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The Emergence and Change of Materials Science and Engineering in the United States

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Availability of external funding influences the viability and structure of scientific fields. In the 1980s, structural changes in the manner in which external funds became available started to have an impact on materials science and engineering in the United States. These changes colluded with the search for a disciplinary identity of this research field inside the university. The solutions that arose were intended to find a mediating structure between external demands and resources and disciplinary orientation. Interviews with seventeen scientists in seven universities revealed the impact in local university settings. The rise of research centers as new organizational units in universities can be linked to two periods. In the 1960s, expensive instruments stimulated unit formation; in the 1980s, the increase in application-related funding forced new administrative ways. It is shown that organizational changes also have an impact on disciplinary identity as witnessed by a strong increase in interdisciplinary materials Ph.D.s awarded.

Recent changes in the academic organization of science and engineering research have been analyzed from a variety of angles. In particular, attention has been paid to changes in the university structure (Peters 1989; Blume 1987; Geiger 1988), the changing relations between university research and industry (Etzkowitz and Peters 1990; Varma 2000), the interrelationships between organizational structure and faculty attitudes (Etzkowitz and Peters 1991), and the role of university research centers in academic transformation (Peters 1989). Attempts to systematically link changes in university research organization with changes in funding and the structure of scientific fields are lacking. In this article, we will make this step by analyzing the effects of organizing research in centers for the field of materials research.

A number of recent publications discuss the organizational transformation process of sciences. For example, it is argued that new forms of

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knowledge production require a higher level of flexibility and involvement of a variety of organizational forms (Gibbons et al. 1994; Stinchcombe 1990, chap. 9; Chompalov and Shrum 1999). The observations suggest that organizational theory may contribute to the explanation of the emergence and stabilization of organizational arrangements within science.

Our approach will be based on the resource-dependent model (Pfeffer and Salancik 1978) and the institutional theory (Scott 1991) as have been developed in organization theory. Research units such as departments, centers, and laboratories have to deal with a turbulent environment in which changing resource patterns stimulate strategies to deal with acquiring critical resources.

Acceptance of the mediating effect of local organizational units within universities contrasts with the standard perception of how the science system functions. Peer review and the theoretical structure of science are traditional, thought to be the most important factors governing the distribution of funds for science (Mulkay 1985). It is the received wisdom that even when other funding organizations are actively involved, the mechanism to ensure distribution of funds should adhere to this reputational model (Whitley 1984).

We propose that this view needs to be modified by taking the mediating influence of the university and other organizational forms into account. In an increasingly complicated situation, it is necessary to distinguish among the various local and national processes that influence resource conversion into research programs. Universities can be regarded as large organizations with their own missions and internal uncertainties (Stinchcombe 1990). However, they can also be regarded as localities in which conflicting options for the use of external resources exist. American universities in general have had more options than the European universities to define their missions and structure the organization as best as they can to serve this mission.

In this article, we deal with the relationship between organizational structures and intellectual dynamics in the evolution of scientific and technological fields. In particular, we study the emergence and early development of materials science and engineering in the United States. The objective is to establish the effect of changing resource structures on scientific fields.

To us, this causal relationship between resource structure and organizational form seems the salient feature in need of explanation instead of being taken for granted. It is necessary to analyze mechanisms that ensure agreement between providers of resources and users of resources on the particular products to be provided by the field under study. Within science, it would be necessary to investigate the manner in which some scientific fields are able to survive and thrive while others decline. Attention to the organizational level below that of discipline and university can bring some of the critical issues to light.

Resource Patterns as Structural Constraints on Strategy

A variety of approaches in the organization literature deal with the mechanisms through which organizations interact with their environment. Some of these approaches propose that organizations have the capacity to adjust to their environment, and that in part the strategies for doing so relate to the structure of the environment. In broad terms these could be called theories of organizational adaptation. One approach—the resource dependency model—in particular seems to be able to contribute to our understanding of organizational strategies by scientists. The best known formulation of this theory has been advanced by Pfeffer and Salancik (1978); they argue that the basic strategy choices in organization will lean toward internal mechanisms and external interactions that optimize organizational behavior to acquire critical resources. To give an example, Pfeffer and Salancik concluded in a study of the organizational control of hospitals that the hospital organization was dominated by various segments of the organization depending on the scarcity of certain resources. If financial problems were great, administrators would dominate the hospital administration. If the critical resources were related to technical capabilities, doctors dominated the board.

