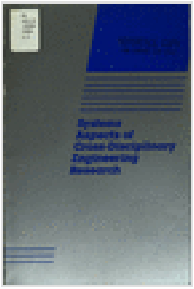

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SYSTEMS ASPECTS OF CROSS-DISCIPLINARY ENGINEERING RESEARCH

Steering Group for Systems Aspects
Cross-Disciplinary Engineering Research Committee
Commission on Engineering and Technical Systems
National Research Council

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PREFACE

The Engineering Research Centers are being created by the National Science Foundation with the explicit goal of enhancing U.S. technological competitiveness through better engineering. Their function is both research and education, in equal parts. It has become clear that American technology has been weakened by the absence of close linkages between universities and industry; as a result, university engineering research and education do not have sufficient applicability to industry's needs. The cross-disciplinary nature of research within the Centers, and a focus on the "systems approach" and systems-oriented goals, are parts of a conscious effort to correct this situation by producing a new generation of research, researchers, and graduates that reflect the realities of contemporary engineering.

The Cross-Disciplinary Engineering Research Committee of the National Research Council was formed to assist the NSF in evaluating the newly formed Centers from several standpoints. One of these was the extent to which they can be effective in achieving the goal of a systems orientation in engineering research and education. This report distills and expands upon the discussions that took place at meetings held during the summer and fall of 1985 by a steering group of the Cross-Disciplinary Engineering Research Committee to examine this and related questions.

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SUMMARY

A focus on the "systems aspects" of engineering is an important feature of the Engineering Research Centers (ERCs) being established by the National Science Foundation. The driving force here is a belief on the part of NSF that a better understanding by U.S. engineers of how to synthesize, integrate, and manage engineering systems would improve the technology development process, and with it the nation's industrial competitiveness. However, the concept of systems and the systems approach to engineering is not clear to many engineers in industry and academe and thus requires some elucidation and definition.

The need for a systems approach to engineering research, education, and practice derives from the increase in emphasis on science and mathematics--on theory and analysis--in the engineering curriculum since World War II and the corresponding loss of emphasis on design and manufacturing practice. That shift in emphasis has meant that students are better prepared for engineering graduate study and research in highly specialized technical fields. It also means that graduates are equipped with the necessary in-depth knowledge to adapt to rapidly changing technologies. What has suffered, however, is the crucial orientation toward industrial practice and needs that traditionally helped to ensure technological eminence for the United States. The focus on analytic solutions is valuable, but in some cases it has gone too far. Engineering graduates entering industry no longer have the same "feel" for system synthesis that they once possessed, and the emphasis on specialized tasks in industry has done little to strengthen that orientation among practicing engineers.

The systems orientation involves focusing on the "big picture". It implies a set of values relevant to engineering in both industry and academe. There are distinct goals for education, research, and practice:

- Education. Students should learn how systems are designed, manufactured, and supported in the field, and what the goals of good engineering are. Such understanding is best obtained by hands-on experimentation in system design and development, and through exposure to industry personnel and methods of practice.

- Research. Systems-oriented engineering research involves a cross-disciplinary approach in which engineers and scientists from separate disciplines work as a team to solve problems bearing directly on the needs of industry or society. Wherever possible, there should be a focus on the development of generic processes and principles.

- Practice. There should be an interdepartmental approach to design and manufacturing as an integrated whole, with no "walls" between functions. The key is cooperation and open communication among participants at all levels of the manufacturing process. The separate activities ought to contribute toward solutions that will improve both product and process.

This report presents three different models exemplifying an integrated systems approach to the design/manufacturing process: (1) a "Two-Level Manufacturing Systems Structure" depicting the human and hardware components of manufacturing and their interactions, (2) the "Foundry Concept" for producing custom-designed integrated circuits, and (3) a series of models depicting the evolution of the software development process.

The ERCs are intended to expand and strengthen interactions among universities and industrial organizations. As points of interface between academe and industry, one of the functions of the ERCs will be to transmit positive cultural values between these two environments. An important set of values will be those associated with the systems aspects of engineering. The ERCs will thus be role models, catalysts for cultural change.

To facilitate that role, existing ERCs have established (or plan to establish) a number of specific programs. There are in every case two or more levels of company participation in technical or managerial aspects of ERC programs; the interaction may entail program review, joint research, joint teaching of courses, and a variety of mechanisms for technology transfer. To communicate the culture and goals of the Center to the rest of the university, ERCs use joint faculty appointments, a strong emphasis on cross-disciplinary research, and extensive involvement of both graduate and undergraduate students in ERC research, as well as straightforward information campaigns involving devices such as annual reports, brochures, and open-house exhibits.

To be successful as the agents of change envisioned by those who developed the ERC concept, the Centers will have to accept responsibility not only for doing the best possible research on highly specific projects, but also for conducting that research within the context of a larger engineering system, in active cooperation with industry. And they will have to spend part of their time and energy in transmitting the meaning and importance of this approach to the academic engineering community at large. Effectively done, this aspect of the ERCs' work will be as valuable as the research effort they were organized to perform.

This report also offers some specific recommendations for changes in the wording of the NSF Program Announcement for ERCs, regarding the systems concept.

INTRODUCTION

Over the past year or two there has been considerable discussion within the engineering research community of the "systems approach" to, and the systems aspects of, engineering research, education, and practice. The main focus for this topic has been the National Science Foundation's new program for the establishment of Engineering Research Centers (ERCs). The National Academy of Engineering report Guidelines for Engineering Research Centers, in discussing the impact of the proposed centers on education, suggests that:

> While the ERCs should be encouraged to emphasize the systems aspects of engineering and to help train people in synthesizing, integrating, and managing engineering systems, they should be careful to avoid focusing too rigidly on any particular engineering problem. They must retain flexibility in their program orientation if they are to remain current in their approaches to engineering practice.[1]

Accordingly, the NSF's FY 85 and FY 86 Engineering Research Center program announcements state that the Centers are expected to:

> ...Emphasize the systems aspects of engineering to help educate and train students in synthesizing, integrating, and managing engineering systems.[2]

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[1] National Academy of Engineering, 1983. Guidelines for Engineering Research Centers, p.5.

