3.0 RESEARCH MANAGEMENT

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CONTENTS

3.1 INTRODUCTION AND OVERVIEW 3

3.1.1 Chapter Organization and Objectives 3
3.1.2 The Nature of ERC Research 3

3.2 STRATEGIC RESEARCH PLANNING 6

3.2.1 State-of-the-Art Analysis 6
3.2.2 Vision 7
3.2.3 Identification of Technical Barriers 7
3.2.4 The Research Strategy 8
3.2.5 Achieving Participant Buy-in 15

3.3 IMPLEMENTATION OF THE RESEARCH PLAN 18

3.3.1 ERC Research Management Team 18
3.3.2 Initial Implementation Steps 19
3.3.3 Updates and Revisions to the Research Plan 20
3.3.4 Management of Research Funds 22
3.3.5 Industrial Collaboration and Technology Transfer 25

3.4 RESEARCH INTERFACE WITH OTHER ERC PROGRAMS 26

3.4.1 Education 26
3.4.2 Knowledge Transfer/Outreach 28

3.5 OVERALL IMPACT ASSESSMENT 29

3.5.1 Intellectual/Academic Advancements and Achievements 29

3.6 CROSS-DISCIPLINARY RESEARCH IN A DISCIPLINARY ENVIRONMENT: CHALLENGES AND REWARDS 31

3.1 INTRODUCTION AND OVERVIEW

3.1.1 Chapter Organization and Objectives

A key distinguishing feature of a National Science Foundation Engineering Research Center (ERC) is strategic planning of the activities of the center, including cross-disciplinary research. The objective of this chapter is to describe methods for carrying out strategic research planning (Section 3.2) and its implementation (Section 3.3). The interface between research and other ERC components – such as education and outreach – and the impact assessment of ERC outcomes are covered in Sections 3.4 and 3.5. A final section (3.6) summarizes the challenges and rewards of research in a cross-disciplinary environment.

3.1.2 The Nature of ERC Research

Engineering Research Centers are changing the culture of academic research and education. They do this by providing an environment in which academe and industry can focus on advancing the science and engineering concepts underlying complex engineered systems that are important for industry and the Nation's future. ERCs create a synergy between a critical mass of scientific and engineering disciplines and industrial practice. They produce a culture where faculty, graduate and undergraduate students work in research teams, blending their in-depth disciplinary knowledge to achieve the system-level goals of the center. They also provide the foundation for academe and industry to form long-term, trusted partnerships where industrial personnel collaborate with faculty and students on generic, mid-term, and long-range challenges. ERC teams explore these challenges at the fundamental level, carrying them through to proof-of-concept testbeds, thereby producing the knowledge base for steady advances in technology and speeding their transition to the marketplace.

A successful ERC develops a research strategy that addresses key barriers that lie in the pathway of needed advances in next-generation engineered systems, blending discovery-driven fundamental research with research focused on technological advancement.

To realize its full potential, an ERC must develop a research strategy that integrates the entire research effort, from discovery to development of testbeds, while ensuring that all participants -- including students, faculty, and industrial partners -- are drawn in and actively contribute to reaching the goals of the center. The interdependence of the breakthroughs in fundamental knowledge and enabling technology (i.e., tools that permit further research and development), and how these discoveries lead to proof-of-concept testbeds at the systems level, must be clear to all center participants if the ERC is to succeed (see Figure 3-1). The strategic plan supplies the framework on which the ERC's research is organized and enables the ERC to become more than the sum of its individual parts. The research strategy and the process of planning are key to communicating to each participant how his or her research project and/or expertise fits into and enhances the efforts of the entire center. Subsequent management of the research program, properly carried out, ensures that the plan has the maximum chance of succeeding.

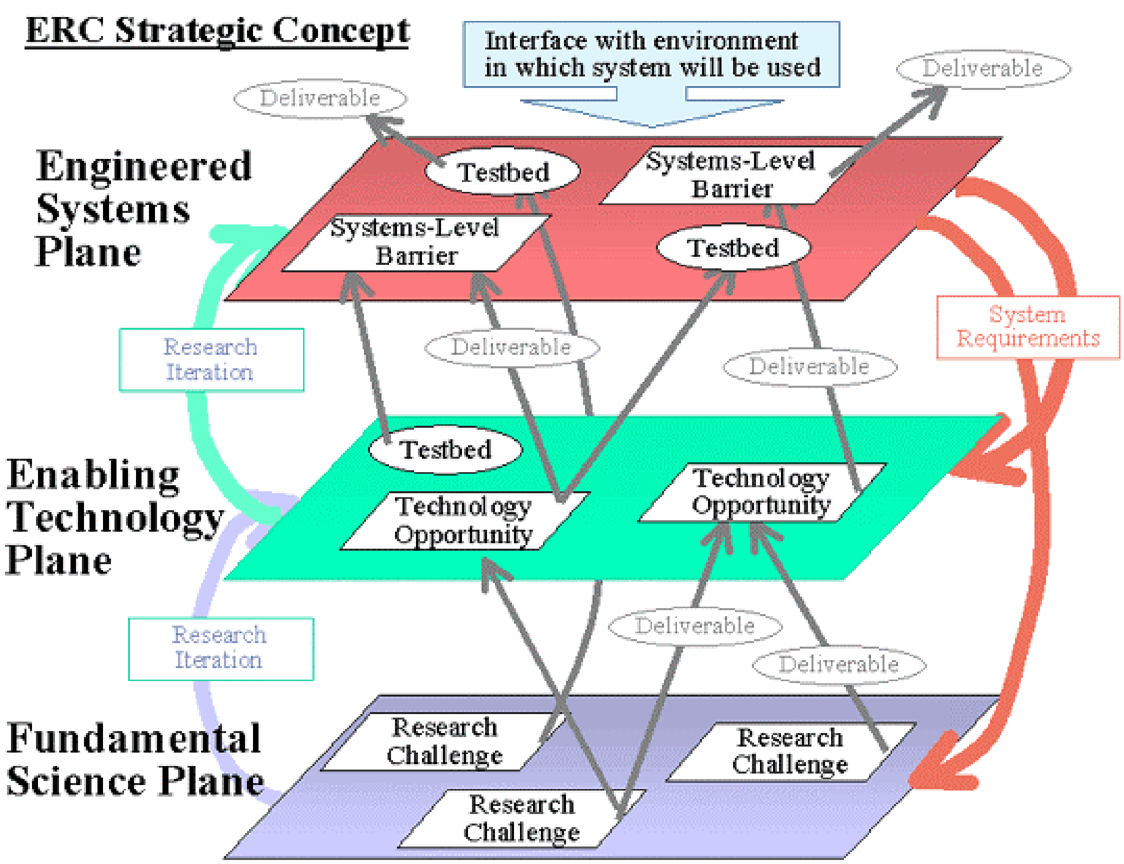


Figure 3-1

Although the features of a research plan are addressed in a linear fashion in the following sections, the actual planning process often is less methodical. To be most effective, the planning process should be adaptive and reconfigurable as conditions change, goals are achieved, prospects end, or new goals emerge throughout the life of the center (see Figure 3-2). The strategic research plan is a multi-purpose tool that will aid in team building, setting common goals, communicating effectively within the center, and facilitating discussions about future research directions.

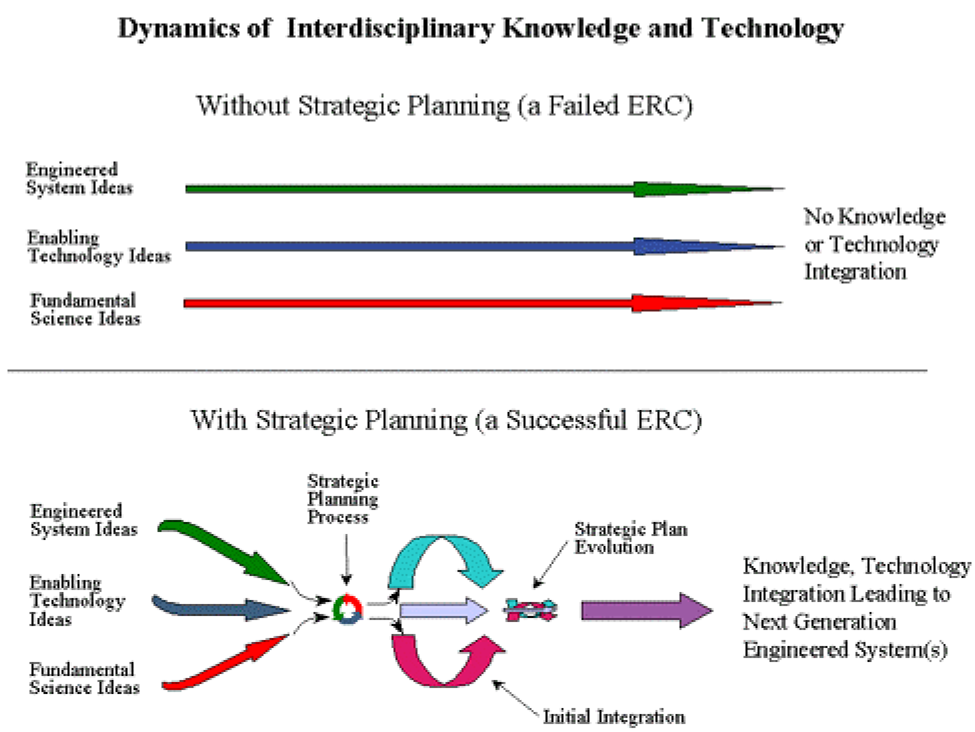
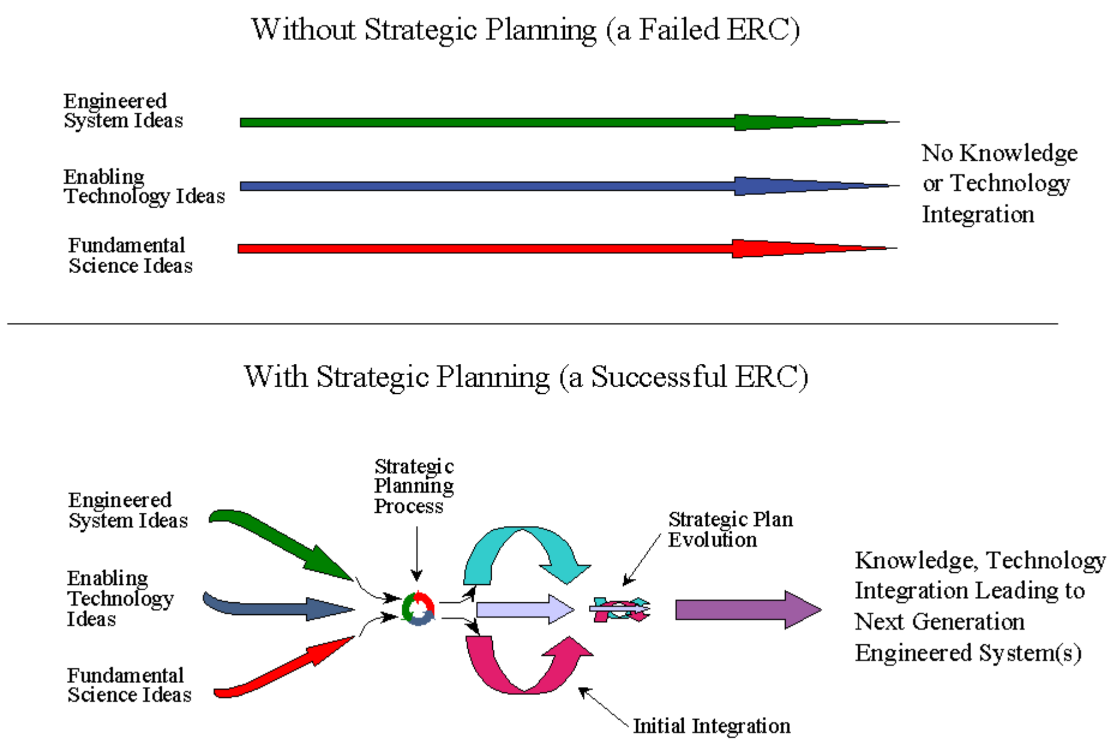


