THE ERC MODEL FOR A "NEW PhD"

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Abstract: The NSF-sponsored Engineering Research Centers are producing PhD graduates who are thoroughly educated in a classic engineering or science discipline and who also have extensive experience with interdisciplinary team research , as well as substantial exposure to industrial problems and practices. With their "dual channel" system of graduate education , the ERCs offer a proven model for producing the "new PhD" called for by a prestigious national policy committee.

INTRODUCTION

The National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine have formed the Committee on Science, Engineering, and Public Policy (COSEPUP) and this joint committee issued a 1995 report entitled *Reshaping the Graduate Education of Scientists and Engineers.* This report noted that industry has replaced academic institutions as the primary employer of graduates from American science and engineering doctoral programs, and that the demands of this new marketplace differ radically from those of previous decades. Based partly on their perceptions of industry's priorities, and partly on their perceptions of changes in graduate education that will best serve their own disciplines, the members of COSEPUP have called for new PhD programs that emphasize interdisciplinary team research and close relationships with industry.

In June 1996, COSEPUP organized, with the cosponsorship of 37 American professional and educational societies, an invitation-only National Convocation entitled *From Discussion to Action: Meeting the Needs of Future Generations of Graduate Scientists and Engineers.* Director Neal Lane represented the National Science Foundation (NSF) at this pivotal meeting. Dr. Lane took a very active and effective part in the efforts of the delegates, many of whom were educational activists, to move the educational establishment away from the traditional pattern of narrow single-discipline PhD programs. Suggestions form the floor included radical remedies, like the designation of graduate student support directly to the students so that they could choose faculty mentors who would help them "custom make" degrees that would make the graduates more competitive in the new marketplace. Gradually, when the more impractical ideas had run their course, the model of the Engineering Research Centers (ERCs) and of other interdisciplinary educational entities began to emerge as positive examples of new programs that emphasize interdisciplinary research and industrial connections. The proceedings of the June 1996 meeting are available on the Internet (http://www2.nas.edu/convo). In fact, the ERC model of PhD education does provide a useful model for the reshaping of the graduate education of scientists and engineers, as envisioned by the COSEPUP committee. We recommend extensive use of the ERC model and describe here the rationale for that recommendation.

The Development of the ERC Model of Graduate Education

When the Engineering Research Centers (ERC) program was established by the National Science Foundation (NSF), in 1984, its legislation-driven objective was the reinforcement of American competitiveness by the smooth linkage of high technology industries to the country's best academic research. A significant proportion of NSF's limited resources ($10 million/year initially, now about $50 million/year) was allocated to this enterprise, and the ERC Directorate gradually developed a set of pragmatic, experience-based working principles in order to achieve this clear objective. First, the basic scientific and engineering research that formed the basis of any proposed ERC must be right at the cutting edge of the field(s), and must have important practical applications in a complex engineered system. In addition, almost all of the creative nexuses discovered in the ERC Directorate's call-for-proposals lay in areas between classical disciplines (e.g. between Materials Engineering and Cardiac Surgery) and the Directorate provided the resolve and the means to bridge these long-standing divisions. Interdisciplinary research, in the ERC context, is simply a practical necessity if the program's central objective is to be realized. In the ERC program, as in industry, there is no time or patience for the disciplinary rivalries and parochialism that fuel the fires of internecine warfare in the "sacred groves" of academe.

Because virtually all of the "hands on" research in any academic setting is actually done by graduate students and postdoctoral fellows, the ERC program management realized that the central objective of the program would be best achieved by a cohesive corps of dedicated students and fellows. Very few barriers can long resist the momentum of a corps of spirited and talented students pressing on to a clearly stated common objective of mutually agreed importance. In the ERC program there is strong adherence to the principle of interdisciplinary graduate education, and an equally strong belief in the value of high-quality research experience for students at all levels of their academic progression; but the driving force is the realization that the student team is the engine of an ERC.