[2] National Science Foundation. Program Announcement: Engineering Research Centers, Fiscal Year 1986, p.1.

While this is but one of the many features expected of the Centers, it is thought to be an especially important--perhaps pivotal--one. However, there has been a degree of uncertainty over what is meant by this concept, and by the wording of this and other statements in the program announcement.

Therefore, the NSF sought from the National Research Council's Cross-Disciplinary Engineering Research Committee some clarification and definition of the concept of systems aspects, along with suggestions for implementing it in ERC research and education. This report responds to that request by:

1. Describing developments that led to concern over the nature of engineering education and research in relation to the competitiveness of U.S. industries.

2. Defining the systems aspects of engineering, especially as they relate to the research and educational missions of the ERCs.

BACKGROUND: THE GAP BETWEEN ENGINEERING EDUCATION AND PRACTICE

Emergence of a Problem

Prior to World War II a typical engineering curriculum included (in addition to science, mathematics, and courses related to specific engineering disciplines) courses in graphics, manufacturing practice and design, and engineering ethics. The typical faculty member was one who had entered the teaching profession after obtaining significant industrial experience, and who possessed a master's degree rather than a doctorate. The overall educational philosophy was pragmatic, with the emphasis on professional practice.

After the war the curriculum began to change. Spurred by wartime advances in science and technology, and encouraged by the needs of government and industry, engineering schools introduced much more mathematics and science into their programs along with a new emphasis on graduate training. Industry began pressing for a new breed of engineers to staff advanced project offices and research laboratories, people with expanded training in the sciences and with advanced degrees.

The changes in curriculum were not welcomed by all engineering faculty members, nor were they instituted in every school or every department to the same degree. Still, they proceeded steadily. As the emphasis shifted to a more theoretical and science-based curriculum that was essentially preparation for graduate study and research, it was apparent that something had to go to make room in the program. The courses that dealt with the vocational aspects of engineering clearly contributed least to this new type of training and were thus deemed expendable. As federally funded university engineering research experienced a postwar boom, graduate programs grew correspondingly. The process fed on itself. Research provided graduate students with support, and they in turn provided the young faculty needed to further expand the research program and graduate training. The continual emergence of new technologies and new high-tech areas of research provided a momentum that sustained and justified this expansion.

Some aspects of this enormous change were good. Young professors brought to the classroom the excitement of cutting-edge research. They imparted a greater emphasis on the fundamental aspects of the topics being studied and invested the curriculum with greater flexibility. Students were thus well prepared for research in fast-changing areas of technology. But in the process some important things were lost. As "applied science" began to predominate, not only did the courses in graphics and shop practice disappear; design courses were also increasingly edged out. And as the hands-on, product-and-practice orientation of engineering education decreased, so did much of the identification with the engineering profession. A certain snobbism appeared: Those who preferred to think in terms of the synthesis or design of products, rather than research, became in some vague way second-class citizens.

Realization of the Problem

By the early 1960s these changes in content and orientation were firmly entrenched, with patterns of support for engineering education and research continually reinforcing them. It seemed that an appropriate and beneficial revision had been made, and on a grand scale. But were those changes good? What would be their long-term effect on the nation's engineering enterprise? Ultimately this would be the only real measure of the adequacy of engineering education.

It took the increasing success of other nations competing against U.S. industries throughout the 1970s to jolt this country's engineering community into an awareness that the postwar orientation of engineering education might not be ideal. Industry was first to feel the need for engineers with a different set of skills and perspectives. Noticing that engineers with advanced degrees often could not adapt readily enough to the rapidly shifting and highly development-oriented requirements of commercial engineering, industry began to demand larger and larger numbers of B.S. graduates. These people were not as specialized (or as highly paid) and could be trained to meet a company's particular requirements. Even in high-technology fields there was a continuing need for hard-headed engineering design--utilizing new materials and processes, to be sure, but requiring the skill in system synthesis that engineering schools were no longer inculcating in their students.

The emphasis on theory and analysis at the expense of a practical orientation toward synthesis and design is now generally seen as having gone too far in certain areas. Students may in many cases be acquiring the notion that analysis itself--rather than the solution of engineering problems--is the focus of engineering work. Rigorous grounding in fundamental engineering science is essential, as these are indeed the building-blocks of engineering; but the existing curriculum tends not to impart an integrated picture of engineering, nor does it give a sense of the relationship of analysis to the design and synthesis of complex engineering systems. From the standpoint of industry needs, these are serious shortcomings.

To some extent, the current gap between engineering education and practice reflects changes in industry, in its structure and practices with regard to manufacturing. By the late 1970s, the great competitive inroads being made by foreign industries had begun to prompt a reexamination of the entire procedure by which that enterprise has been conducted. Gradually it became apparent that the very practice that had made possible the enormous technological advances of World War II and after--the breaking of tasks into specialized segments that could then be optimized--was now inadequate for the cost-effective development of complex systems.

There are no villains in this story. The changes in industry have been a natural outgrowth of the same pressures that caused the shift to a research orientation on the campuses. When specialized groups were welded into an organization by people who in the course of their experience had developed an intuitive feel for the importance of the overall system, the results were highly effective. Through the years, however, people gaining experience in specialized groups--even though exposed to several different ones--tended to lose this vital systems orientation. At the same time, industrial management practices tended to drive the enterprise toward short-term profits and a near-term outlook, rather than toward long-term optimization of the overall manufacturing system. Academic and industrial practices (as well as government funding policies) reinforced each other until our national economic well-being was finally threatened, not by an enemy nation, but by our trading partners around the world.