Figure 3-2

Figure 3.1: Dynamics of Interdisciplinary Knowledge and Technology



3.2 STRATEGIC RESEARCH PLANNING

Each ERC develops an overall strategic plan that encompasses all areas of its operation. This level of planning is discussed briefly in Chapter 2, "Center Leadership and Strategic Direction." However, the core of the ERC's strategic plan is its research strategy. Strategic research planning is generally a systematic, stepwise process, as described below.

3.2.1 State-of-the-Art Analysis

The first step in developing an ERC research strategy should be to conduct an analysis of the state of the art in the field. An understanding of the state-of-the-art underlies the development of a center's vision of achieving major advances in a next-generation engineered system. This understanding aids in identifying the barriers that stand in the way of further progress, culminating in a set of research objectives that, if met, move the center toward achieving its vision. Thus, the state-of-the-art analysis gives the current situation, the vision statement describes the desired future state, and identified technical barriers elucidate what needs to be done so that the future outlined in the vision statement can be achieved. As the center progresses, the state-of-the-art analysis should be continually updated, tracing the development of the work in fields closely aligned with the center's vision and documenting the contributions made by the ERC's faculty and others around the world. This documentation provides the center with a history of its contributions, and those of others, to the field.

3.2.2 Vision

Just as a well-thought-out research strategy is essential for effective research management, a compelling and well-articulated vision of the center's purpose and advances to be achieved is the key to a compelling research strategy. The vision should motivate and encourage participation and interest in the center and its activities, aid in recruiting faculty and industry to become involved in the center's research agenda, and attract industry and government support. It is important to have the broadest possible understanding and acceptance of the vision among ERC participants. Without this, it will be difficult to keep the research integrated and focused on achieving the goals of the center. It is essential that all participants understand the vision, why it is important, and the means the center plans to employ to achieve the vision. The steps required to achieve the vision and how these steps will be undertaken should then be articulated in the strategic plan.

All ERC participants responding to a questionnaire distributed by the authors of this chapter agreed that it is the Center Director who is responsible for initially articulating the center's vision. Usually it is the Director who recruits research faculty and staff who have expertise in a particular area considered to be essential for achieving the center's vision. The challenge is in formulating a shared vision that balances "top down" management with "bottom up" faculty expertise. The Director is responsible for putting in place a *process* for formulating the center's shared vision. If this is skillfully done, faculty should take part in contributing to an achievable vision, developed through a logical, participatory process, not one mandated from above.

3.2.3 Identification of Technical Barriers

As in engineering practice, where definition of the problem is one of the most important steps in the process of developing a solution, in academic research management articulation of the technical barriers is essential in carrying out a successful research strategy. Otherwise, the center faculty could easily work on solving problems that may be of interest to them but that would not lead the center toward achieving its vision.

In some cases, there may be a number of technical barriers to achieving the ERC's next-generation systems goals and a center may choose to focus on only a few of them. It may be that the barriers represent different approaches that could be taken to achieve the same vision, and by choosing a subset of them the center is making a statement about what it believes to be the optimum method for achieving progress. Or the center may choose certain barriers on which to focus based on the core competency or expertise of the majority of the center participants. No matter the reason for the choice of problems to tackle, the center should make it clear to all participants why the technical barriers it chose to address were selected. This will help in further elucidating, to those inside and also outside of the center, the strategy the center plans to follow in achieving its vision.

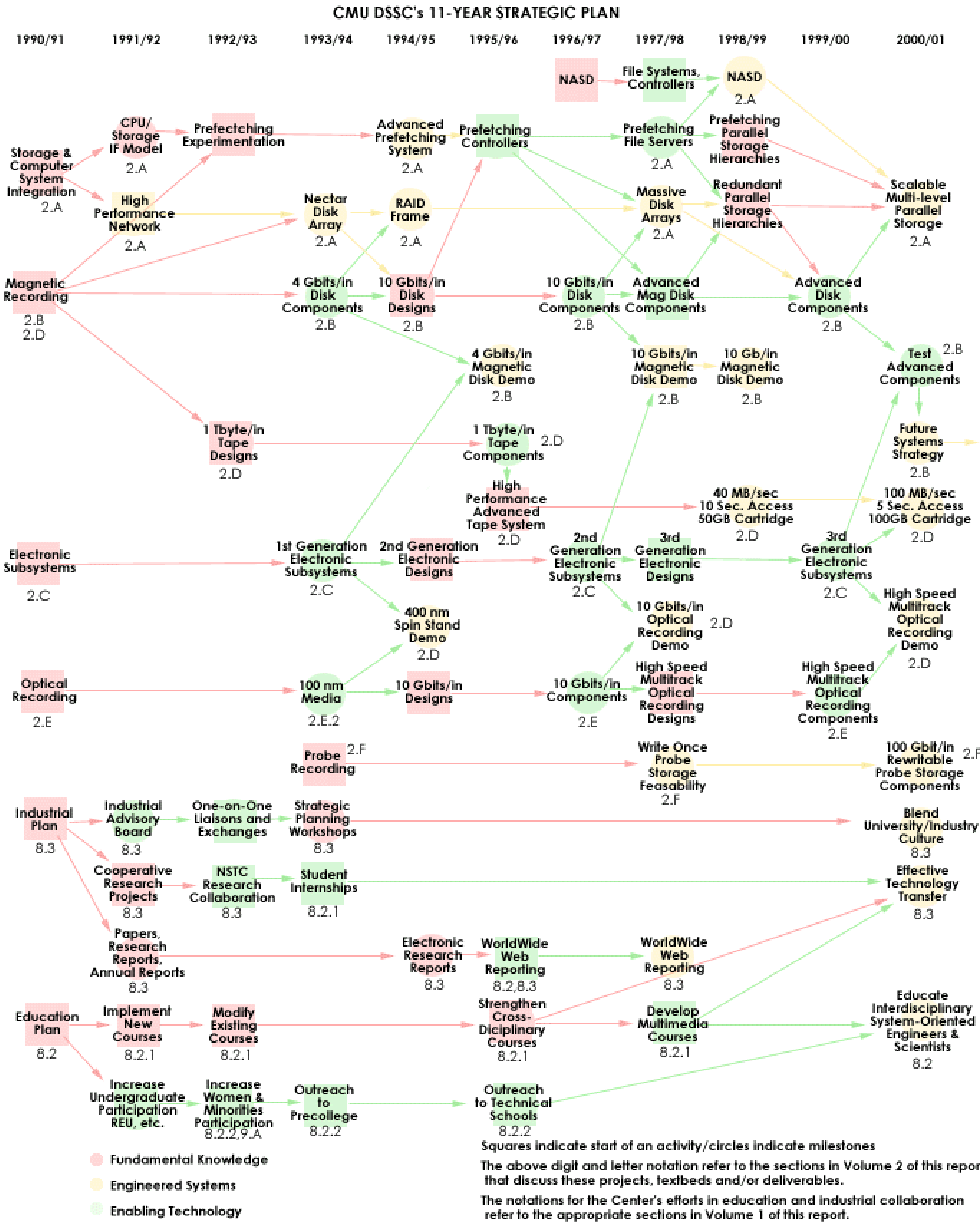
A center must also identify broader barriers to success that are not strictly technical, such as costs, policies, and regulations. In some fields, industry is in an excellent position to thoroughly appreciate these issues. They develop products for various applications and understand the forces that may prevent their products from being accepted in the marketplace. One forum for identifying barrier issues is at a strategic planning meeting that includes industrial representatives, where technical discussion sessions focused on barrier issue identification may be held among faculty, students, and industrial colleagues.

3.2.4 The Research Strategy

The research areas on which the center has chosen to focus in order to achieve its vision should follow from its understanding of the state of the art and identification of the technical and system-level barriers yet to be overcome. The heart of a center's strategy is how its research is brought to bear on these barriers, which cannot be overcome without the integration of interrelated research activities.