This strand of organizational theory seems to us particularly relevant to understand the manner in which social elites—inside and outside science—pursue strategies with regard to resources. Science policies are directed at reaching specific national, economic, or cultural goals through manipulation of resource patterns (mainly funding) but also supply of technical professionals. The effects that are expected are derived from a (sometimes implicit) model of how resource distribution will affect specific outcomes. In a similar manner, explanations of internal processes of science have stressed the critical role of internal resources (reputation) in securing external resources (instruments, financial support). Implicitly or explicitly, both policymakers and analysts propose a role for resource distribution in the rate and direction of growth of scientific and technological fields. The resource dependence approach emphasized the following:

> If organizational actions are responses to their environments, then the external perspective on organizational functioning argues strongly that organizational behaviour is determined through the design of organizational environments. The focus for attempts to change organizations it would appear, should be the context of organizations. (Pfeffer and Salancik 1978, 278)

Therefore, we infer that organizations are an important feature of the impact of resource distribution on the structure of science and technology fields.

Organizational theories are clearly more often employed in explaining the role of organizational transformation in changing environments than they are with regard to explaining the mechanisms of cognitive change in such fields. Thus, the resource dependency theory is lacking with regard to the explanation of relation between the pattern of resources distributors and particular organizational forms of scientific fields. A critical addition seems to be the inclusion of perceptions or beliefs both of resource providers and of organizational members about the structure of resources as well as the goals of the scientific field.

> In organizational learning under ambiguity, we confront a different form of incentive. If lack of clarity in the situation or in the feedback makes several interpretations possible, what are the incentives that might lead a particular person, or part of the organization, to select one interpretation rather than another. (March 1988, 350)

Taking a cognitive concept such as interpretation into account introduces a logical element into the mechanism of coupling resources and organizational form in the case of science. With certain latitude in the interpretation of what in particular the critical resource is, beliefs and/or perceptions become critical. The belief of the actors with regard to which resource is critical clearly informs their strategies. Moreover, beliefs would offer a mechanism that would allow a degree of common opinion between resource providers and scientists on matters relevant to the development of a field. While resources and knowledge production might be used as concepts to denote, respectively, the environment and the tasks of research organizations, shared beliefs about the goal and function of specific fields of inquiry ties organizational and resource choices together. Therefore, the resource dependency model for scientific development should be extended to include the beliefs of the actors.

Change in existing fields might start by changing beliefs about resources or by shifts in resource patterns themselves influenced by broader trends in society. Changes might occur largely simultaneously or separately over time, but conflict between beliefs and the availability of critical resources has to lead to changes in one or the other.

To give an example of this process, accessibility to a synchotron (as a critical resource) will reinforce the internal belief structure that valuable work can be done on such machines. In turn, this belief structure will suggest work on problems that use the synchotron as a critical resource. To ensure availability of such machines, the central tenet of this belief needs to be legitimate in society, as such funds by their sheer size cannot be acquired from the existing resource flows within the scientific community.

The question is how resource availability and beliefs about critical resources influence the evolution of scientific fields. One way is pointed out by Weick's (1979, 177) discussion of enacted environments, conceived to be the manner in which people in organizations understand their environment; thus, actions and interpretations accommodate to enacted environments not the current environment (see Figure 1).

Building on this argument, our scheme couples resource availability to emergence and consolidation of institutionalized patterns of behavior (see Figure 2). Environments are revealed in this line of argument through "institutionalized beliefs, rules, and roles—symbolic elements capable of affecting organizational forms independent of resource flows and technical requirements" (Scott 1991, 165).

Scott (1991) suggested, "*Institutional* sectors are characterized by the elaboration of rules and requirements to which individual organizations must conform if they are to receive support and legitimacy from the environment" (p. 140). The argument by Pfeffer and Salancik (1978) invoked the question of legitimacy, regarded as a societal evaluation of organizational goals. Scott (1991) argued that legitimating is also cognitive, for example, explaining or justifying social arrangements in such a way that institutional arrangements are subjectively plausible, "motivating actors to enact actions locating them within a comprehensible meaningful world" (p. 169).