Major industries are already overhauling their organization, process, and management. The benefit of so doing has become evident enough to convince most of the rest of U.S. industry of the value of emphasizing the systems aspects of their enterprise. But this cannot be accomplished through management science alone; it will require engineers, and these engineers must come from engineering schools. It is to be hoped that, by emphasizing the systems aspects of their work, the Engineering Research Centers will spearhead a change, not so much in curriculum as in attitude and outlook on their respective campuses. We may then hope that this change in outlook--in "culture"--will begin to permeate the industrial establishment and foster much closer and stronger ties between the universities and industry.

DEFINING THE "SYSTEMS ASPECTS" OF ENGINEERING

Definition

Most U.S. industrial firms design and manufacture systems. Systems are their end product; indeed, most manufacturing <u>processes</u> are in themselves systems. However, the concept of "systems" means different things to different people, depending on an individual's background and experience, and upon the context in which the term is applied. The "systems aspects" of engineering is thus an elusive notion, one which is perhaps best defined indirectly, by example and suggestion.

The Engineering Research Centers employ a cross-disciplinary approach to research and education. In attempting to clarify what is meant by the systems aspects of cross-disciplinary engineering, we should begin by understanding what it does <u>not</u> mean. First, it is not the cross-disciplinary feature alone; i.e., it is not simply a matter of having several disciplines at work on a problem. Likewise, it is not "systems engineering"--or, rather, it is not <u>just</u> systems engineering. It encompasses that discipline and its general goals, but it is much broader.

As was pointed out in the Introduction, it is not just the systems aspects of engineering practice that are at issue in contemporary engineering, but those of engineering research and education as well. Perhaps a more useful term than systems <u>aspects</u> might be systems <u>orientation</u>. To have this orientation is not necessarily to be a generalist in lieu of a specialist. The specific (i.e., depth of disciplinary knowledge or education;

specialized skills) is as important as ever. However, the boundaries of one's goals and responsibilities are broader. They encompass, in the case of a researcher, not just the excellence and elegance of analysis but also a potential usefulness in the design of systems. In the case of a practicing engineer in industry (i.e., the manufacturing industries), they encompass not just the timely design or synthesis of a functional product but also its overall efficiency in the use of corporate resources of all kinds (e.g., labor, materials, equipment, capital, and corporate reputation). In the case of an engineering educator, they encompass not just the thorough transmittal of a body of specialized knowledge, but also the communication of a set of values and experiences relevant to the overall systems environment of engineering in industry.

What is this "systems environment"? Exhibit 1 (on page 29) shows the levels of concern that comprise the systems environment for manufacturing. There are three levels, going from the narrow technical aspects of manufacturing to the broader "techno-economic" aspects, to the broadest "techno-social" concerns for national impacts of various kinds.

The systems environment for engineering research and education is the same, except that these elements become background concerns--goals whose achievement is facilitated by the product of the research or by the educational product, the graduate. Awareness of these concerns represents a set of values--a "culture"--to be inculcated in the student. Taking primary importance in their stead is the need to combine knowledge from many engineering and non-engineering fields in a way that leads to a broad understanding of the manufacturing process and the role of engineering in that process. Key elements of that understanding would be the ability to make engineering decisions on the basis of judgment (i.e., with insufficient data), to balance trade-offs, and to perceive the human and economic consequences of those trade-offs. In engineering research, a primary value is the need for team interaction and an awareness of how individual effort contributes to the overall effort.

Thus, the "systems orientation" can be summarized in this way:

Education. Imparting, within the context of a discipline-based curriculum, an understanding of the systems environment that characterizes contemporary engineering practice. The graduate should understand how systems are designed, manufactured, and supported in the field, and what the goals of good engineering are. The ability to discriminate between the "art", or intuitive, aspects of a problem and those requiring science or engineering is important. What is required is not the introduction of extensive curricular changes, but an increased exposure to the practical application of existing course material to the synthesis of engineering systems as solutions to problems for which there is no single correct answer. Such understanding is best obtained by hands-on experimentation and experience in system design and development and through exposure to industry personnel and methods of practice.

Research. This can involve a cross-disciplinary approach in which engineers and scientists from separate disciplines work as a team toward the solution of engineering research problems that have a direct bearing on near- and long-term needs of industry or society. The systems approach to engineering research involves a focus on the development of generic processes and principles, rather than on an optimized product alone. Thus, the expansion of the knowledge base in view of the ultimate ends of that research is an essential element of the systems approach to engineering research.

Practice. An interdepartmental approach to design and manufacturing as an integrated whole, with no "walls" between functions. An understanding and due consideration of all the elements of the systems environment are essential. Design is the key element, as it sets the parameters within which trade-offs can be made; but the overall manufacturing enterprise involves cooperation and open communication among participants at all levels of the process. System developers must be able to ask: Are all the separate activities contributing to a solution that will improve both product and process?

The common threads running through these three descriptions are (1) the need for a sense of teamwork and team goals and (2) the need for a sense of mission--i.e., to put forth a superior engineering effort that leads, ultimately, to improved national engineering capabilities. The designers of the ERCs are convinced that these values are fundamental to strengthening American engineering, and that the ERCs can be a key means of disseminating them.

It is also important to note that neither the systems approach nor the cross-disciplinary approach to research and education implies that discipline-based, specialized studies are obsolete. Cross-disciplinary and systems approaches are not meant to supplant the disciplines. As more than one major study of engineering has forcibly asserted in recent years,[3] disciplinary fundamentals are essential to flexibility. Certainly, without continued strong grounding in the basics, students would be poorly equipped to deal with future engineering challenges emerging in rapidly changing technologies. Without the disciplines there could be no vitality in cross-disciplinary approaches. What is needed, however, is a renewal of the former orientation toward systems synthesis, a new sense of the utility and integration of engineering knowledge and experience, suffused throughout the traditional disciplines.

Useful System (Process) Models

Members of the steering group studying this question for the Cross-Disciplinary Research Committee have formulated three different examples, each of which might serve as a model of the integrated design/manufacturing process. The models could also be useful as a starting point in codifying knowledge about the systems integration process for use in education and research.