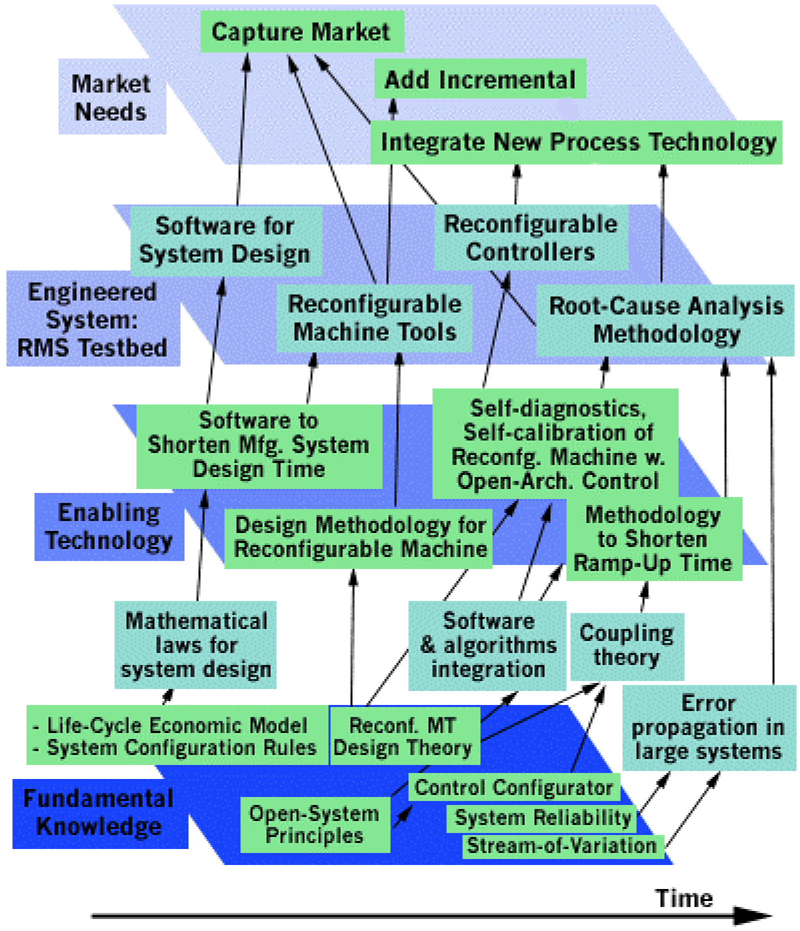
Each ERC focuses its research efforts at three levels: fundamental research, development of enabling technology/tools, and the engineered systems level. The relative distribution of effort across these three levels will differ from center to center, and across time at a given center. The research strategy should identify what breakthroughs or developments in fundamental science and/or enabling technology are required initially, how they are interconnected, how further progress will build on these achievements and contribute to a convergence on the systems level, and which projects can and should proceed in parallel.

Each ERC should include in its plan the components discussed here. However, creativity in the development of individual center plans is valued and expected. Various approaches to strategic planning will be found to be preferable in individual centers, depending on their field and their specific circumstances. Attachment 3-1 to this chapter shows actual strategic plans of three ERCs. All are examples of effective plans, yet they cover a spectrum from loose/conceptual to tight/detailed and highly defined.


CMU DSSC's 11-YEAR STRATEGIC PLAN
1990/91
1991/92
1992/93
1993/94
1994/95
1995/96
1996/97
1997/98
1998/99
1999/00
2000/01
NASD
File Systems, Controllers
NASD 2.A
Storage & Computer System Integration 2.A
CPU/ Storage IF Model 2.A
Prefetching Experimentation
Advanced Prefetching System 2.A
Prefetching Controllers
Prefetching File Servers 2.A
Prefetching Parallel Storage Hierarchies
Scalable Multi-level Parallel Storage 2.A
High Performance Network 2.A
Nectar Disk Array 2.A
RAID Frame 2.A
Massive Disk Arrays 2.A
Redundant Parallel Storage Hierarchies
Magnetic Recording 2.B 2.D
4 Gbits/in Disk Components 2.B
10 Gbits/in Disk Designs 2.B
10 Gbits/in Disk Components 2.B
Advanced Mag Disk Components
Advanced Disk Components 2.B
4 Gbits/in Magnetic Disk Demo 2.B
10 Gbits/in Magnetic Disk Demo 2.B
10 Gb/in Magnetic Disk Demo 2.B
Test Advanced Components 2.B
Future Systems Strategy 2.B
1 Tbyte/in Tape Designs 2.D
1 Tbyte/in Tape Components 2.D
High Performance Advanced Tape System 2.D
40 MB/sec 10 Sec. Access 50GB Cartridge 2.D
100 MB/sec 5 Sec. Access 100GB Cartridge 2.D
Electronic Subsystems 2.C
1st Generation Electronic Subsystems 2.C
2nd Generation Electronic Designs
2nd Generation Electronic Subsystems 2.C
3rd Generation Electronic Designs
3rd Generation Electronic Subsystems 2.C
400 nm Spin Stand Demo 2.D
10 Gbits/in Optical Recording Demo 2.D
High Speed Multitrack Optical Recording Demo 2.D
Optical Recording 2.E
100 nm Media 2.E.2
10 Gbits/in Designs
10 Gbits/in Components 2.E
High Speed Multitrack Optical Recording Designs
High Speed Multitrack Optical Recording Components 2.E
Probe Recording 2.F
Write Once Probe Storage Feasability 2.F
100 Gbit/in Rewritable Probe Storage Components 2.F
Industrial Plan 8.3
Industrial Advisory Board 8.3
One-on-One Liaisons and Exchanges
Strategic Planning Workshops 8.3
Blend University/Industry Culture 8.3
Cooperative Research Projects 8.3
NSTC Research Collaboration 8.3
Student Internships 8.2.1
Effective Technology Transfer 8.3
Papers, Research Reports, Annual Reports 8.3
Electronic Research Reports 8.3
WorldWide Web Reporting 8.2,8.3
WorldWide Web Reporting 8.3
Education Plan 8.2
Implement New Courses 8.2.1
Modify Existing Courses 8.2.1
Strengthen Cross-Diciplinary Courses 8.2.1
Develop Multimedia Courses 8.2.1
Educate Interdisciplinary System-Oriented Engineers & Scientists 8.2
Increase Undergraduate Participation REU, etc.
Increase Women & Minorities Participation 8.2.2,9.A
Outreach to Precollege 8.2.2
Outreach to Technical Schools 8.2.2
Squares indicate start of an activity/circles indicate milestones
The above digit and letter notation refer to the sections in Volume 2 of this repor that discuss these projects, textbeds and/or deliverables.
The notations for the Center's efforts in education and industrial collaboration refer to the appropriate sections in Volume 1 of this report.
Fundamental Knowledge
Engineered Systems
Enabling Technology

Example 1

Example 1 U. Michigan ERC/RMS Strategic Plan



Example 2

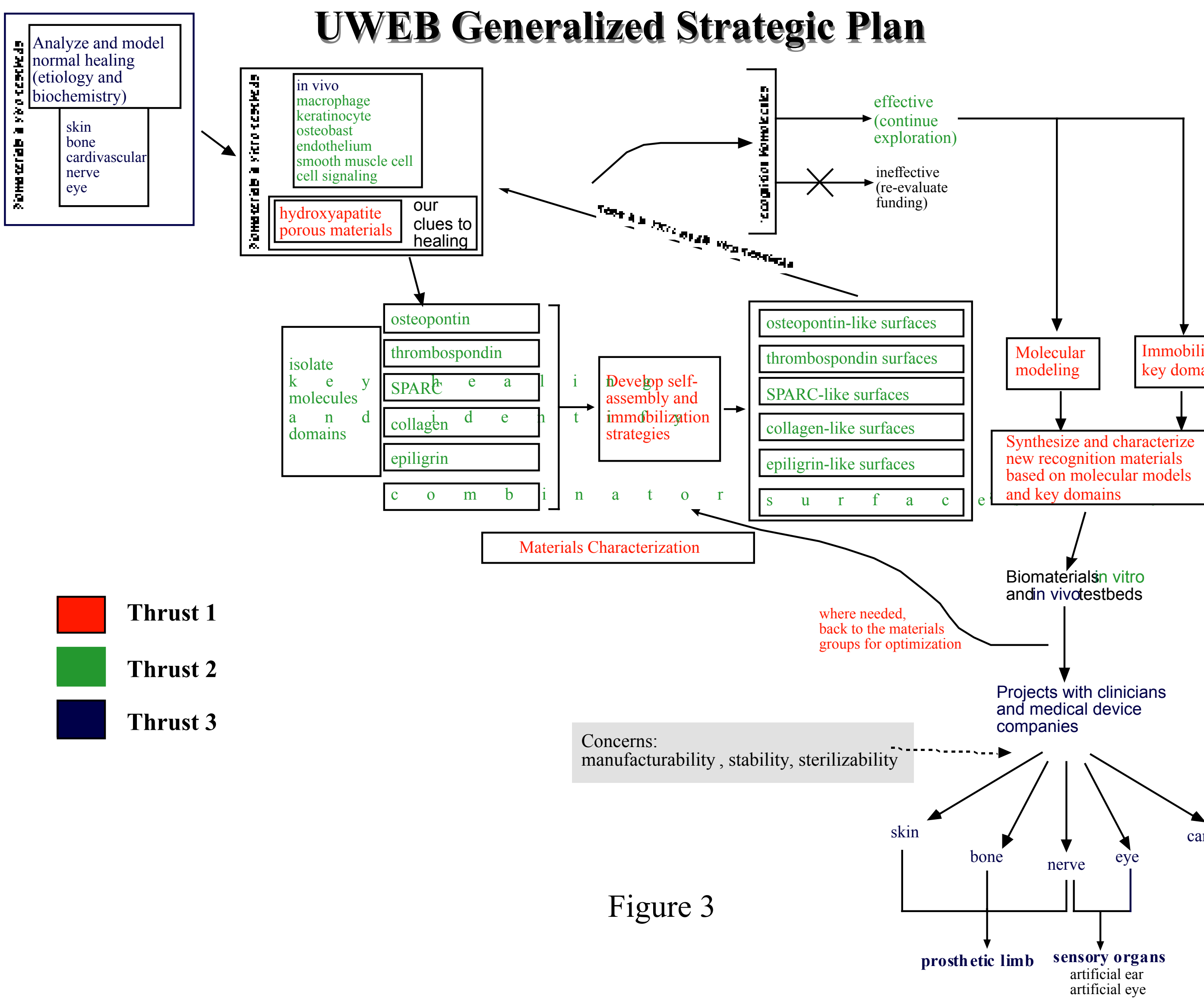


Figure 3

Example 3

3.2.4.1 Goals and Objectives

In organizing its research strategy, a center should formulate major goals that must be met as a demonstration of progress toward achieving its vision. The formulation of clear-cut goals will aid in defining a pathway toward major accomplishments, along with the outcomes expected from specific projects or research areas.

As in any academic research activity, projects within a center should have objectives and an estimated time required to meet those objectives. As a center strives to meet its longer-term goals, objectives should be specified in the strategic plan that bring to a culmination parts of many individual projects. For example, consider the following related but separate projects: (1) developing the analytical hardware to take atomic-scale images of chemistry differences on a surface, (2) deriving techniques to engineer controlled patterned chemistry at that surface, and (3) refining tools to measure the resultant patterns of biological cells that adhere at different locations on the patterned surface. These projects all have objectives and tangible deliverables. The goal that their combined results achieves is the ability, for the first time, to affect biological cell adhesion in a quantitative way by controlling surface chemistry.

The case study below illustrates the way that objectives support the achievement of goals in the context of a center that strives for large improvements in the performance of electronic systems.