Similarly, the interdisciplinary cohort of students in an ERC are the actual mechanism by which center research is presented to sponsoring companies, and by which center technologies are actually transferred to these companies by internships and by employment. Within the ERCs, interdisciplinary education and close contacts with industry are not vaguely held intellectual concepts or abstract educational theories; they are an important means of achieving the central goal of the program. The reason that the ERC model of PhD education has evolved with power and focus, at a time when an effective model of the "new PhD" is urgently needed, is that interdisciplinary industry-oriented graduate education is a *sine qua non* of the success of the ERC program and of each individual ERC.

This objective-driven evolution of the education programs of the ERCs contrasts sharply with the theory-driven experiments in interdisciplinary education conducted in many American universities during the last three decades. In the biological sciences, for example, departments have merged to create hydra-headed entities with names like "the Department of Cellular Organismic and Molecular Botany Zoology and Microbiology," in which the names and the pedagogic traditions of the original disciplines are all jealously guarded. Many of these polyglot departments have now dissolved, but not without first having produced thousands of graduates including many PhDs whose main strengths are in their interdisciplinary approach, but whose main weaknesses lie in their lack of complete mastery of any one discipline. Very few of these interdisciplinary departments made any attempt to contact industry. In fact, most companies preferred to classic departments that clearly led the world in specific areas; the companies then simply made the necessary interdisciplinary correlations "in house".

The Mechanics of the ERC model of Graduate Education

With a couple of exceptions, the ERCs are not degree-granting entities within their universities. Graduate students are based in their "home" departments, which will grant their degrees. The ERCs provide and sustain a compelling research focus and an opportunity to work in interdisciplinary teams with strong industrial connections. For this reason the ERC model of graduate education demands that the PhD student satisfy her home department that she has mastered their common discipline. The classic departments that serve as the home bases of ERC students have all of the same problems of relevance found throughout the modern university, and many have encountered severe problems in graduate placement as they focus on increasingly minute and arcane subjects. But teamwork between an ERC and several university departments often produces an excellent graduate education program, in that the department provides thorough contact with at least one classic discipline while the ERC provides exposure to other disciplines, experience in team research, and industrial relevance. This"dual channel" system of graduate education imposes many pressures on ERC graduate students, as they struggle to meet the demands of both their home department and the center, not the least of which is required attendance at as many as six seminars per week.

In the most fortunate cases, and in the most homogeneous centers, the ERC graduate student and her Research Advisor will both be members of the same department. If this is the case, the student has a mentor and ally on the departmental front, and the PhD thesis will readily align itself alongside the departmental norms when it needs to be defended. These students will conduct their research in interdisciplinary center teams with strong connections with industry, and it is likely that they will form very close relationships with graduate students from other disciplines and with R& D personnel from companies interested in their research. Typically, their research teams will be led by faculty members from several different disciplines, and they will be forced to be strong proponents of their own disciplinary perceptions from an early stage as the team begins to "gel". In the most successful cases, ERC graduate students can have a significant impact on center research programs, become thought leaders on interdisciplinary research teams, and become mentors to large numbers of undergraduate students involved in small projects in the same area. It is difficult to imagine a doctoral new-hire more valuable to an industrial employer than an ERC PhD who is thoroughly educated in a classic discipline but who is already skilled in team research, adept at involving several disciplines, articulate in many different settings, and trained in effective supervision.

In cases in which the graduate student's Research Advisor is not a member of the ERC, her integration into the center is more a function of her own ability to balance the demands of her classic training with the excitement and attraction of center research. In these cases it is important that supervisory committees meet regularly to ascertain that the student's component of the team research fulfills the requirements of her PhD thesis, and that the departmental members see her progress as a synthesis of different fields and not as a diversion from her own discipline. If the departmental elements of the graduate student's committee are broad-minded and receptive, there is no reason why she should not come to epitomize the ERC model of the interdisciplinary industry-oriented "new PhD". The extent to which a graduate student from a peripheral department or laboratory becomes integrated into the interdisciplinary spirit of the ERC depends largely on the collegiality of the particular center, and on the availability of suitable space for team research and for student interactions. The extent to which the graduate student "lives" in the ERC, as opposed to spending most of her time in her home department, will determine the extent to which she eventually assumes the attributes of the ERC model of the "new PhD".