A Manufacturing System Process Model. James F. Lardner has formulated a "Two-Level Manufacturing Systems Structure," consisting of (1) a human-based data/information processing system and (2) a hardware-based material transformation system (Exhibit 2,

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[3] See, for example, Engineering Education and Practice in the United States: Cornerstones of Our Techno-Economic Future (National Academy Press, 1985).

on pages 30-31). These systems comprise (in a sense) the software and hardware of manufacturing. At each level there are a variety of component tasks or tools. Level I (the "software", or human-based subsystem) consists of those people who are responsible for technical and techno-economic activities such as product design, marketing, and support. Level II (the hardware-based subsystem) is comprised of the devices and equipment that support and effect manufacturing operations.

This model emphasizes that a continuous, balanced cross-flow of information and data between the two levels is the essence of the manufacturing process. Traditionally, research has been actively pursued in Level II, but not in Level I. The lack of corresponding research in Level I means that the two levels remain largely isolated from one another. Yet computer-integrated manufacturing (CIM) will never be achieved without research in Level I and on integration of the two levels. So far, only a few American companies have begun to implement in their operations the kind of systems thinking described by this model.

A Model of the Design Process. Robert R. Fossum describes the "Foundry Concept," which is a system, first devised by Carver Mead, for producing custom-designed integrated circuits. The modern integrated circuit is a systems product in the classical sense. That is, it is a synthesis of many cells, all interconnected to perform a specified system function. The design and first-article production using the silicon foundry concept includes iterative steps that illustrate, in a micro sense, the product design process that is seen on a larger scale in manufacturing systems such as that modeled in Exhibit 2.

The design process and the foundry are illustrated in Exhibit 3, on page 32. The two levels seen here (design--Level I, and manufacturing--Level II) correspond to the two levels described in Exhibit 2. The Level-I activities are performed at remote locations using higher-order computer languages incorporating physical and electrical design rules appropriate to the basic technology to be used. The design function involves the placement and interconnection of functional cells on the chip. The detailed subsystem design of these standard cells is usually available in local data bases or, alternatively, is accessible from a central data base at the foundry.

A system design, once completed in the Level-I remote sites, is transferred to the silicon foundry by an appropriate telecommunications system. The foundry performs the needed Level-II functions of manufacturing. In particular, the foundry accepts the designs via the telecommunications system from multiple remote sites, goes through the entire integrated-circuit manufacturing process (with multiple designs on a wafer), and returns the packaged chips to the Level-I designers for test. A given system design usually requires multiple passes through the foundry before an adequate first design is achieved. The process is similar to a remote batch-entry system in software design.

This illustrative system is potentially useful as a generic model of the system design process. It is applicable to other kinds of engineering problems beyond information processing. It could be valuable in education because of the relatively small capital investment for the remote terminal equipment involved. Consideration should be given to creating smart design systems on the college campus for mechanical design, robotics, etc., along with corresponding foundries.

<u>Models of Process Evolution</u>. Alan J. Roberts discusses the evolution of the design process, using as examples models of the software development process (Exhibit 4, on pages 33-35). The first model (Exhibit 4A) depicts conventional techniques of software development. Because the time frame for development is long, and because the user, systems designer, and programmers are in different organizations, much is lost in translation. Little of the applications software is available for reuse. And because of the large number of interfaces, it is difficult to modify functional components without disturbing the entire system.

The second model (Exhibit 4B) depicts the system development process when the system is designed around reusable products that pertain to the application. The system has existing modules better integrated into its structure, so that they can be replaced or modified with less overall impact. Finally, the third model

(Exhibit 4C) shows the large-scale use of expert systems to encapsulate knowledge of the development process. An important feature here is that the end user is the same person or organization that generated the requirement and the design.

Thus, the direction of evolution depicted in these models is toward a simpler system structure with fewer, better-defined subsystem interfaces, and toward a closer match between stated requirements and final performance characteristics. The customer does not have to "look inside" the "boxes," and there are fewer of those boxes. In terms of the process itself, the trend is toward fewer on-line developers and, eventually, fewer off-line developers as well.

THE ERCs: MECHANISMS FOR INTRODUCING A CHANGE IN CULTURE

The Engineering Research Centers have been established in response to the perceived need for some form of government-industry-academic partnership to help reverse the decline in the nation's competitive position in world trade. Central to the problem of competitiveness is the need for increased productivity. As industry after industry has been confronted with the question of survival, it has become increasingly clear from the self-examination they have undergone that many of their productivity problems stem from inadequate handling of the systems aspects of their respective enterprises. This lesson has not been an easy one for industry to learn.

Likewise, engineering schools have not yet generally recognized the importance of treating the system as a whole. One of the functions envisioned for the Engineering Research Centers is to serve as an interface between industry and academe. Certainly the vital importance of the systems aspects of engineering is one of the most important messages that must flow across that interface. But it is even more important that the message be received, understood, and assimilated into the offerings of our engineering schools so that it becomes an integral part of the process of U.S. engineering education.

Thus, the ERCs are a catalyst for cultural change. Each ERC represents a departure from the traditional culture--some more so than others. Telecommunications, for example, by its very nature involves enormous systems problems, so the ERC at Columbia University is not revolutionary in that regard. But the Biotechnology Process Engineering Center at MIT is involved in a new and fundamentally cross-disciplinary field that poses a great many systems problems which are as yet undefined.

Considerable resistance to the cross-disciplinary and systems approach may be encountered from engineering departments and even other schools within the university. Traditionally, cross-disciplinary collaboration has been risky for a young, untenured professor. Even where interdisciplinary and cross-disciplinary research has made headway (and it has made considerable headway at many schools in recent years), the ERCs represent something threateningly new. "Business as usual" is not intended to be their credo. ERCs at Purdue University and the University of Delaware will be building on preexisting programs, to be sure, but the flavor of their work will change. Their culture will be different. This will be even more evident at the other Centers.