CASE STUDY:
The strategic planning process utilized at Georgia Tech's Packaging Research Center (PRC) begins with the identification of system-level goals, such as a next-generation pager or PC or camcorder. The next-generation pager can be used as an example: Today's pager has some 500 components, weighs 6 ounces, has certain functions, operates at a microprocessor speed of 900 MHz, and costs about $120 to manufacture. The goal might be to improve all these features by a factor of 10 (e.g., in the case of the pager, to achieve 9 GHz operation).

The question is then asked, what packaging technologies are needed? For any electronic device, the answer involves 11 areas: electrical design, electrical testing, high-density wiring, large-area intelligent manufacturing, integral passives, optoelectronics, RF electronics, flipchip assembly, thermal management, reliability, and system prototyping. Each of these represents an enabling technology, and constitutes a research thrust toward the system-level goal. Working with their industrial partners, the PRC then develops a roadmap for each enabling technology. Next, they define the fundamental research projects. A testbed is then formed (this is termed a "test vehicle"), which is a generic prototype for a given electronic device or product such as the pager. The faculty are asked to focus on testing their research results in the context of the test vehicle. This requirement keeps the researchers disciplined in the directions their projects take.

Finally, systems manufacturing companies from among the industrial members use portions of the prototype to build a prototype specific to their industry. For example, Motorola might build a prototype pager, and Boeing might build the power supply for an F-22 fighter.

Thus, the strategic plan provides a structure for the PRC's research and systematizes it in a way that results in a wide range of useful applications.

Just as the PRC's research is drawn from specified systems goals, similarly in the Data Storage Systems Center (DSSC) at Carnegie-Mellon University all strategic planning is focused on attaining a specified system specification (e.g., hard drive or optical drive performance) that is very advanced and ambitious. An example might be to attain 100 Gbit/sq. in. recording density, when the current industry standard is 2 Gbit/sq. in., along with the entire configuration for such a system. Such an approach makes it easier to implement a strategic plan; the goal is finite and concrete. Some ERCs operate in a field that is amenable to this approach; not all do.

In identifying goals for the center, a useful question to ask the faculty during strategic planning is: "What should we expect to see in a year (or two, or three) if you were to be successful?" One ERC research manager who asked this question found that most people replied fairly specifically – enough so that objectives could be derived from the responses. The idea to do this came from the center's industrial partners; it was the kind of information they themselves asked within the company.

3.2.4.2 Deliverables

The ability of the ERC to achieve industrial use of its knowledge and technology is a key element of a successful ERC, one that requires a strong partnership with industry. Deliverables can take many forms, including fundamental knowledge advances and discoveries, new theories or models describing physical properties or behavior, access to students, experimental techniques, software, and new materials and processes. The opportunities to develop these deliverables, and their possible utility to the industrial partners, should be recognized and considered during the development of the research strategy. Deliverables may stem from research at all levels of investigation, ranging from basic science to engineering testbeds. It should be noted that how a deliverable can best be understood and incorporated into a company's workflow is not necessarily straightforward, as students and faculty may have different expectations from those in industry regarding the utility and user-friendliness of the tools they develop.

Experienced ERC research managers find that a steady flow of deliverables is important for keeping industry engaged and satisfied with the center. One recommends that the ERC always try to give industry <u>something</u> every year out of each project. Some centers have hired one or more professional engineering/technical staff members whose job is to turn research results into products that industry can readily understand and use.

See Section 3.3.5 for a discussion of industrial collaboration and technology transfer.

3.2.4.3 Testbeds

The key to determining if the center's research agenda will successfully lead to a next-generation engineered system and achievement of the center's vision is to periodically pull together the research outcomes and test the system. Thus, the research strategy must involve the development of proof-of-concept testbeds, which integrate elements of the system to determine if all components work together as planned. These testbeds not only ensure that the research outcomes are integrated and tested, they also serve to drive the research. They act as focal points for the researchers when planning their research projects. They also supply a framework for faculty, students, and industry representatives to work together and to gain a better understanding of the system they are working with. In addition, and perhaps most importantly, testbeds highlight which areas of the center's research require further investigation, ensuring that the research is focusing on the critical problems that must be addressed in order to achieve the center's vision. Thus, testbeds facilitate modification of the center's research strategy based on what is being learned as the center works toward achieving its vision.

Many ERCs have had highly successful testbeds. An early one, at the Purdue University ERC, was an integrated manufacturing software system called the Quick Turnaround Cell (QTC). The QTC combines computer-aided design and computer-aided manufacturing in a single software package that automates the several operations and processes involved in designing and machining limited numbers of prismatic parts. The QTC testbed was the Research, Development, and Engineering Laboratory of the U.S. Army Missile Command at Redstone Arsenal, near Huntsville, Alabama. In the early 1990s this project broke new ground in inter-institutional collaboration and research, eventually moving from Huntsville to application in industry.

Testbed development relies on research focusing on both fundamental scientific knowledge and the development of enabling technology. Although the balance between fundamental research and technology development may vary from center to center, all centers will have some aspects of both, as both are needed to make significant progress toward the development of the next generation of engineered systems.

3.2.5 Achieving Participant Buy-in

3.2.5.1 Faculty Involvement

When putting together a research strategy and agenda, both the research required to achieve the vision and the research interests of the faculty must be taken into account. If there is not a good intersection of the two, it will be difficult to recruit enthusiastic researchers to the center. Also, in the academic setting, a directive "command approach" generally does not succeed in motivating faculty. A center is most likely to reach its goals if all participants feel a sense of ownership of the research strategy. ERC research managers have found that it is very important to obtain agreement to the research strategy of the whole ERC team up front. Trying to achieve consensus later on is impossible unless there is agreement at the outset.

Obtaining and maintaining faculty buy-in to the strategic research plan are not the same thing. Centers often encounter the problem that, once they have agreed to a strategic plan, faculty members are obliged to modify their own personal research objectives to an extent. Some will try to weave their own research into the center's agenda whenever possible. One Center Director commented that it is important to make it obvious to the faculty fairly quickly (i.e., within 6 months) that they are gaining value from their participation. In his center this issue was "a major continuing challenge, requiring endless discussion." Another Director noted that it is the Director's job to determine which of the faculty has a broad enough intellectual portfolio to make changes that the center needs, at the expense of their personal intellectual pursuits. The faculty cannot do this as objectively as the Director can, and some will resist making major changes in the direction of their research. There must be at least a critical core of faculty who are flexible enough to adapt to changing needs.

The full range of research expertise required throughout the lifetime of the center as it works to achieve the vision may not be resident at the university at which the center is based, nor at any of its partner universities. The need for additional expertise, when it exists, must be recognized and filled by means of outreach to researchers at other institutions. Normally these would be paid research projects; continued involvement of these faculty in the ERC would depend on the quality of their work and its continued relevance to the ERC's needs.

3.2.5.2 Industrial Buy-in

A key element in building a strong industry partnership is to actively involve industry in the strategic planning process. Both the creation and evolution of an ERC and its strategic plan must involve frequent input from the industrial members. Most ERCs have constructed formal mechanisms through which to continually draw upon industry's advice and experience in technology development. These mechanisms are described in detail in Chapter 5, "Industrial Collaboration and Technology Transfer." However, because they are crucial to obtaining industrial buy-in to the center's research program, they will be discussed briefly here.

Typically, initial industrial participation in an ERC is based upon the prior direct interaction of companies with participating faculty members and/or a long-term association with an academic department. Upon proposing an ERC to NSF, several prospective centers have made the effort to involve industries from the relevant technology sector in an intensive workshop to construct and review a proposed strategic plan.

Once an ERC is established, all ERCs devise ways to engage industrial participation. For example, every ERC has an Industrial Advisory Board (IAB) or the equivalent, often with subcommittees for obtaining more specific technical input at the level of Thrust

Areas and projects. Most ERCs hold some form of semiannual IAB meeting. These meetings serve to present research progress to industry and to seek industry's assessment of new research directions. ERCs report that the actual content of specific projects frequently has been "course-corrected" by means of industrial advice. Personnel exchanges in both directions, involving faculty and students as well as industry engineers, are perhaps the best way to increase industrial involvement through technology transfer.

Keeping industry continually involved in the center's strategic planning process can present some difficulties. For example, the Institute for Systems Research at the University of Maryland found it hard to conduct two-way, joint strategic planning with industry because very few companies were willing to open up their own strategic plans. It was much easier to get input from them on the ERC's projects and plans. A couple of observations: Long-term industrial visitors tended to give much more useful input about their company's plans. And individual companies in private meetings with the ERC management gave much more specific input on their plans than they were willing to do in open meetings. This reluctance will vary across centers and industries.

Each center's IAB now carries out analyses of the strengths, weaknesses, opportunities, and threats to survival of the ERC, both for the benefit of the center and for input to the NSF site visit team. (See Chapter 5 for a description of this analysis.)

Such interactions serve to draw the industrial and ERC communities together, but they do not necessarily convince industry to accept or buy into the ERC philosophy. Ultimately, the ERC's responsibility is to develop fundamental discoveries or new technologies that they can then present to industry for further development into competitive, "on-the-shelf" technology. ERCs and their industrial members must resist the tendency to expect the ERC to solve industry's immediate problems. An ERC must not become a research "job shop" for any single company or group of companies. To that end, ERCs should not turn project selection over to their industrial members, as the projects are likely to become skewed in the direction of meeting industry's more immediate needs. Instead, each center must create a mechanism to maintain the collective interest while addressing the specific needs of member companies. In most cases, ERCs promote the funding of specific projects, funded directly by a single company or a small consortium, that address practical industrial needs. Under this mechanism, research results are the property of the company under common licensing agreements and are not shared with all the industrial members.

A center must strive to develop with its industrial supporters a rapport where each recognizes its role in the ERC technology development philosophy. Industry's role is to present the ERC with "model systems" or realistic conditions, so that the ERC's fundamental research has pertinence. A rule of thumb is, "If the ERC cannot pass its discoveries to industry, then it should not do the research." Industry should realize that the time horizon for most technology development in academic basic research is 5-10 years, while in industry it may be measured in months. Again, each ERC must erect infrastructures or mechanisms to draw industry into the active role of taking discoveries and creating technologies. If all an ERC did was to make its industry aware of the basic research without involving industry in the center's pursuit of those advances, the center would be a failure. Mechanisms to develop jointly sponsored research projects or research initiatives that lead to ERC testbeds should be in place at an ERC by Year 3. It is in these joint activities that the ERC and its industry members begin not only to solve problems jointly but also to create new technologies

3.3 IMPLEMENTATION OF THE RESEARCH PLAN

Management of a complex research strategy involving multiple teams, multiple team members, and varying objectives and goals is difficult at best. Section 3.6 summarizes some of the many challenges as well as rewards of research management in such an environment. The complexity of a multidisciplinary undertaking such as an ERC makes a research management plan all the more important. While the strategic plan sets out a unifying vision of what is to be accomplished and establishes overall center research goals and objectives, ultimate success for the entire undertaking requires the establishment and integration of project goals and objectives, including the proper prioritization of time, effort, and resources to be applied to each. This level of research management requires that each project or groups of projects include firm estimates of the resources required to address the project – including people, money, and equipment – in the time given to complete the project.

