-technological enterprise.

The most successful achievement of ceramic education is undoubtedly associated with the properties of objects, their composition, structure, and the ways in which structure and composition affect properties and are determined by processing. A broadening of this focus on materials synthesis, materials preparation, design and manufacturing on the one hand and materials use and performance on the other hand, would be welcome. A major challenge facing ceramic educators is to work together with historians and social and behavioral scientists to develop engineers prepared for full and effective participation in the professional careers they face in socio-technological endeavors. The contributions of historians and social and behavioral scientists should not be optional or as context, but as a substantive constituent of required professional education. This will only happen when engineering educators initiate the process of learning how to succeed in this endeavor.

A significant part of the resistance to change in engineering education is a conception that four years is already inadequate for professional training. There have been a number of calls for a minimum five years at university. My own view is that a few courses more or less won't make much difference in the long run. There are revolutionary changes occurring in the practice of ceramic science and engineering. Educators need to focus on the basic skills of not only solving problems but also recognizing and defining problems, and selecting challenging and important problems capable of solution. There is a strong need to succor learning how to learn and learning about engineering as a socio-technological activity.

It is proposed that the Academy endorse the following:

1. The core task of ceramic education is developing skills in learning how to learn.

2. Learning how to select problems worth solving is equally as important as learning methods of solution.

3. Developing insights and judgments as to how technological innovations occur is an essential component of ceramic education.

4. Methods of education preparing students for their roles in socio-technical activities need to be developed.