In the course of examining these questions, the Cross-Disciplinary Engineering Research Committee brought the directors or designated representatives of five of the six existing ERCs together to participate in a general roundtable discussion of the systems concept. In addition, they were asked to describe what they are doing in their Centers to promote the systems approach through their interactions with industry and the rest of the university. A summary of their responses follows.

Mechanisms in Use at Existing Centers

ERC Plans for Industry Interaction

Among the six existing ERCs, most structures for interaction with industry involve at least two levels (e.g., MIT, Purdue, Maryland/Harvard, and Columbia) and several categories of interaction. The first entails executive-level participation in the setting of research directions and review of the Center's progress, along with extensive participation in the research program. This level is formal, restricted in number of participants, and relatively expensive for the companies involved.

A second or intermediate level involves technical (rather than managerial) collaboration, such as in the second of Maryland's "sustaining, sponsoring, and affiliate" levels. This is also the case with MIT's lower (second) level. Columbia has recently introduced a Telecommunications Engineering Program for this purpose. The second level is also fairly expensive.

The third level involves lesser participation and access to information. Because it does not entail close interaction with Center personnel or input to Center programs, it is sometimes termed "observer" rather than "participant" status. At this level members may, for example, receive newsletters and attend open house functions. The third level is much less exclusive and expensive, with many members and a relatively low annual fee.

<u>Joint Research</u>. Joint research is the most common form of substantive interaction. It can range from long-term participation of individuals in the Center's research (e.g., Purdue's on-site representative and Maryland's Resident Fellow), to exchanges of personnel (termed "industrial internships" or "visiting scholar" programs), to industrial membership on specific project teams. MIT, for example, advertises its industrial internships in industry magazines and journals.

There are several innovative formats in use. For example, the University of Maryland will sponsor intensive, 1-week work-study groups focused on technical problems and including government-industry-university participants. This Center also has a program to examine each project for collaborative/interdisciplinary possibilities. In addition, the Center will not accept industry money unaccompanied by people. Its director insists on having true joint research projects.

<u>Joint Courses</u>. Some of the Centers have provisions for joint (i.e., faculty member with practicing engineer) teaching, under "adjunct" programs. An example again is Maryland, which is sponsoring several joint industry-university courses at the undergraduate level. Most of the Centers have plans for equipment sharing or gifts of equipment from industry.

<u>Technology Transfer</u>. Provisions for technology transfer (especially from the Center to industry) are a

major consideration in the plans of all ERCs. The degree of this activity varies according to the level of participation (and support) of a particular company.

Mechanisms include:

- Workshops, seminars, and conferences on a regular or occasional basis.
- Educational opportunities for industry engineers (specially developed short courses are offered by at least three centers).
- Site visits at both Center and industrial facilities.
- Joint development and/or use of software.
- Personnel exchanges at varying levels, as described above.
- Special mechanisms (a good example is Delaware's "Composites Design Encyclopedia").

There are some interesting innovations here as well. For example, Purdue has a new policy to give $30,000 of the fee back to each industry site representative for discretionary use in technology transfer. (It is worth noting that these representatives are described as being top quality, both technically and personally.)

Summary. All of the Centers appear to have well-developed plans for at least a moderate amount of industry interaction, usually at two or more levels. Some of the programs are based on preexisting university-industry interactions, which will be modified and/or expanded to fit the ERC's organization and activities. All of the interactions require some degree of support or fee from the companies. In most cases this is expected to lead toward the ERC becoming self-supporting, and there is thus a strong motivation for the plans to succeed.

As in any university-industry interaction, ups and downs in industry support resulting from business fluctuations are a problem that is beyond the ERC's control. One possible solution is for companies to make the ERC support funds part of their R&D budget. (R&D is never too deeply cut in difficult times.) The ERC connection ought to be sold as a "new product," as the right way for a forward-looking company to do business.

Plans for Interaction With the University

Given the built-in resistance referred to earlier, the interaction between the ERC and the rest of the university is the biggest challenge facing the Centers. The ERC representatives outline a range of mechanisms that are planned or in place to improve acceptance of this new force for change on campus.

Cross-Disciplinary Emphasis. Perhaps the most prevalent mechanism is joint faculty appointments. All centers have at least some faculty members who are also associated with a department. At Columbia University, every participating faculty member must be in a department. There are joint appointments, but no full ERC appointments. At the University of Delaware, at least two professors from every engineering department are now involved in the Center. These faculty members are selected on the basis of proven talent in dealing with the interfaces between departments and elements of the manufacturing process. There is also collaboration across college lines; at MIT, input from the sciences is important in the biotechnology research.

The emphasis on a cross-disciplinary focus within the ERCs is strong. Purdue's ERC, for example requires that all research proposals carry joint authorship from at least two departments. Maryland has a review procedure, mentioned earlier, to look for collaborative potential in every project. Another level of cross-disciplinary collaboration comes when the centers themselves collaborate, as Purdue, UCSB, and Delaware are doing.

The physical location of the center has an important impact on its ability to become integrated into the campus. If the center itself is in a separate building, joint appointments become a crucial means of avoiding isolation. Most centers have faculty members spread throughout the departments and communicating regularly, generally with some common space available specifically for the Center's purposes (as with Purdue's "technical/social" area).

Departmental resistance is not so large a problem for Columbia's center, since there are effectively no boundaries between departments in the telecommunications field. Here, other "systems" problems (e.g., market, the regulatory environment, international law) are more prevalent. There is a strong history of interaction between the Columbia labs comprising the Center and the four departments involved.

Students. Involving undergraduates will be crucial if the ERCs are to bring about cultural changes in education. Exposure to industrial practices and personnel is an important element. Joint industry-university courses are one mechanism. As was mentioned earlier, the University of Maryland plans several of these, including one on AI signal processing and one on the integration of manufacturing. MIT has an Undergraduate Research Opportunity (UROP) program, as well as graduate programs in chemical and biochemical engineering and a planned Interdepartmental Biotechnology Program. At the University of Delaware, even English literature students will be trained as technical writers.