The success of the ERCs in the *Reshaping of the Graduate Education of Scientists and Engineers* derives from their uniqueness in the structure of American universities. They are not classic academic departments. They are not degree-granting entities. They are welcome in the academic community, because they represent research excellence and massive financial support; but they are initially outside of the academic fabric and must weave themselves into the warp and woof of the educational process in order to have continuity. They solve the basic problem of interdisciplinary education (i.e. dilution of academic excellence) by insisting on complete depth of coverage in a classic discipline, while offering a very attractive supplement of experience on industry-oriented interdisciplinary research teams. The ERC model of the "new PhD" is, therefore, radically different from previous academic experiments aimed at the interdisciplinary education of scientists and engineers, and its success in this area is greatly enhanced by the added element of effective integration with industry.

DEFINITION OF THE ERC MODEL OF THE "NEW PhD"

Because of the stated interest of the academic community, and of the National Science Foundation, in the ERC model of the "new PhD" a significant portion of the most recent annual ERC meeting (October 27-30, 1996) was dedicated to the precise definition of this imaginative new model of graduate education. NSF's acting Deputy Director, Joe Bordogna, emphasized the importance of new paradigms in graduate education in his projection of the ERC program into the next decade. The ERC Division's Deputy Director, Lynn Preston, stressed program management's resolve to forge a stronger link between research and education in individual ERCs, and announced substantial funding for new supplemental educational initiatives in new and existing ERCs. The new "swap shop" format, organized by Danny Wang (Director, Center for Biotechnology Process Engineering, MIT), afforded several ERCs the opportunity to showcase their recent accomplishments in graduate education. The largest portion of the time available for this meeting was allocated to an interactive discussion entitled *Integrating Research and Education: The ERC Model* which was introduced and chaired by Bill Costerton (Director, Center for Biofilm Engineering, Montana State University). During this interactive session, the attendees broke up into smaller groups to compare their individual experiences in *Reconciling Traditional PhD and ERC Culture Models of Industrial Internships* and *Multidisciplinary Course/Degree Programs: Student and Faculty Teaming Across Disciplines.* Because all of the currently funded ERCs were represented at this meeting, our collective input may be useful in defining the precise nature of what has come to be called "the ERC model of the new PhD".

In his opening remarks Bill Costerton noted that a 1991 COSEPUP survey of 437,000 holders of PhD degrees indicated that only 45% worked in the universities, and that only 31% occupied tenure track positions. Industry employs 36% of the total number of PhDs, while the federal government and medical institutions employ an additional 13% of holders of this advanced degree. Estimates of the pattern of employment of PhDs in Engineering all suggest that an even smaller proportion are employed in academic positions. A somewhat sinister trend was also detected in the COSEPUP survey, in that candidates receiving PhD degrees in science and engineering in 1991 had spent an average of 8.7 years in their graduate program, as opposed to an average of 7.0 years in 1960. These data raise the disturbing possibility that degree programs are being elongated because of dismal employment prospects in academe, and because of the use of graduate students as cheap labor in a "depressed" research climate. These statistics are noted in the COSEPUP report (abstract appended), and the COSEPUP committee has made the following observations on their importance:

1) *Graduate Schools have traditionally seen their mission as producing the next generation of academic researchers.*
2) *Graduate scientists and engineers now contribute to national needs in many other ways...outside of the framework of academic research.*
3) *To contribute more effectively to the need for highly trained scientists and engineers, graduate schools need to review their missions and consider new approaches.*

The COSEPUP committee also surveyed the job market for newly graduating PhDs and made the following observations:

Many future job opportunities will favor students with a greater breadth of academic and career skills than graduate students typically acquire today. The committee therefore recommends a new model of PhD education.

Because we perceive that the ERC model of PhD education embodies all of the attributes suggested by the COSEPUP committee for the "new PhD," the ERC meeting undertook a detailed definition of the salient characteristics of the graduate education programs of its component Centers. This definition was guided by the process of providing answers to specific questions which form the headings for the following sections.

Does your ERC grant graduate degrees?