It is important to realize that research management is not a smooth process. It involves continuous experimentation – especially in the first 5-6 years. The optimum management approach is different for every center, and also will change over time.

3.3.1 ERC Research Management Team

The research management team at an ERC may consist of a varying number of individuals in different functions, depending on the center. At a minimum, the Center Director holds ultimate responsibility for the planning and direction of the overall research program, with a faculty member designated as the leader of each Thrust Area (there are usually three to six such areas); sometimes two individuals share the responsibility for day-to-day Thrust Area management as Co-Principal Investigators (Co-PIs). In some ERCs there is a single Associate Director for Research who is the focal point for all Thrust Area management issues and who reports to the Director.

Every ERC also has an executive group, often called the Research Review Committee, that meets periodically to review and assess progress in the center's research areas, select projects, allocate and adjust research funding, and make adjustments to the center's strategic plan as necessary. This committee typically consists of the Center Director, possibly the Deputy Director, the Associate Director for Research (if applicable), Thrust Area leaders, and one or more representatives from the center's industrial members – or some combination thereof. Thus, another function of the research review committee is to provide direct industrial input into the planning and direction of the research program. In some cases, the committee membership also includes one or more faculty members and even a graduate student.

An example of an ERC research management team is the Directors' Committee at the DSSC. This committee meets every week. Planning is continuous, through the committee, with major inputs from industry twice a year. Project selection is done "more or less in consensus style" by this committee, with the Center Director making the final decisions.

Research management apparently has only subtle effects on the life of the ERC Director. Surprisingly, out of 15 ERCs responding to a survey conducted by the authors of this chapter, all but two Directors reported that they still maintain an active teaching load, with only about a third receiving reduced teaching loads. Also, save for the same two persons, all ERCs Directors maintain personal research programs that are supported by grants independent of the ERC -- although in about half of these latter cases the Directors indicated that their research activities did decline due to the demands of ERC management.

3.3.2 Initial Implementation Steps

In establishing the resources required to complete the research, the relative priorities among intersecting projects must be established, assuring that those projects that must be completed or substantially completed before other work can progress are recognized in advance. The research team must set priorities among and between projects that compete for resources and must set deadlines for deliverables from each project. These actions most often require the creation of a research review committee or some other organizational management entity charged with overseeing the research plan (see Section 3.3.3). Some thought will be required as to how deliverables from each project or set of projects will be communicated to other teams and team leaders as well as to industrial advisory boards.

Defining timetables and milestones for basic research can be both subjective and contentious. Being too specific tends to restrict the center's creativity in pursuing its goals. To get around this difficulty, it is a good idea to develop broad objectives for basic research and review the objectives periodically throughout the year.

It is necessary to establish a finite duration of projects – not much longer than 1-2 years in most cases. Project support through the ERC should never be considered permanent – even for the core faculty. As one Director puts it, "There is no tenure at an ERC." It is the responsibility of the Thrust Area Leaders to hold project leaders accountable for achieving milestones on schedule. Similarly, it is the responsibility of the Center Director and Associate Director for Research, along with the research review committee, to hold the Thrust Area Leaders accountable for programs in their areas.

Management of the research program should take into consideration the objectives of other program elements of the ERC, such as education (see Section 3.4). Processes should be established and exercised to ensure frequent faculty/student interaction across the disciplines or research teams. One of the most important elements of the ERC program is the creation of interdisciplinary activities to address difficult engineering problems. Often this feature of an ERC is under-appreciated because of the demands of specific fields, areas of investigation, or projects. Within projects and fields there is considerable interdisciplinary activity, which is often taken for granted (if it is working well) but which should be identified regularly, drawing attention to what worked well, what didn't, and why. One way to do this is to develop internal workshops and symposia for center personnel to share and discuss their interdisciplinary efforts. Involving the students in this activity is one of the most important contributions an ERC can make to the field of engineering, as it helps in creating a competent, cross-disciplinary work force capable of working on difficult problems in industry and academe across disciplinary boundaries. Similarly, involvement of experienced students in research management team meetings strengthens the ERC and helps prepare students better for the future.

3.3.3 Updates and Revisions to the Research Plan

Research managers must establish and exercise processes to revisit and revise the research strategic plan regularly, incorporating progress in research efforts as goals are achieved. The plan is only as good as the benchmarks it sets, so in order to be a useful tool, it must be modified as progress is made or as the overall center strategy changes. The plan helps keep the entire effort on track and communicates the progress and timeline to all members of the team. It is useful to establish a method for frequent exchange of information -- on a Web site for example -- where basic assumptions about the plan can be seen by everyone. A time should be set for a regular *brief* review of the plan by the entire team. The outcome of this review might include new time schedules, integration of activities, or new goals and objectives discovered as a result of ongoing work.

Research managers also must establish and exercise processes to determine which projects to terminate and which to add. Within the competing demands of a strategic plan, it is important to regularly review the steps being taken to achieve the center's goals and their relative priority. To preserve valuable resources and enhance the productivity of the center, it may be necessary to terminate projects that once seemed important in isolation or in relation to other facets of the effort, but that upon reflection appear to be unrealistic or non-viable. Projects may also be terminated if they have not progressed as planned or expected. In general, projects that do not involve more than one center faculty member <u>and</u> that do not relate directly to other projects or communicate with other Thrust Areas should not continue to receive ERC support. (Occasional exceptions will occur with projects that are providing crucial support to the ERC's efforts.) On the other hand, in the regular review of the strategic direction of the center and its goals, it is equally important to launch new efforts as soon as they are discovered to be potentially vital to the achievement of the goals and objectives of other projects or the overall goals of the center. The main criterion for selection <u>or</u> deselection should be "Is the project on the ERC's critical path?" That is, does the project contribute directly toward the achievement of one or more of the milestones? (For further discussion, see Section 3.3.4, "Management of Research Funds.")

In the early stages of implementation of the plan, there is a natural coalescence of individual PI-driven projects into fewer, more substantive and collective efforts within each Thrust. More senior ERCs relate that, from Years 1-6, the Thrust Areas become "horizontally" integrated, with projects within a Thrust Area being carried out by multidisciplinary teams and all project teams within the Thrust Area communicating regularly to cross-fertilize the various projects.

However, ERCs that evolve only to the stage of horizontal integration of projects within a Thrust Area are only partially successful. An indication that a "systems approach" has been achieved is when the center research projects become integrated, not only within themselves but also between Thrust Areas to address the system-level goals of the ERC. Generally during Years 3-6, linkages appear between the various thrusts. Projects and procedural mechanisms can be created that explicitly blur Thrust Area boundaries and permit the merging of thrusts.

In developing and using a research plan, managers should use charts and graphs or other visual means and a database to track progress and document plans for future directions. A simple spreadsheet can be used to display the current state of all elements of the research program. In each of the activities above, illustration by means of flow charts, graphs, and databases may enhance the message. Illustrations also serve as a reminder of significant milestones, both positive and those that have been discarded. They will serve to link all of the members of the team together -- including faculty, staff, students, and affiliated sites and individuals -- giving each a stake in the efforts of the center.

3.3.3.1 Seeding New Opportunities

One center uses the following method for seeding new research opportunities:

CASE STUDY:

Projects are funded in principle for three years at a time, corresponding to the three major phases of the ERC life-cycle. The first year is funded at 100% of the amount deemed necessary to carry out the research. The second year is funded at a 90% level. This encourages faculty to find outside funding, which promotes collaboration with industry and government researchers while freeing up resources to seed new opportunities. The third year is funded at 75%-80% of the original level. By now, testbeds have been established and new technical barriers and research directions identified that can be supported with funds freed up by this diminishing formula.

The new projects are selected through a discussion between the center Executive Committee (or research review committee) and center faculty. Jointly they discuss areas where the center needs more focus. These areas often are pointed out by a center's industrial advisory board or NSF site visits teams, or they are suggested by results of center research or findings of colleagues working in the field.

After new project areas have been discussed, the research committee asks for short descriptions of potential new project starts. The projects will have a set maximum duration -- say, up to three years. The evaluation criteria for project selection include:

- *Relevance to the prioritization of center needs*
- *Quality of the proposed effort*
- *Whether the work is likely to be world-class*
- *Relationship to work outside the center*
- *Synergy with ongoing center research*
- *Interest by industry.*

After evaluation, projects are seeded for a period of one year and reviewed at six months and one year. If the project results appear to merit continued funding, then the project is continued for the full three years.

3.3.3.2 Issues Regarding Phased-out Projects

When projects are to be discontinued, a phasing-out mechanism is required to ensure that students are not adversely affected by the evolving strategic plan. In the case of the mechanism described in the above case study, some of the funds generated by the 10% per year cut in the operating budget are used to support the students on discontinued projects for a period of nine months to a year. This allows senior graduate students to finish their dissertation and new students and faculty members to find additional support.

One consequence of merging research thrusts that is sometimes unavoidable is the need to cut faculty from the ERC. For example, when Maryland's ISR decided to reduce its Thrust Areas from 5 to 3, this restructuring entailed also reducing the faculty from about 40 to about 35. The affected faculty members naturally were troubled by this decision, which, as a result, took about a year to implement.

3.3.4 Management of Research Funds

Funds received from NSF for an ERC are meant to create an academic infrastructure that will enable the center to produce world-class research, facilitate industrial/academic research cooperation, create a new level of technology, and devise innovations in engineering education. Each ERC must, together with its School of Engineering and university administration, put in place the mechanisms needed to orchestrate resources to meet these goals. Resources must be diverted not only toward the research infrastructure but also toward education and technology transfer. Relevant budgeting and accounting practices are discussed in detail in Chapter 6, "Administrative Management."

3.3.4.1 Financial Oversight

In many ERCs, financial management and oversight of funds allocated to the research program may be within the province of the center management or administrative staff. Some ERCs involve ERC faculty in financial oversight or planning committees that are responsible for making short- and long-term spending decisions, while the ERC financial manager tracks finances, grants and contracts, and daily expenditures.