Public Relations. Finally, all the Centers are employing a certain amount of public relations, whether formal or informal, to transmit their industry/systems orientation to the rest of the campus. MIT has an information program for this purpose. Maryland will emphasize "success stories" via seminars and will sponsor the systems-oriented, industry-taught courses just mentioned. The centers realize that simple, straightforward information about their goals and plans can overcome a great deal of resistance to the change they represent.

Proselytizing for the Systems Approach

As an effective interface between industry and academe, the ERCs have a major role to play in producing the cultural changes outlined in this report. Yet the relatively limited numbers of research projects and researchers active in the Centers can scarcely be expected to have a highly significant impact in this regard.[4] That broad impact will have to derive from some form of "magnification effect", whereby the activities of the Centers affect a far wider community than those directly associated with their programs. Part of this magnification will result from their function as role models, but it is likely that more direct and focused activities will be required to bring about widespread change.

Education is an essential element of that magnifying function. Thus, it is critical that whatever projects are undertaken be clearly identified with some larger industrial system, and that this relationship be underscored constantly by resident industrial participants. To the extent possible, the tasks of the individual researchers, students, and faculty alike should be structured to provide the greatest opportunity for the individual to see and understand his or her role as part of the larger system.

Even if the systems aspects of the work are heavily emphasized in the Centers' research, there is still a likelihood that they will be isolated from the day-to-day activities of the departments cooperating in the cross-disciplinary project. If they are to have the required impact on their parent institutions this must not be allowed to happen. It is incumbent upon the Centers to constantly proselytize their institutions to develop a systems awareness.

In terms of education, this does not mean teaching additional or different courses. It implies presenting problems to the students in a different manner, generally reducing the amount of information supplied and stating the problem in broader terms, thus requiring the student to formulate several possible solutions and then to

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[4] In late 1986 the National Research plans to hold a workshop to address, for NSF, the question of how to evaluate the ERCs. It is likely that the cultural aspects of the Centers' work will be considered as one basis for evaluation.

describe which represents the best compromise of the factors involved. The analysis of a structure, for example, becomes much more meaningful if, instead of being given an existing design with certain applied loads, the student is asked to propose a design that can handle the task by utilizing the smallest amount of material, the minimum number of field-fabricated joints, pieces not exceeding a certain weight, or any other set of realistic constraints. In seeking solutions, the student may discover the limitations of the available methods of analysis, thereby becoming receptive to new concepts; or he or she may discover that a seemingly minor design change can produce a significant difference in the amount and cost of material required, thereby beginning to appreciate the importance of careful design.

Such an approach is already being taken at some engineering schools around the nation. It is more common at the graduate than at the undergraduate level, and more needs to be done if the systems thinking required by industry is to become an integral part of the skill and expertise an engineer brings to each new task. Regardless of the outcome of the type of unbounded exercise suggested, students will have been required to use the tools of their technology in a creative manner. By doing so they will have been exposed to the strengths and limitations of those tools, thereby broadening their understanding of the educational process itself. The approach will not be easy for either student or faculty, both of whom will be challenged and stretched; but both should profit and the educational benefit should be substantial.

If the Engineering Research Centers accept as their responsibility the necessity not just of doing the best possible research on a number of highly specific research projects, but of conducting that research within the context of a larger engineering system, in active and effective cooperation with industry, and if they spend part of their time and energy transmitting the imperative of this approach to their campus colleagues, they may indeed become the agents of change envisioned by the proposers of the Center concept. They may indeed start a much-needed "cultural revolution."

RECOMMENDED CHANGES TO THE ERC PROGRAM ANNOUNCEMENT

We have examined the background in which the concern for the systems aspects of engineering has arisen. We have also attempted to define that concept and to identify ways in which the existing ERCs are attempting to implement it in their programs. But it will be important for institutions planning future ERCs to understand the concept as well, and to realize that it is a significant element of their proposals.

With this in mind, the Cross-Disciplinary Engineering Research Committee has developed a number of suggested changes in the wording of the NSF program announcement for Engineering Research Centers. Previous announcements specified "features" that the Centers are expected to possess; some of these referred to "systems" in a way that could be ambiguous. The steering group, together with the ERC representatives in attendance, examined these passages with an eye to changes that might be made in future announcements.

The consensus was that the use of phrases such as "systems aspects" and "systems nature of engineering" (as in previous announcements) is not essential, and that other wording could be substituted without significant loss. Indeed, the introductory paragraphs on the first page of the existing announcements highlight the concept of systems quite effectively without any use of that term. Therefore, the following changes are recommended.

Bullet item #2

<u>Current wording</u>:

o Emphasize the systems aspects of engineering to help educate and train students in synthesizing, integrating, and managing engineering systems.

<u>Recommended wording</u>:

o Emphasize in their research and educational programs the synthesis, integration, and management of engineering systems.

Bullet item #4

<u>Current wording</u>:

o Include in the Center the participation of engineers and scientists from industrial organizations in order to focus the activities on current and projected industry needs and enhance the education of students in the systems aspects of engineering. State and local agencies or government laboratories involved in engineering practice may also be participants.

<u>Recommended wording</u>:

o Include in the Center the participation of engineers and scientists from industrial organizations in order to focus the activities on current and projected industry needs and enhance the education of students in the systems aspects of engineering (e.g., engineering design, reliability, and economic factors). State and local agencies or government laboratories involved in engineering practice may also be participants.

Bullet item #5

<u>Current wording</u>:

o Include a significant educational component involving both undergraduate and graduate students in the Center research activities, since such participation would expose future engineers to aspects of many engineering fields and better prepare them for the systems nature of engineering practice.