Twelve of the ERCs represented at the meeting stated that they do not grant graduate degrees, but that this is a exclusive function of the student's home departments. However, some ERCs are heavily embedded in a particular university department and can therefore influence and control specific degrees programs. Examples are the PhD in Computational Engineering at Mississippi State, and the PhD in Manufacturing Engineering at the University of Michigan. The ERC at the University of Maryland similarly controls an MSc program in Systems Engineering, the ERC at the University of Southern California controls an MSc in Multimedia, and the ERC at MIT offers an MSc in Engineering Management that bridges the Schools of Engineering and Management. However, it is generally true that the ERC model of PhD education relies heavily on the ability of the ERC to "seduce" students onto cutting-edge interdisciplinary teams without compromising their academic progress in their home departments.

Do the ERCs actually produce a different kind of PhD?

Discussion revealed that there is a distinct "spectrum" in the interdisciplinary characteristic of ERCs, in that some centers focus on a fairly narrow field, involving one or two departments, while others span as many as 13 departments in as many as 4 faculties. Generally, the meeting felt that the ERCs produce graduates at the PhD level who are notably much more familiar with a wide breadth of scientific and engineering disciplines than the graduates of traditional programs. The mandatory connection of ERC graduate students with industry produces graduates with a very highly developed understanding of the industrial "mindset", and a detailed knowledge of the problems facing specific companies. Because industry works predominantly in interdisciplinary teams, ERC graduates waste very little time in accommodating to the industrial *modus operandi* and most of these ERC graduates integrate rapidly and painlessly into corporate R&D teams. Because all of the ERCs are currently urged to include large numbers of undergraduate students in their research programs, several centers report that their PhD graduates have gained extensive supervisory experience and are already excellent managers when they join industry. ERC representatives also claimed that ERC graduates excel in communication skills because of the emphasis that the centers place on both departmental and industrial interfaces. The metric that supports these contentions most effectively is that several ERCs report that 60-80% of their graduates have chosen industrial careers, and that they have risen rapidly through the ranks of the companies that have employed them.

Within the academic rubric, the ERC representatives contend that their graduate programs are "ahead of the curve" because they are both interdisciplinary and industry-oriented. The obvious nature of these programs tends to attract a different kind of engineering graduate student, including those who are most comfortable with associations with both "hard" and "soft" sciences. While the ERCs attract graduate students with an focused plan for employment in industry, they also attract students who value the interdisciplinary nature of the ERC programs, and are willing to "pay the price" for this kind of education in terms of sharply increased work loads. Representatives from even the newest of the ERCs (e.g. Georgia Tech) state that ERC graduates are very valuable to the university system because they are visionary, and because they tend to reject the traditional disciplinary rivalries that constrain new educational initiatives in academe. Supplementary conversations indicate that several universities that have ERCs have used the ERC model of graduate education to forge effective connections between departments with common research interests but with dispartite academic traditions. The emphasis that several ERCs have placed on innovative, often multimedia, educational techniques are also quoted as examples of how the ERC culture exerts a positive impact on the universities in which they have developed.

Do the ERCs graduate programs embody the COSEPUP ideals for the "new PhD"?

The three ideals that the COSEPUP report sets forth for the "new PhD" are that it be interdisciplinary, and that it emphasizes team research and industrial relevance. The ERC representatives concluded that the ERC model is truly interdisciplinary, and that this characteristic is driven by the ERC focus on interdisciplinary research. We are agreed that a vague academic resolve to develop interdisciplinary education programs is doomed to failure, but that a well-funded interdisciplinary research program can drive an interdisciplinary education program very effectively. Team teaching is especially effective in the delivery of interdisciplinary education, and several of the ERCs have extensive experience in the coordination of as many as four professors from as many as four different departments in the teaching of courses taken by most of their graduate students. One of the ERC representatives made the accurate observation that team teaching leads, inevitably, to team learning on the part of the faculty and that this process of team teaching is inherently a team building exercise within the ERC.