Over the years since the ERC Program was founded in 1985, two ERCs have lost control of their financial resources at a certain point. In both cases, a major factor was the type of university accounting system that was in place. Regardless of support received from the host institution's Grants & Contracts or Sponsored Programs Office, it is a good idea for an ERC to establish its own independent electronic accounting system. If possible, the accounts administrator should provide a numerical account code system that provides each Thrust Area and research activity with its own operating budget.

3.3.4.2 Use of Internal ERC Funds

How an ERC initially negotiates resource returns to the center varies across institutions. A number of ERCs receive no indirect cost (IDC) recovery from their host institution, while other ERCs recover a considerable amount of the indirect costs they generate, to use at their discretion. Some ERCs explicitly restrict the amount of money a PI may receive in salary for participating in the ERC. Most ERCs pay no salary to faculty members who are simply team members of a project, while some will support no more than one month's summer salary. Thrust Leaders at most ERCs receive no more than two months' salary support for their efforts. There are exceptions; for example, one ERC chooses to pay several participating faculty significant portions of their academic salary (3 months or more) for about 15 faculty. Such decisions, often not made solely by ERC management, have a direct impact on resources available for ERC activities. It is critical for ERC management to negotiate up front (i.e., at proposal submission time) what the arrangement will be for IDC recovery, matching, etc.

Given some rough idea of the income available to the research program, decisions must be made as to how to dispense these resources among the many Thrust Areas and industrial activities. Some ERCs decide to fund individual projects for 1-2 year periods and then to collect, administratively, common projects under a Thrust Area umbrella. Other ERCs choose to fund the research budget requests of a Thrust Area, with the dispensation of funds within the Thrust being left to the discretion of the Thrust Area leader and the PIs in that Thrust. Continued funding of any project should be reviewed every year, so that no Thrust Area thinks of itself as an "entitlement program." Each ERC has its own policy regarding the cessation of ERC support and the termination of a project. PIs should be given enough notice of the termination of ERC funds to allow them to secure other sources of support. In this regard, if all projects – and possibly even Thrust Areas – are made aware that support is of finite duration and based upon clearly stated performance criteria, then the need to seek external support should be a constant goal, not an unexpected surprise.

Certain ERCs hold aside small sources of money to "seed" new projects or to leverage research support from industry. This requires setting aside funds for such programs, which indirectly removes resources from the mainstream research program.

Almost unanimously, ERCs surveyed reported that providing seed money to projects outside the ERC made PIs and their department chairs happy but the practice tended to be abused and the resources wasted. There is a risk that the ERC comes to be viewed as a "mini-NSF." Such negative experiences could have stemmed from the ERC not clearly stating the expectations in return for support. One variation on this theme that may be more productive is to request participation from PIs outside the ERC on new ERC project teams on an ad hoc basis, rather than simply providing them with seed money. However, there is a potential for two classes of ERC faculty – core and external – to become established. To avoid this situation, all PIs funded by the ERC should be expected to participate in meetings, write ERC reports, and otherwise function as ERC faculty members.

Each ERC should plan how it intends to involve industry financially in the task of taking ERC discoveries and transferring them to new technologies. Industrial membership in an ERC can cost a few thousand to several hundred thousand dollars in fees. A proprietary research project may require industry support well in excess of the ERC membership fee. In order to secure such funding, some ERCs leverage industrial support by committing graduate students and faculty to such projects. Other ERCs also provide travel funds for faculty to visit industry for the express purpose of promoting joint projects.

In summary, ERCs must plan at an early stage those "uninteresting" but critically necessary mechanisms for distributing research support, evaluating research success, and promoting the continual efforts by all to secure external research support.

3.3.4.3 Encouraging the Search for External Support

Because actual direct support of ERC faculty salary is relatively small, most ERCs encourage center faculty to seek outside support. As one research manager noted, "Faculty members are not doing their job unless they either get outside support or bring in Center membership money to support their work." ERCs employ a variety of different means to accomplish this. Listed below are some responses excerpted from the questionnaire.

"We have an industrial interactions incentive program which provides funds for travel to industry, to support student research visits to industry, and to provide critical research resources specific to collaborative research with industry."

"The Center informs the faculty team members of outside opportunities and, when feasible, helps in arranging/providing required matched support."

"In some instances, it is required that industrial commitment to certain projects has been made before ERC funds are committed. In this case, the ERC will help Co-PIs to identify potential industrial sponsors that might support such activities. Furthermore, when preparing proposals for outside contracts, the ERC will make a commitment to the Co-PI for additional funding, should industrial funds be secured. This dual leverage factor has also proved to be very useful."

3.3.5 Industrial Collaboration and Technology Transfer

As described in Section 3.2.5.2, "Industrial Buy-in," ERC research programs are designed and managed with the continual involvement of industry. All ERCs have involved their industrial member companies directly in the establishment and refinement of their strategic plan. Certain ERCs align industrial representatives with specific projects within a Thrust Area in a way that provides both ERC students and faculty with a continuous industrial perspective on the fundamental research. Many ERCs develop joint projects, in which personnel from a firm or a consortium of firms work alongside the ERC students and faculty on the project. This involvement creates a climate, within the ERC, in which industry not only participates on specific projects they subsidize but also has direct input into the evaluation of the fundamental Thrust Area research.

Mechanisms to involve industry should not be confined to just the research program; to be truly successful, ERCs must also strive to draw industry into the center's education program. One successful method is the alignment of each ERC graduate student with an industrial "mentor" who periodically reviews the student's progress, perhaps during the annual industrial meetings, and periodically discusses the project with the student, either by telephone or by electronic mail. Formal programs can provide for graduate student internships in industrial labs during a summer hiatus. In one variation of this program, industry will recognize a student-developed technique or analytical method it wants to import into its standard operating repertoire. The most effective way to transfer technology is to have that student spend a few months in the company's facilities, working with industrial personnel. Hiring ERC graduates is probably the single best way for a company to absorb the broader range of knowledge inherent in an ERC; and it tends to bind the company even closer to the center. In several cases, a former ERC student has become the company's representative to the center.

In the early years of an ERC’s existence, cultivating industrial commitment to the strategic planning process and the ERC philosophy is paramount. In later years, an ERC must strive to transfer tangible ERC discoveries to industry. Some of the many different mechanisms that ERCs use to transfer technology to their industrial partners were described in Section 3.2.5.2. They include person-to-person exchanges, such as through internships of selected ERC students with industry and industrial employee internships at ERC facilities, and ERC/industry collaborative testbed research projects at either the ERC or at the corporate location. Other involvement mechanisms include: (1) fostering academic interaction with industry by providing interested faculty with travel money to visit prospective industry for research support and (2) requiring all ERC-supported research projects to seek industrial support after a certain time period or lose ERC funding.

In many ERCs, industry participates throughout the technology development process; it is a process of "mutual development." The ERC takes the process as far as is necessary to effect a successful handoff to industry. As one Center Director says, "It's a question of how far we have to carry it before they become believers."

3.4 RESEARCH INTERFACE WITH OTHER ERC PROGRAMS

Management of an ERC's research program is best carried out in conjunction with interaction at all levels with the other components of an ERC. It is tempting to segregate the management of an ERC program along the lines of sections in an annual report, but such compartmentalization does not lead to a true systems approach. Those ERCs that obtain recognition for their various programs and succeed in NSF reviews have not designed each component in isolation from the others. Rather, significant accomplishments are more likely to emerge from a concerted effort to intertwine the management of all ERC components.

3.4.1 Education

See Chapter 4 for a complete discussion of ERC education programs.

3.4.1.1 Graduate Education

Education of a new generation of engineers and scientists is the shared mission of all ERCs. ERC education programs serve the following pragmatic roles: (1) to bring undergraduate, graduate, and postgraduate students into the center; (2) to maintain harmony among the diverse curriculum requirements placed on ERC-sponsored students; (3) to develop new graduate and undergraduate education vehicles that go beyond traditional engineering educational approaches; and (4) to actively engage academic and industrial researchers with students on teams directed to solve problems pertinent to industry.

Research program management is implicitly connected to the education programs in all ERCs. Research activities are driven by faculty ideas and student manpower. The attraction and retention of superior graduate students is critically necessary to the success of any ERC. How an ERC actually carries out this activity depends upon the relationship of the ERC to a host department or college (if that is the case), the degree to which the ERC research spans different colleges, and how the ERC financially supports research projects.

Most ERCs do not engage directly in the recruitment of graduate students to selected projects within their strategic plan. In these ERCs, research goals are addressed by supporting projects of faculty in various departments or colleges across the university. In this mode, the ERC has no direct responsibility for recruiting students, supporting them financially, shepherding those students through their degree program, or affecting directly their curriculum requirements to graduate. Those responsibilities lie with the PI receiving ERC support and with the students' departments.

One advantage to supporting research projects, rather than directly supporting a student, arises when the ERC decides to reduce or terminate project support. If support of a research project is proffered for only one or two years, then the project PI is aware that a student requiring four years to complete his/her PhD degree will require additional funding support. Thus, the ERC does not have the tacit responsibility to support a student until graduation without regard to the project's continued relevance (or irrelevance) to the center's strategic plan.

Certain ERCs satisfy their strategic plan by creating team research projects that require a collection of students from different disciplines. This mandates that the ERC education program, in direct communication with the research program, satisfy specific demands for graduate students of different backgrounds. An ERC education program in such a center can identify potential candidates by interfacing with the graduate advisor in departments around their university and also by maintaining an active ERC recruitment activity. Such an approach has the advantage of specifically identifying student expertise for each project; but the disadvantage is in the resource costs associated with independent recruiting and admissions efforts.

Often graduate students are brought into the ERC research program through formal courses, especially those involving team projects. Such mechanisms draw students into the work of the center naturally. Once students are involved in ERC research, faculty must ensure that their participation provides a solid educational experience. Most of the educational benefits are derived informally. The cross-disciplinary systems approach is absorbed through participation in regular project group meetings, through interaction with industrial collaborators, and, in some centers, through participation in center-wide strategic planning exercises. If education is taken into account in structuring the mechanisms for conducting research, then an "ERC education" is a natural outgrowth of a student's participation in research.

As ERCs near the end of their life cycle and begin planning for potential phase-out of ERC funds, a number of centers have elected to reduce their NSF budget direct cost requests for graduate student funds. Some senior ERCs mandate that they will support only non-personnel-related costs of a project. Other ERCs have elected to operate research programs in their final years utilizing MS and postdoctoral researchers, rather than PhD students, who require longer-term commitments.

3.4.1.2 Undergraduate Education

Undergraduate involvement in research is one of the cornerstones of the ERC concept. Since the early 1990s, NSF has increased its emphasis on the impact of ERCs on undergraduate education; a variety of programs now provide supplemental funding for ERC educational activities for undergraduates (see Chapter 4). Some students come to the center through undergraduate courses the ERC faculty teach in the academic departments. Often, undergraduates simply come to the center and ask for employment and/or to work on research projects. To attract new prospects, some ERCs distribute announcements, host dinners, etc.