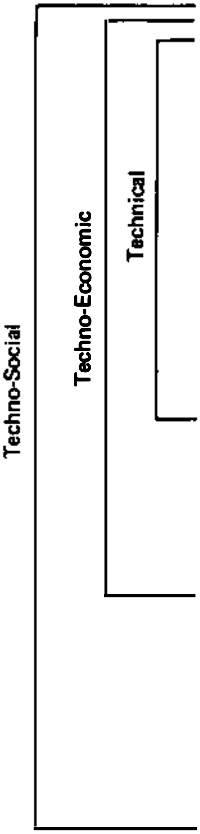
Recommended wording:

- Include a significant educational component involving both undergraduate and graduate students in the Center research activities, since such participation would expose future engineers to aspects of many engineering fields and better prepare them for engineering practice.

The steering group also recommends that NSF prepare a brief summary of the systems concept as it is defined in the context of the ERCs and have that document available for distribution on request or as an attachment to the program announcement in future years. This summary could be based on the "Definition" section of this report.

EXHIBIT 1

Elements of the Systems Environment for Manufacturing



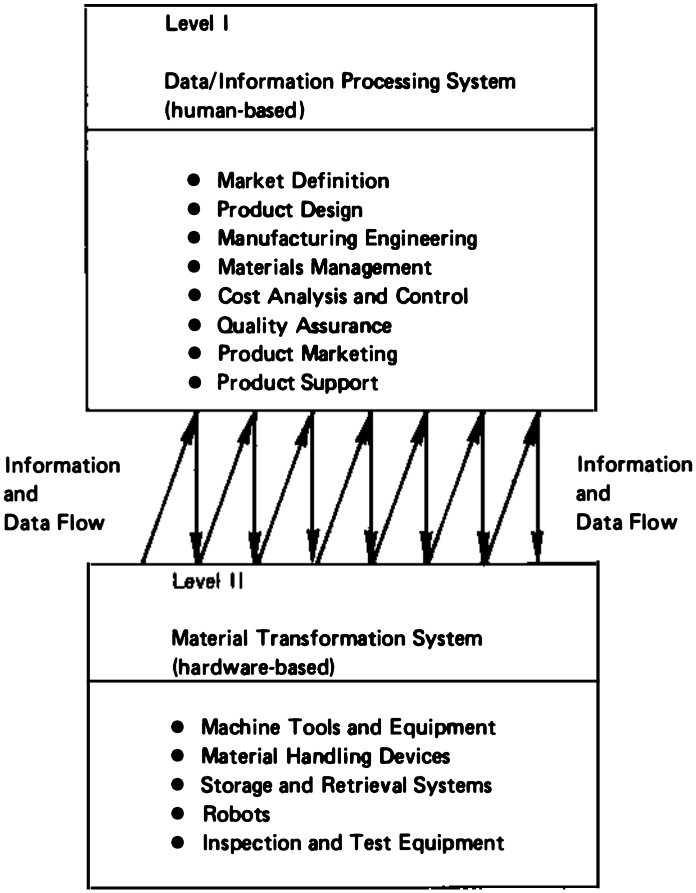
- Design
- Components
  - Materials
  - Parts
- Functional Subsystems
- Manufacturing Process
  - Parts inventory
  - Manufacturing equipment/tooling
  - Materials handling
  - Production process control
  - Quality assurance
  - Data management
- Functional System (product unit)

- Marketing
- Distribution
- Field Support/Maintenance
- Enterprise Management (corporate)
- Financing/Cost Accounting

- Environmental Impact
- Economic Impact
  - Market competitiveness
  - Jobs
  - Taxes
- Social Acceptance/Resistance
- Political Impact (derives from all of the above)

EXHIBIT 2A

Two-Level Manufacturing Systems Structure



Level I

Data/Information Processing System (human-based)

- Market Definition
- Product Design
- Manufacturing Engineering
- Materials Management
- Cost Analysis and Control
- Quality Assurance
- Product Marketing
- Product Support

Level II

Material Transformation System (hardware-based)

- Machine Tools and Equipment
- Material Handling Devices
- Storage and Retrieval Systems
- Robots
- Inspection and Test Equipment

EXHIBIT 2B

Level I (Human-Based)

Principal Functions

- Create Data/Information
- Transmit and Receive Data/Information
- Store and Retrieve Data/Information
- Interpret Data/Information
- Derive Data/Information
- Input Data/Information
- Record Data/Information
- Modify Data/Information
- Analyze Data/Information
- Evaluate Data/Information

Principal Objectives

- Define Product to be Manufactured
- Establish How Product is to be Manufactured
- Determine Tools and Equipment Needed
- Determine Quantities to be Produced and Manufacturing Schedule
- Establish Sources and Procure Materials
- Coordinate Material Transformation Activities
- Evaluate Results of Material Transformation Activities
- Determine Adjustments or Corrections Required
- Define Marketing Activities
- Determine Product Support Required

Level II (Hardware-Based)