Mississippi State involves a team of professors in the teaching of courses in Computational Field Simulation, and puts the resultant synthesis on the Internet to advance the cause of cross-training between Mathematics and Computational Engineering. The ERC at Texas A and M has had some positive experiences with capstone design courses taught by interdisciplinary faculty teams. The ERC at Georgia Tech has turned some of its testbed facilities over to interdisciplinary teams of both graduate and undergraduate students, and these students run education programs based on these testbeds without significant faculty participation. Those ERCs that are housed in contiguous space have, perhaps, the greatest advantage in interdisciplinary education in that graduate students from as many as 13 different departments work in close proximity, and develop associations and friendships that make them truly interdisciplinary in every respect. Participants in the ERC meeting addressed the subsidiary question - How do you know when your field is "ripe" for an interdisciplinary course/program? The answers were very revealing in that several people said that you know you field is ready when industries in the field form interdisciplinary teams. Others pointed out that funding agencies often reflect their judgement in the structure of their Requests for Proposals (RFPs), and that interdisciplinary teams are often formed by independent researchers long before ERCs or traditional departments perceive the need for cooperation.

Many participants stated that team supervision of graduate students is often a particularly effective means of fostering interdisciplinary education. Our own ERC (Montana State) has recently recorded an unusual case in which an MSc candidate in Microbiology was advised by a faculty team comprised of a Civil Engineer and a Microbiologist, in which the engineer was the official supervisor. The ERC at the University of Washington is experimenting with team supervision of two PhD candidates, but this ERC is new and the results are not yet obvious. A device that has been useful in several ERCs has been to involve the graduate student very intensively in the choice of her research area, and then to involve her again in the choice of her supervisors, who may well constitute an interdisciplinary team if the thesis lies in a "border" area. Many pivotal choices are made as the "seats" on the graduate student's supervisory committee are filled, and input from members from ancillary disciplines may be very useful. To date no inter-university PhDs have been granted within the ERC rubric, even though several ERCs are "shared" between two universities. In the process of developing an interdisciplinary PhD program it is especially important to hold frequent meetings of the supervisory committee to be assured that the student is not veering out of her declared area, under the strong pressures of team research. Additionally, it is important to be certain that the graduate student is not being unfairly loaded with "chores" for the team that do not contribute directly to the progress of her thesis. Students undertaking an interdisciplinary graduate program, within the framework of an ERC, should be clearly apprised of the additional obligations involved, including attendance at two full sets of seminars and at team research meetings.

The industrial relevance that lies at the heart of the ERC program must be seen in terms of an opportunity for graduate students, and not as an obligation to form functional links with specific companies. ERC graduate students comprise a spectrum of degree of commitment to industrial research that ranges, from the fully committed to the "otherworldly" and academically detached, and both ends of the spectrum should be served. Most ERC students actually plan a career in industry and the ERCs constitute clearly the best vehicle for their ambitions within the academic framework. All ERCs provide their graduate students with regular opportunities to interact with R&D people from industry, and many of these centers encourage internships and other structured interactions that result in more than half of their PhD graduates finding employment with companies with which they have already interacted. The ERC at the University of Michigan has created a "PIM" program in which the graduate students spend two years in industry, as a part of their structured education program, and graduates of this program have shown the depth and breadth of education prized by industry.

It is of paramount importance to industry that newly-graduated PhDs should have some of the skills that will make them successful in industrial research. We are told by industry that general problem solving skills are more important than detailed knowledge of the problems facing a particular industry, and ERC programs provide these skills because most ERC research projects are inherently problem-based. Strategic planning is an important process in industry, and several ERCs (notably those at the Universities of Colorado and Maryland) have involved their graduate students in this process to give them experience that will benefit their careers in industry. The ERC at the University of Maryland teaches project management at the MSc level, and the ERC at the University of Minnesota teaches communication skills to all of their graduate students. Because virtually all modern industrial R&D is carried out by interdisciplinary teams, ERC graduates can integrate directly into virtually any corporate research team without the "lag" time required by graduates of traditional departmental programs. Because most engineering departments have at least some contact with the industrial world, it is difficult to imagine the naivete of the average PhD graduate from a science department, with regard to industrial research. For this reason, scientists graduating from ERCs have, perhaps, the most to gain from this new paradigm in graduate education.