Most ERCs practice similar programs that immerse their engineering undergraduates directly into ongoing research projects. NSF emphasizes the development of teams in which undergraduate students work closely with graduate students, technicians, postdoctoral students, faculty, and industrial scientists on active research projects. Such undergraduates may receive academic credit, credit toward graduation with honors, or may simply receive financial remuneration for their efforts. The educational vehicles can be quite standard, such as placing an undergraduate honors student on a team research project, a graduating senior's thesis project, or a capstone design project. In such cases, the research program is not designed solely for the undergraduate experience; rather, the education program avails itself of the opportunity to expose undergraduates to real academic research.

However, as they move into those years stressing the successful creation of research testbeds, a number of senior ERCs actively manage selected research projects to purposely address industrial knowledge transfer and educational issues. The following case study illustrates such an instance.

CASE STUDY:
The ERC at Montana State University was approached by an Industrial Associate to develop several alternative bioremediation protocols to detoxify an existing hazardous waste contaminated site. Through collaborative discussions with the company and various components of the ERC, a unique educational vehicle for undergraduates was developed. In conjunction with company scientists and Center faculty, students enrolled in an undergraduate course were given the task to survey, sample, assess, and recommend suitable biological treatment protocols for the site. Students were exposed to actual field sampling and practical lab analytical procedures. Participating graduate students carried out fundamental research on the biodegradation processes. Each successive semester of the course moves the reclamation project closer to completion. This is a case where active cooperation between research management, industrial interaction, and education has produced fundamental research, created an undergraduate teaching experience, produced a course text documenting the project, provided industry with a problem solution, and resulted in a truly interactive testbed project.

3.4.2 Knowledge Transfer/Outreach

Knowledge transfer is an umbrella term for outreach activities that transfer ERC-generated research discoveries or educational innovations to the academic scientific and engineering communities. Knowledge transfer activities comprise dissemination of basic ERC discoveries and educational opportunities to other researchers and students in the field through mechanisms such as the following: visiting graduate student/faculty research exchanges, subcontracts to outside universities for specific collaborative research projects, administering summer research experiences for undergraduates (REU) programs, generation of interactive or passive educational vehicles (e.g., textbooks, interactive CD teaching modules, computer-aided design programs, video tutorials, and Internet homepages), and ERC faculty service to professional societies in staging national and international symposia.

The focus of all ERC knowledge transfer/outreach activities is both educational and technical, but the emphasis varies greatly across activities. At one extreme, undergraduate REU programs emphasize primarily the exposure of students from other institutions to ERC research as an educational mechanism; the purely technical value beyond education is limited. At the other end of the spectrum, faculty exchanges or visits are aimed primarily at maximizing the flow of knowledge between researchers from different universities; here, the educational value is secondary, although it becomes quite significant when the visiting faculty member returns to the home institution. Most outreach activities involve a more balanced mix of knowledge/technology transfer with educational value. It is a characteristic of ERCs that the two are never entirely inseparable and are often fully intertwined.

The survey of ERCs indicated that, while knowledge transfer activities are a direct result of a productive research program, the evolution of the research program is little affected by the knowledge transfer activities. There does not appear to be an equivalent two-way impact or feedback. The process appears to be linear rather than circular -- that is, the success of an ERC is predicated on first generating research discoveries and education innovations and then transferring those successes to industry and the academic community.

An important exception to this rule is when personnel are exchanged between the ERC and another research institution. In that case, research projects are planned to fulfill portions of the strategic plan that require the collaboration of ERC researchers and others outside the ERC.

3.5 OVERALL IMPACT ASSESSMENT

3.5.1 Intellectual/Academic Advancements and Achievements

From a research standpoint, the impact of an ERC is measured through its industrial interaction and knowledge/technology transfer successes, along with traditional academic measures such as published papers, patents, software products published, students graduated, etc. Thus, some yardsticks are more tangible and objective than others are.

The particular metrics used by ERCs vary, but they include the following, as excerpted from the responses by ERC Directors and research managers to a questionnaire.

- *We tabulate the number of goals reached based on six-month reviews and an internal report card. Research success is measured in the number of publications and an assessment of whether new and relevant knowledge has been created. Research success can also be recognized by success in obtaining additional research funding from other sources.*
- *In addition to the usual publication and patent counting metrics, we consider the health of our industrial interaction in general and technology transfer specifically. Involvement of undergraduate students in the research and student research visits to industry both are useful metrics for the integration of education and research.*
- *The ultimate metric is the application by the industry of knowledge or technology developed by the Center. Progress toward the goals of the strategic plan comes about through deliverables that go into use. We try to measure output, success, and impact by what influence we have on how engineering is accomplished within the industry.*

The emergence of a center as a recognized national resource in its field is a strong indicator of its impact. A number of ERCs have become firmly established as national resources. For example, as a result of its established excellence in the field, the Carnegie-Mellon DSSC was able to organize the National Storage Industries Consortium; some 34 companies (and 25 universities) are members of the consortium.

Although technology development has not traditionally been a route to academic recognition for excellence, that is changing – at least in engineering. To a significant extent it is the ERCs that have wrought this change. As a result, another contributor to acceptance of the ERC concept as an important academic research strategy are the numerous developments that have helped ERC member companies to commercialize products, advances which they claim would not have been possible without their participation in the ERC. The widespread application of center technology in standards is another reliable indicator of the center's impact.

Start-up companies often are spun off by ERCs, based on center-developed technologies and usually with ERC graduates and faculty members as principals. Research accomplishments of the ERCs have resulted in the formation of nearly 300 new companies based on ERC technology – further evidence that they are valuable national resources.

Positive impact is apparent if center faculty often are invited to present papers at major professional symposia in their fields. The formation of large industrial consortia around the ERC, the operation of unique testbeds and testing/simulation facilities which are heavily used by industry, and the hosting of well-attended international conferences all provide tangible indications of this status.

At the beginning of the ERC Program, in the mid-1980s, the academic community was largely skeptical about the relative merits of multiple-investigator, industry-oriented, cross-disciplinary research centers. Among the less tangible but most important impacts of ERCs has been the change of culture in many fields and ERC host universities from single-investigator, single discipline, narrowly focused work to cross-disciplinary team research attacking larger problems using a systems approach. In addition, ERCs have pioneered new models for education and for academic administration and management that are being widely adopted throughout their host universities.

Perhaps the greatest measurement of success, however, is articulating an original vision far ahead of the university community or the industrial sector in specific areas of research, to which the rest of the community is gradually converted as the accuracy of that vision is demonstrated over time. The case study gives an example.

CASE STUDY:
The Center for Biofilm Engineering, at Montana State University, is developing novel techniques for the control and mitigation of biofilms, the slimy coatings that adhere to surfaces wherever microbes can establish a foothold. Recent work at this ERC has led to a revolution in the prevailing idea of how biofilms organize themselves. The novel perception was that biofilms form tower-like "slime skyscrapers," structures that are much better

organized than biofilms were previously thought to be. For example, they have a primitive circulatory system. Due to the ERC's research, the accepted paradigm regarding biofilms shifted over a period of three years from random, unstructured systems to a sophisticated, structured system.

The key to this breakthrough was the identification of a mechanism for communication between bacteria of different species that would allow the bacteria to avoid filling in the spaces in the structure and thereby shutting off circulation of liquid. "Quorum sensing" among floating bacteria was the key to identifying this mechanism for cell-cell communication in biofilms.

As an immediate practical application of this discovery, the ERC was able to identify the bacterial signaling gene and "knock it out," preventing the bacteria from building towers. Consequently, these bacteria no longer adhere to the surface and do not form biofilms. This knowledge of the bacterial signaling language will enable engineers to manipulate biofilms, using real or "counterfeit" signal molecules, and eventually to control both the formation and the detachment of biofilms from surfaces. Already the ERC has found a synthetic analog of a blocking compound that eliminates slime fouling in a type of kelp; the synthetic compound can be used in many applications.

This project is a powerful example of the ways that an ERC can produce useful innovations. The center was focusing on biofilms because of the industrial problems they produce. However, says Center Director William Costerton, the center's industrial partners were "not at all interested in the center's work on understanding why biofilms form. They wanted, instead, to know how much toxin to flood biofilms with." The center had to press for resources to work on the underlying mechanisms. In the end, their persistence paid off in the form of unexpected and very useful breakthroughs. "Interdisciplinary work is precious," Costerton says, because the different disciplines perceive a problem from different angles; putting the various perceptions together can stimulate novel approaches.

3.6 CROSS-DISCIPLINARY RESEARCH IN A DISCIPLINARY ENVIRONMENT: CHALLENGES AND REWARDS

Working within this new model for university research, the ERC, has from the beginning of the Program presented a number of challenges. Meeting those challenges has required hard work, ingenuity and, at times, organizational courage on the part of Center Directors and other research managers. At the same time, the operation of an ERC yields special rewards for all those involved -- leaders and managers, faculty, industrial members, and students.

One of the first challenges that an ERC Director, or prospective director, faces is to oversee the collective planning of a long-term research strategy by a group of people from different disciplines, many of them already quite successful in their individual research programs, who may not have even worked together before. The reward, for the research manager, is in being able to persuade the members of such a group to aim their research in a direction they may not have wanted to go and may not initially have understood -- and then to see them arrive at the recognition that the center's vision is valid and that they can succeed in the context of the strategic plan.

It is certainly challenging for a group of disparate faculty members collectively to determine where the "uncharted territories" lie in a given field, especially when the field itself is new. The reward for faculty participating in this exploration is the ability to enter a new field of research with funding provided and with the support of other faculty in the center. Essentially, faculty are rewarded with the opportunity to do pioneering work.

However, funding per se is not sufficient for most ERC participants. In any ERC, some faculty members may have personal research support rivaling that of the entire center. Their incentive is that they can both contribute and gain as a team player in the center's pioneering work. Part of the validation of a center's success, for the research manager, is the continued willingness of independently successful investigators to participate, even adapting their well-regarded work to the center's vision.

A related challenge for the Director is in finding ways to build camaraderie and team spirit among researchers accustomed to working independently. The Director must be able to recognize the type of individuals who <u>can</u> be effective team members.

A significant challenge lies in the fact that industry has an inherently different vision than the center faculty do. In general, they simply do not take as long a view. Consequently, industry's input can be a deterrent to the development of a vital, sustaining vision for the center. Yet their viewpoints and needs must be taken into account in a way that maintains their commitment to the center.