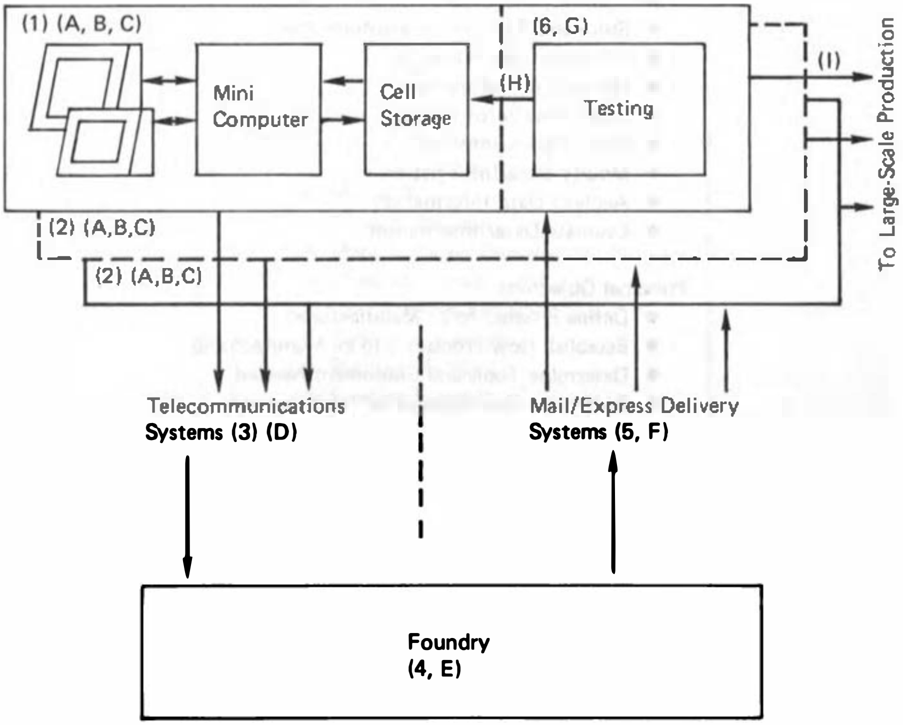
Principal Functions

- Transform Material as Required by Product Definition (product design)
- Transform Material at a Rate and in a Sequence Which Will Permit Manufacture of a Product in Sufficient Volume to Meet Market Demand and at a Cost Which is Competitive in the Market
- Transform Material Consistently and Reliably
- React to Data Input and Information Flow From Level I and Feed Back Results

EXHIBIT 3

Foundry Concept for Design of Intergrated Circuits

Level I Design: Data/Information Processing (Remote) Systems



Level II Manufacturing: Material Transformation System

System Components

(1) Level I—Remote Design Workstations
- **Smart terminals (human input/output)**
- **Minicomputers (local information processing)**
- **Disks (storage of subsystems or functional cells)**

(2) Other Remote Design Workstations
(3) Telecommunications (transmission of designs)
(4) Foundry
(5) Mail or Express Delivery System (delivery of chips to designer for testing and revision)
(6) Testing Laboratory

Design Process

(A) Problem Definition
(B) Initial Design
(C) Design Simulation and Check
(D) Transmission to Foundry
(E) Manufacture
(F) Return Packaged Chips to Design Stations
(G) Test
(H) Iterate Process (back to [B])
(I) When Adequate Design is Obtained, Pass to Large-Scale Production

EXHIBIT 4A

Evolution of the Software Development Process

Conventional Techniques

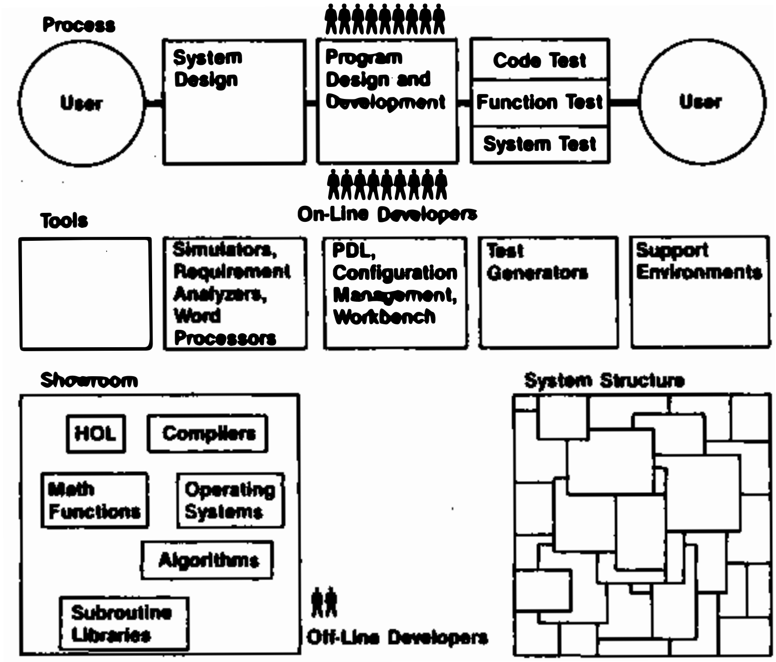


EXHIBIT 4B

Reusable Code or Functions or Requirements

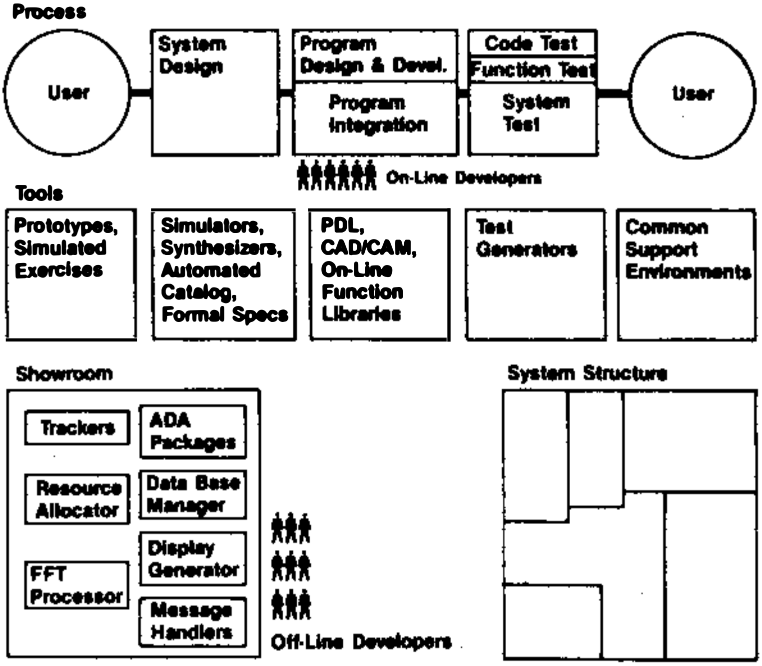


EXHIBIT 4C

Knowledge-Based Systems