What are the problems inherent in implementing the ERC model of graduate education?

The participants in the ERC meeting divided the problems in implementing the ERC model of graduate education into those encountered in academe, and those encountered in industry. Most agreed that traditional university departments resemble centrifuges, in that they exert minimal stress on research and education programs that lie near their "center of gravity," and maximum stress on those that lie at the periphery. Perhaps the university departments that are the most amenable to interdisciplinary cooperation are those that realize that their centers have "cavitated," and that some central areas (notable Particle Physics and Polymer Chemistry) offer few grants and very few jobs. Educational managers within ERCs, and those in all units that hope to emulate the graduate programs of the ERCs, must maintain excellent relations with all of the traditional departments in their area of interest. This useful exercise involves constant vigilance to be sure that students do not suffer because of the competing demands of the center and the department, and to be sure that faculty who commit themselves to the center are not penalized in departmental evaluations. Because the ERC may effectively "poach" graduate students from traditional departments, the center should share the costs of graduate student recruitment with the departments. Cordial relationships with department heads should be cultivated at all costs, because the departments are the degree granting units of the university and the academic "homes" of virtually all ERC faculty.

Most of the faculty who become involved in ERCs and their analogues are "ahead of their times," by the standards set by the COSEPUP committee, and universities must publicly subscribe to these standards, if these innovative faculty members are to be free to function. Many scientists are involved in ERCs and engineering administrators must recognize that these disciplines are further apart on the continuum of ideas, than are disciplines within engineering. Most potential problems with university departments can be solved if the ERC personnel remember to reassure their colleagues that the centers do not seek to dilute academic standards, in the interests of interdisciplinary education, and that depth of training is a prerequisite of effective membership in any research team. The most pressing problems faced by graduate students in interdisciplinary programs is the strenuous simultaneous pursuit of a senior degree in a rigorous discipline and the equal rigorous demands of cross-training, team research, and relationships with industry. There appears to be no solution to this problem, but the value of this accomplishment should be widely recognized.

We must not think of the industries that will employ the majority of our graduates as being much less varied than the universities within which we operate. Some industries still seek to hire PhDs who are well trained in a traditional discipline, and resolve to cross-train them "on the job." This is especially common in industries who hired "interdisciplinary" PhDs from the diluted programs of the 1960s and 1970s. Some industries will value management skills and a detailed knowledge of their peculiar problems more highly than intellectual accomplishment, and may seek to constrain the research of their new hires. In some rare instances, important discoveries made by graduate students may stimulate greed, in either or both the university and the sponsoring company, and the student's progress may be impeded by proprietary considerations if the ERC management is not firm and vigilant. It is reassuring that these academic and industrial problems in the ERC model of graduate education have been steadily overcome, during the 14 years that the program has been in operation, and that any academic supra departmental entities following the same path can have the benefit of our experience.

Specific Instances of Success Within the ERC Framework

While agencies may develop innovative educational programs, and seek to implement these initiatives by a familiar mixture of positive and negative incentives, the real measure of success is the degree to which the educators themselves buy into these programs. If the educators themselves are completely "on side," they will extend the scope of the program with imaginative extensions of its stated goals and recommended mechanisms. The informal "swap shop" at the 1996 ERC meeting, which solicited projects about which the individual ERCs were most excited, contained the following examples of imaginative educational initiatives within the ERC program.

- These innovations sometimes address educational issues at a very basic level, as in the case of the summer outreach program developed by the ERC at the University of Colorado, in which girls between grades 3 and 5 are enrolled in an "explorers" program in several school districts in the Denver metropolitan area. These girls are selected from a broad range of racial and socioeconomic backgrounds to participate in a "fun" program of optics experiments, and to design a variable angle marshmallow launcher, to stimulate their interest in science and engineering.

- The Data Storage ERC at Carnegie Mellon University has developed a very successful outreach aimed at students in 2 or 4 year technology training programs, who can intern at the center to acquire "hands on" experience that will prepare them for jobs in this fast-breaking area.