The corresponding reward, for the research management team, is in making industry a believer in the ERC's long-term plan and in helping industrial members understand that their needs will be met better by letting the ERC pursue its long-range plans. Several Directors have noted the satisfaction that comes with proving to industry, by means of actual results over a period of years, that this approach will benefit them more than having the ERC address their immediate needs would.

The cross-disciplinarity of the ERC's field of research can itself present challenges, although, as the previous section described, this is no longer the problem it was when the ERC Program began. Still, an area can be so thoroughly cross-disciplinary that ERC faculty encounter difficulties in recruiting within the departments. Tenure and promotion are, of course, vital issues for young faculty members. Early in the ERC Program, there was great concern about the effect of participation in a cross-disciplinary research center, where team research and multiple authorship of papers blurred the contributions of individuals. Tenure and promotion decisions are made in the departments -- so the concerns were well founded. However, out of 15 ERCs responding to a questionnaire, 10 stated that both tenure and promotion were positively influenced by faculty involvement in the ERC. (The other five ERCs reported no direct impact.) Examples of specific responses include:

- *The ERC provides a framework and support mechanism for young faculty which encourages research by setting goals, providing mentorship, and sharing equipment and information.*
- *The culture at our university has long recognized in the promotion and tenure decision process the positive importance of faculty participation in research centers. We rely on the department heads of all departments represented to ensure that departmental promotion and tenure policies encourage center participation.*
- *This question has been exhaustively studied by universities and it is clear and unanimous that being an ERC investigator is a big plus and helps with promotion and tenure.*
- *The ERC provides the faculty with the opportunity to get national exposure, support more students, continually update educational material with the latest research results, and participate in industry-relevant research. Publication is facilitated. The natural result is advancement in the academic ranks.*

There is a risk that if the tenure/promotion process is handled through an academic committee within the department, researchers may tend to focus on publications at the sacrifice of securing funding or extending the research to a useful technology transfer. This prospect can be minimized if the Center Director and Associate Director for Research maintain close ties with the departments and ensure that they have a substantive, direct input to the promotion and tenure process within the departments.

Thus, one of the primary rewards of ERC research program management is seeing the ERC become accepted by researchers in associated fields and watching the mainstream move in the direction the ERC has already gone, so that faculty and students perceive participation in the ERC not as a career risk but as a career enhancement.

ATTACHMENT 3-1
EXAMPLES OF ERC STRATEGIC RESEARCH PLANS

EXAMPLE 2

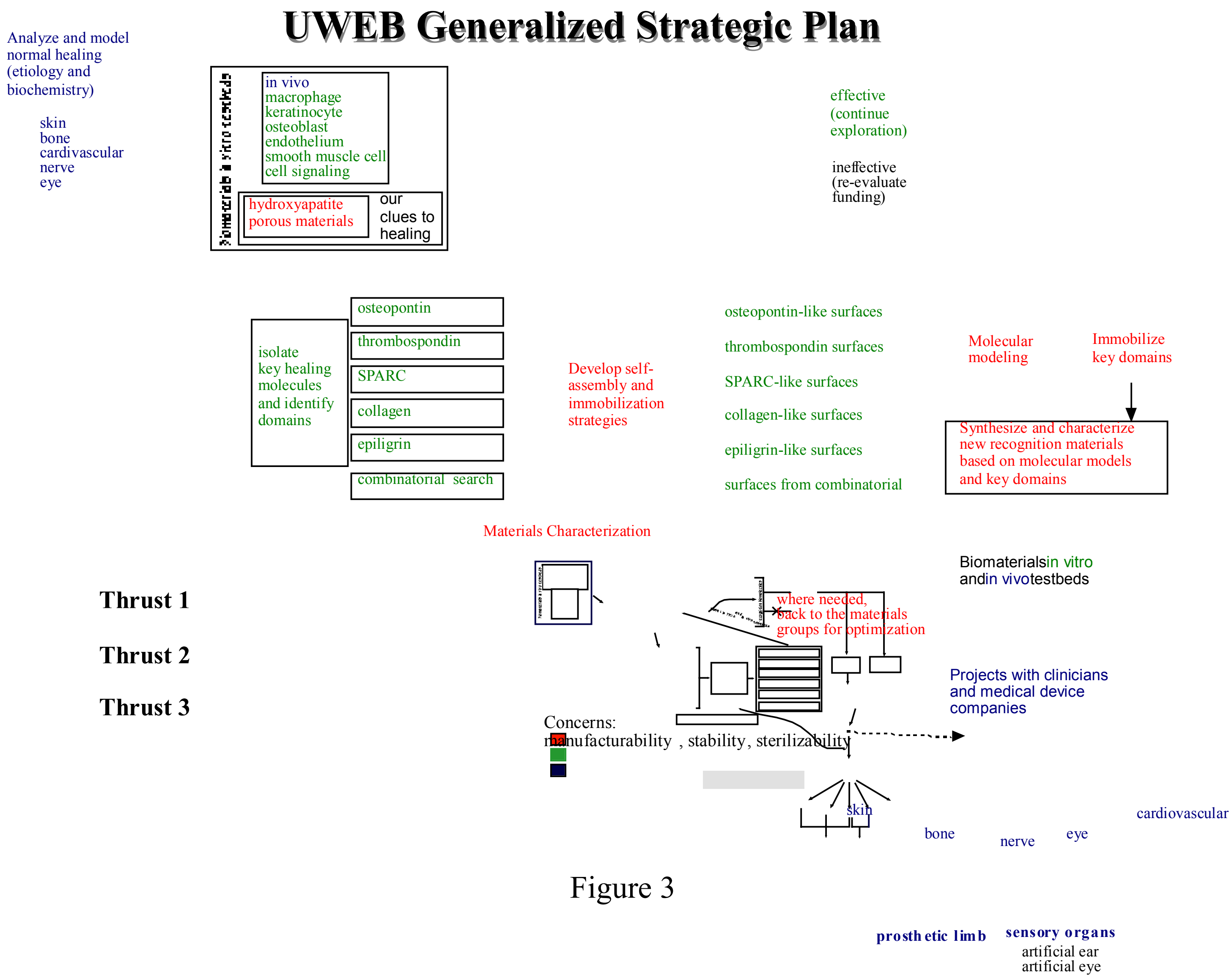
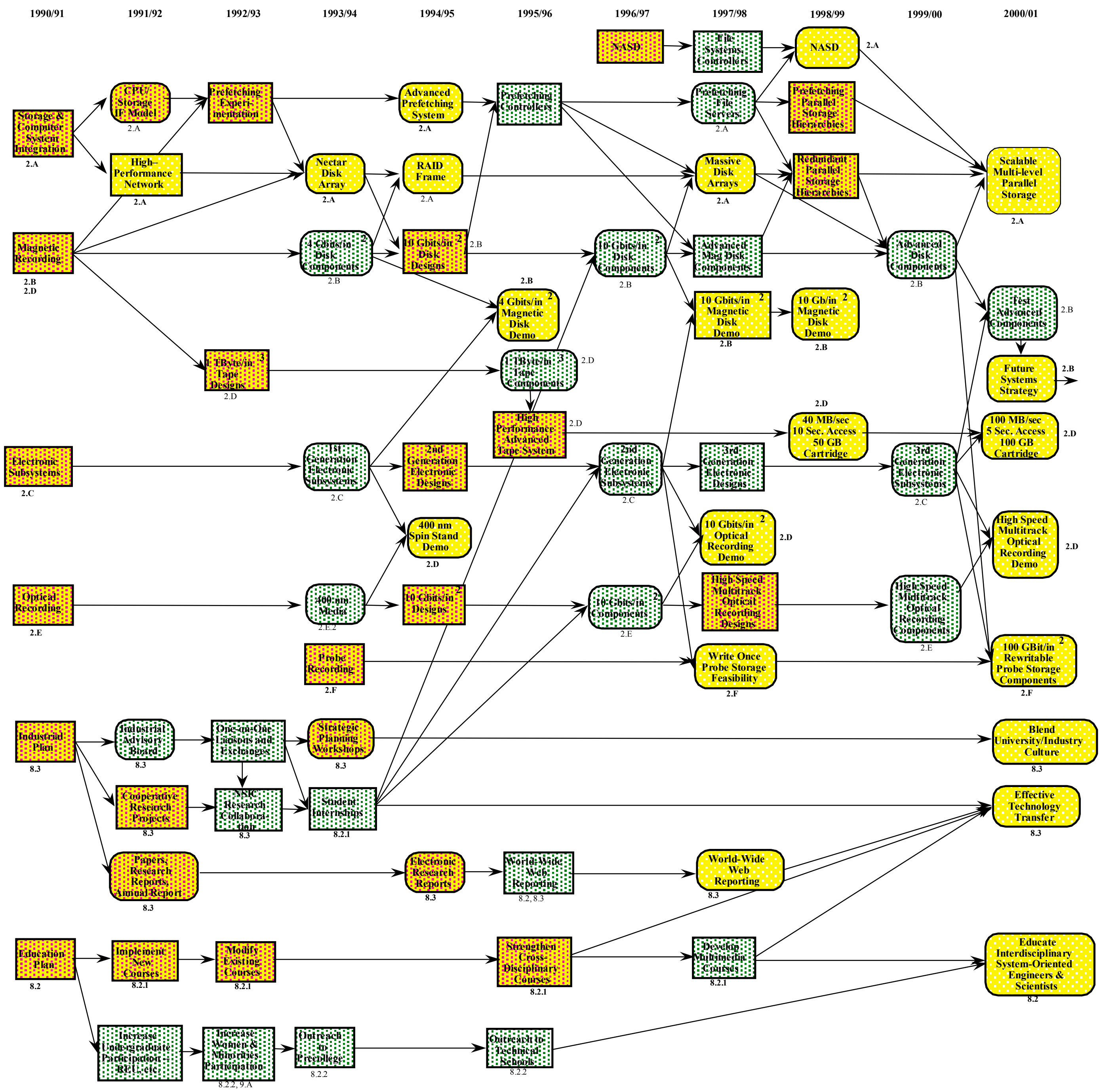


Figure 3

EXAMPLE 3

CMU DSSC's 11–YEAR STRATEGIC PLAN



• Boxes with square corners indicate the start of an activity.
• Boxes with rounded corners indicate milestones.
• The above digit and letter notations refer to the sections in Volume Two of this report that discuss these projects, testbeds and/or deliverables.
• The notations for the Center's efforts in education and industrial collaboration refer to the appropriate sections in Volume One of this report.

Fundamental Knowledge
Enabling Technology
Engineered Systems

EXAMPLE 1
U. MICHIGAN ERC/RMS STRATEGIC PLAN