Geiger (1988) argued that in the 1970s in health sciences the availability of funding at the field level was so abundant that nearly every project could be funded. However, because funding was linked to projects and many projects needed sophisticated equipment and specially trained individuals, the infrastructure became the critical resource. For the same area of science, Hackett (1990) argued that the lack of tenured positions was a critical resource hampering the development of research careers. The findings of these researchers show that regardless of the munificence of financing, a skewed distribution of funding and restrictions of internal organization determines the usefulness of resources in local settings.

From Universities to Scientific Fields

Geiger (1988) argued that research was introduced into the universities as an additional mission to scientists' educational tasks. To work out the relation between education and research has been a subject of considerable debate within the universities (Clark 1995). That education and therefore student enrollment acted as the initial resource basis for organization of universities generally resulted in segmentation along departmental lines. A department

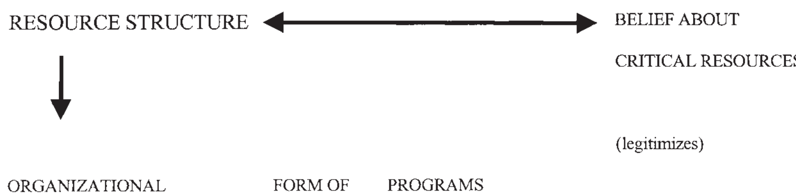

Figure 1. Interaction between resources beliefs and organizational form.

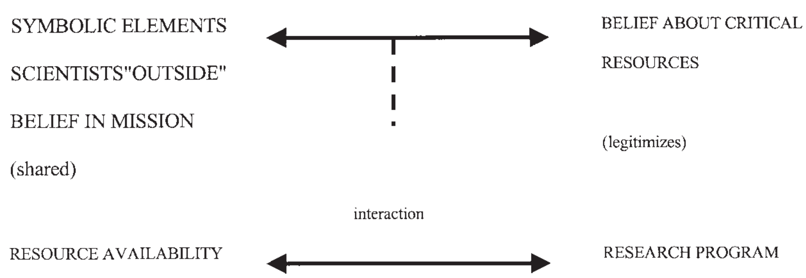

Figure 2. Interaction between field and local structure.

came to stand for a specialized area of education, such as medicine, to which other areas were added later. New fields emerged from these departments, and the turf battle going on between new educational fields and existing department could be resolved by two mechanisms, broadening the mission of the department or setting up a separate department. Education in such cases would be linked to a specific area of professional expertise.

The introduction of research as a second mission within the university system took place through adjustment of existing departmental structures and was linked to education. Funds for research could be acquired by professors as either direct funding of research or as funding for education whereby a large segment of the education itself consisted of research. Gradually, research became recognized as an entirely separate goal; the initial organizational solution reached in the early twentieth century generally was to keep the organization of research within the existing departments. Whether research would serve direct external needs in addition to the educational requirements was a question that was to be solved by the departments. Blume (1987) described how different universities, such as the Massachusetts Institute of

Technology (MIT) compared to the University of California, Berkeley, set out different strategies to organize their chemical research. And differences of opinion on the mission were discernable within one single discipline within the same institute. Servos (1980) discussed far-reaching differences in vision within chemical engineering at MIT. External influences on research through funding were exercised mainly through general university endowments or individual professors engaged in consulting relations with industry. The issue of quality control and immediacy of research goals were the primary points of conflict between faculty members. Within the overall American university system before World War II, only a small minority of universities engaged in externally sponsored research.