- The ERC at the University of Maryland has developed a physically-based dynamic simulation of the semiconductor manufacturing process that has been very successful in providing a "hands on" active learning experience for students ranging from operators with little technical background to graduate students and practicing engineers.

- The ERC at Montana State University has explored the use of its industry-based testbeds as educational facilities. These testbeds include a full scale simulation of a drinking water treatment system, and a field site at which the bioremediation of a gasoline spill is being actively monitored. In this latter case the responsible company has contributed significant funding for the involvement of all of the members of senior undergraduate course (ENVE 534) in field experiments, and in presentations to environmental regulators.

- The ERC at Duke University has developed a program to train future leaders in Biomedical Engineering by enrolling graduate and undergraduate students from four other universities in the goal directed research teams of the center. The program involves a mandatory leadership course in which the students consider team building, ethics, project organization, and legal matters.

- The ERC at the University of Minnesota has developed computer-based instructional modules to teach the fundamentals of both Interfacial Engineering and of Fluid Mechanics to senior undergraduates, graduate students, and colleagues in industry. These modules focus on fundamental concepts, and provide a visually enhanced integration of the mathematical formulation with a minimum of descriptive and interpretative text.
- The Data Storage ERC at Carnegie Mellon University has developed a one day, team taught, workshop in which graduate students are asked to evolve designs for three different advanced recording systems. This workshop draws students away from their specific projects, and teaches them to integrate their concepts into a systems perspective. The success of this workshop has led to the initiation of a new course for graduate students in this very education-oriented ERC.
- The ERC at Montana State University has involved a professional society, the American Society for Microbiology (ASM), in an intense educational exercise aimed at researchers involved in the area of microbial biofilms. The ASM allocated $110,000 for the provision of speakers for a 5 day meeting, at Snowbird (Utah), and a further $40,000 to support the participation of >100 graduate students in what proved to be the definitive meeting of this decade in this fast-breaking field.

What is Industry's Real Response?

In a very real sense industry is a major "customer" that "buys" the largest proportion of the ultimate "product" of the ERC graduate education program - the new PhDs. Industrial managers have responded to hundreds of questionnaires concerning graduate education, but the companies that sponsor specific ERCs have had the unique experience of watching the gradual development of the ERC model of graduate education, and of close interaction with its students. These interactions have been informal, as in expressed interest and mentorships at ERC/Industry meetings, or formal, as in internships and employment. The ERC at Montana State University has formed an Education Subcommittee of its Technical Advisory Committee (TAC), under the chairmanship of Jon Geiger (Olin Corporation), who has taken a very active interest in the new ERC model of doctoral education. Jon attended the 1996 ERC meeting to provide industrial input into the directorate's assessment of the extent to which the ERC program is really producing a "new PhD." His subcommittee has also responded to specific questions posed by Bill Costerton, the director of the ERC with which they have interacted for 4-7 years, and their individual answers are recorded in Appendix A. The respondents included scientific managers from midsized companies, who know this particular ERC's program very intimately, and the Manager of Doctoral Recruiting for a giant company (Procter and Gamble) who can view the ERC program in a broad context.

The high value placed by industry, on an "interdisciplinary education" was confirmed by all respondents, and one even suggested that this emphasis was so self-evident that "only an academic ...... would ask .... this question!" One respondent pointed out that very narrow specialization is often required to enable academic researchers to compete successfully for grants at the cutting edge, whereas a broader knowledge base is required for the applied research more commonly undertaken in industry. There was similar unanimity regarding the necessity of mastery of at least one traditional discipline, by the "new PhD," with the contention that doctoral graduates must bring in depth knowledge of at least one field to the industrial teams within which they will operate. This detailed knowledge of a specific area of science or of engineering must, however, be accompanied by an interdisciplinary mind set. This mindset is fostered by the simple inclusion of thesis committee members from ancillary disciplines, but it reaches significance when the graduate student acquires at least the language of an adjoining discipline, and it reaches its epitome when a doctoral candidate actually becomes functionally conversant with one or more adjoining fields.