After World War II, the funding pattern started to change, and universities came to be seen as knowledge producers in their own right. Funding from the federal government started to increase, and some national research facilities were transferred from government control to university administration, for example, Lawrence Livermore National Laboratory. Funding, such as that from the Department of Defense and the new pure science agency, the National Science Foundation (NSF), was tied to general missions for which unguided tinkering by scientists was thought to be the most successful model. Federal sources of money were increasingly abundant and started to become more important than industry and other sources of funding for university research. This generous availability of money reinforced existing departmental/disciplinary research approaches, which were now reinforced by a national review system self-governed by scientists.[1]

Changes in the funding structure for research at the federal level in the 1970s imputed a large new variety of possible missions to the university research system (Clark 1995, 128-31). In general, this appeared at first sight to lead to an increased support for the existing research system inside the university. However, the specifications of problem-oriented research missions gradually introduced new elements into the system. The previous organization of the university research structure, which could be seen as adjustment to an environment dominated by identified educational practices, came under pressure (Clark 1995, 131-3). By the early 1980s, the university took on an additional mission to contribute in an undirected fashion to national security, national prosperity, and corporate goals (Cozzens and Woodhouse 1995). Thus, the research mission of universities has evolved through increasingly specific demands on university research, which has become more specified (even if still in relatively broad terms), and through more diversely structured funding. Much research today in accordance with externally determined missions is less aligned to educational and departmental boundaries, even requiring interdisciplinary cooperation explicitly.

What problems are posed by these changes in resource structure for the university, and what organizational solutions are sought?

Persistent financial needs motivated American universities to seek more diversified research and development (R&D) funding sources by their own, particularly during the years from the mid 1970s to the early 1980s, when they suffered both from the high prevailing rate of inflation impacting their endowments and from insufficient federal funding for basic research (Peters 1989). The dependency on external funding became particularly clear in the case of new initiatives. With this search for new sources of funding, the universities attracted a new mix of resources than in the 1970s. Thus, in addition to the federal government, the local states and industry came to play an important role (Peters 1989; Geiger 1988).

At the university level, the introduction of new mechanisms for funding research led to debate on two important issues, the first being about the impact on the quality control of research. The prospect of reduced importance of a purely academic peer review system, the main mechanism for quality control in science, led to early disquiet in academia. However, industry was swift to point out that their interest was not to interfere with scientific quality (Kenney 1986). However, recent changes, such as the research centers we deal with here, still raise the question of what will happen to quality control when disciplinary boundaries are purposefully blurred.

The second important question, which still remains unsolved, is on the type of change in research agendas. It would seem plausible that they might be affected by the changing structure of external demands. One of the most eye-catching features in the changing funding of university research has been a shift from single investigator funding to program and center funding. A change that to a large extent has occurred in scientific and engineering fields linked together in efforts like biotechnology and materials science. The centers we will discuss next can be regarded as the organizational solution of changed patterns of resources and establishment of mission oriented communication between scientists and policy makers. The analysis of their emergence also allows us to address the additional point of the impact of beliefs on both scientific resources and scientific program development.

Emergence of Materials Science and Engineering in the United States[2]

Until the late 1960s, research efforts in materials sciences were mainly based on metallurgy. Thirty percent of departments in material science carried the title of the Department of Metallurgy and Materials Sciences (Roy

1970, 1). External pressures to develop the field of materials science built up in the 1950s. The first dedicated initiative, while linked to other policy action in the late 1950s, centered around the "Sputnik crisis." A short paper suggested the desirability of a National Materials Program to the president's Science Advisory Committee during the Eisenhower administration. Defense agencies led by the Advanced Research Projects Agency (ARPA) took the initiative in suggesting interdisciplinary materials science laboratories to be organized to cater for the need of the Department of Defense in the area of materials. In 1960, the first Interdisciplinary Laboratories were funded through the ARPA of the Department of Defense (Schwartz 1987, 29, 30; Roy 1970, 8). This pressure led to a "marked discontinuity in what might have been expected from a 'normal' growth pattern of materials-oriented disciplines, with the consequent emergence of 'Materials Science' in the 1960s" (Roy 1970, 2). The main reasons quoted for this change, in addition to military interests, are general federal support for initiatives in this area, advances in solid state sciences, and the relation between university needs (especially building and equipment) and federal funding (Roy 1970).