Because most academic research is conducted by solitary principal investigators (PIs), and most industrial research is conducted by interdisciplinary teams, the quintessential new PhD faces a steep learning curve when she is hired into industry. All respondents nominated doctoral graduates in the ERC model as their most successful recent hires because of their familiarity with team research. If the truth be told (inadvertently) the greatest barrier to employment in industry, on the part of science graduates, is the inference of intellectual prostitution to a less-than-worthy cause. The industrial mind set of the doctoral engineer is much closer to the COSEPUP objectives than that of the doctoral scientist. The ERCs synthesize these mindsets, in that the sponsoring companies can readily measure the possibility that an ERC doctoral graduate can become a part of their extant research teams, on the basis of their interactions within the ERC from which they graduated. The real conviction that the ERC model of the new PhD is attractive and relevant to sponsoring companies, who know individual ERCs very well, is the hiring record of these companies vis-a-vis their associated ERCs. Industry has absorbed 53% of the doctoral graduates of this highly interdisciplinary ERC at Montana State University. The unequivocal conclusion presented by this well-documented pattern is that relevance and team-oriented interdisciplinary research are major priorities of industry, in hiring at the doctoral level, and companies are "putting money where their mouths are."

POSTSCRIPT

In this examination of the recent history of graduate education, and of the emergence of the ERC model of the "new PhD", we are struck by the extent to which this very important educational process is driven by research, and not by education policy. Education policy makers can gather, as they did at the meeting of the academies in June of 1996, and endorse a "new PhD" program featuring interdisciplinary education, team research, and industrial connections but they will be thwarted by the traditional structures of the universities. The functional unit of the university is the department. Departments are powers unto themselves. Most departments guard their intellectual borders zealously and train their acolytes in single PI labs in which their mentors may actually be penalized, in matters of promotion and tenure, if they indulge in interdisciplinary research and produce multiauthor papers. Very few departments, with a few notable exceptions in the engineering field, have any functional contacts with industry. Political solutions, notably the creation of polyglot "mixed" departments, have not generally been successful. The traditional pattern of research funding, to individual PIs in departmental settings, drives the traditional process of graduate education and produces the "old PhD," whose shortcomings are lamented by the COSEPUP committee and the community.

The strength of the traditional departments is that they make rigorous demands of their acolytes. This strength is maintained in supradepartmental research entities, like the ERCs, that leave their graduate students in their traditional departments, but provide a much expanded research experience in interdisciplinary industry-oriented teams. This system makes huge demands on the graduate student, who must satisfy the demands of both entities, but the result is truly the "new PhD." In a very real way, the ERC model of the "new PhD" is the product of a research strategy. The ERC division of the NSF decided to fund interdisciplinary centers of excellence, with the primary mandate of improving the competitiveness of American industry. The result was sustained high level funding for interdisciplinary research groups that depended, as research groups always do, on the unremitting labor of hundreds of graduate students. The doctoral students in the ERC system caught the contagious enthusiasm of their mentors for interdisciplinary team research, and many made highly satisfactory contact with industry. A research funding strategy provided the driving force for a unique educational paradigm, and hundreds of PhDs were educated in a pattern very close to that envisioned by the COSEPUP committee.

If, as seems to be the case, research funding policy really drives educational innovation at the doctoral level, the ERC program of the NSF and the "centers" programs of other agencies should be seen as educational "engines" as well as research "engines." Within the ERC program the characteristics that produce the "new PhD" are rapidly being expanded into undergraduate education, and even into community outreach. The existence of supradepartmental research entities in the university framework breaks the traditional departmental pattern in the best possible way - it maintains and supplements it. Massive long term grants have served to build supradepartmental centers of excellence in selected universities, and the results have been exciting in an educational context, but the process is inherently limited by financial constraints. The future of these educational innovations depends on the universities themselves. If they really subscribe to the tenants set forth by the COSEPUP committee, they will assess the areas of real research strength on their own campuses and create supradepartmental units that pool their research funding and operate in research teams. If these supradepartmental units are assured of long range funding, and established in contiguous space, their research funding will drive their education programs, and we will see thousands of "new PhDs" whose salient characteristics will delight industry and academe alike.