According to scientists involved in its development, the emergence of materials science was closely linked to external concerns (Roy 1970). "Its emergence . . . signified an important attempt by the federal government to influence (through funding) the direction and modus operandi of university research in the light of society's needs."[3] The establishment of academic laboratories was a key element in the federal government's strategy to gain legitimacy for the field of material science. This was one of the first attempts at the formation of multidisciplinary, interdepartmental, and mission-oriented laboratories. Such an effort did not result in a smooth transition to new organizational forms for research. In a conference held at Penn State in 1969, it was asserted that "there exists a good deal of uncertainty and confusion about the scope of 'materials science,' 'materials engineering' and 'materials research' and their relation to the established disciplines of metallurgy, ceramics, solid state physics and solid state chemistry" (Roy 1970, 1).

At the time, the relationship of corporations to academic material science varied according to a firm's dependence on a particular subfield of material science. The metals sector was usually less R&D oriented and mature and was contracting during the 1960s and 1970s. Fundamental work crucial for a viable technology strategy was thus not done by industry itself. We may speculate that this had a distinctive impact on the outlook of most metallurgy departments.[4] In contrast, in polymers, basic science was essential to the industry. The chemical industry, of which polymer production is a part, is much more research intensive, and it was growing rapidly in the same period as the metals industry was stagnant (Hounshell and Smith 1989).

Federal agencies have remained the main supporters of university materials research, as will be shown in the next paragraph. One question that can be asked is whether the early emphasis on integrating the basic needs for materials applications that occurred in the United States really helped in strengthening its position. Some indication can be reports by the National Science Board's Committee on Materials Science and Engineering assessing the state of the field in the late 1980s, a period in which increased attention to the competitive position of U.S. industry vis-à-vis Japan was a dominant theme.

On the basis of the relative contribution, the integrated scientific research field of materials science scored better than the metallurgy, ceramics, and polymer subfields. However, the committee concluded that the contribution of U.S. materials sciences was considerably lower than the average contribution of U.S. science. Thus, it was argued that continued support for materials science to improve its contribution to economic competitiveness was necessary.

Centers in Materials Research[5]

Around 1960, the first Materials Research Laboratories (MRLs) were founded with funding provided by the ARPA. This funding was regarded as essential to the growth of materials science and engineering because of the need to acquire expensive instrumentation. In this period, solid-state physics shared this need with materials science.[6] Because instruments became too expensive to be paid for by individual researchers, it stimulated cooperation and mutual interest between scientists to acquire this technical resource basis. Therefore, the initial interest in interdisciplinary research within the field itself was based on this access to instruments, thought to be the critical resource for the success of the research.

From the early 1980s onward, in various forms university research centers emerged in numerous institutions in the United States. In part, this was caused by internal reorientation toward securing external funding but also because the resource structure and external demands changed. Two NSF programs from this period can serve as examples of the missions.

University Industry Cooperative Research Centers are an NSF initiative that was started in 1978. The NSF provides seed money for setting up a center for a five-year period and considers centers a success when industrial funding allows the centers to proceed after five years at the same or a higher level than at the start. NSF funding for this program is modest, from an original $1 million in 1978 to $3 million in 1985. The centers receive support from industry (from $0.8 in 1978 to $15.0 million in 1985) and from local states (from $0 to

$10 million in 1985) (Colton and McLaren 1988). Original plans called for the centers to be self-sustaining in five years. As can be seen from the actual budget developments, the local states provide a substantial amount of money, and usually federal funding from various research programs (Department of Defense, NASA, and Department of Energy) provides another portion. This suggests that the centers originating in this program evolved differently from the research organization that the NSF envisaged in the 1970s. The program initiates university research programs with confounding of industrial firms that are compatible with university research objectives and also responsive to industry's research needs.

The Engineering Research Centers (ERC) program was started in 1984 to strengthen the educational base for engineers. This support was thought to be essential for a strong industrial technology. It was intended to foster exchange of generic industrial problems with universities. These problems required changes to engineering education to enable the United States to compete in new technologies. However, ERC was not set up to deal with industrial problems specifically. Its initial goals were modest, but even these modest goals were not met. In part, this was a consequence of the simultaneous initiation of more than one center program by the NSF (National Academy of Engineering 1989).

Regardless of severe shortcomings, these two examples are part of a larger trend. In addition to the NSF and federal agencies, various research centers were initiated by local and federal state agencies to achieve economic aims directly relating the pursuit of science and technology in academia to critical needs in innovation. The last type of centers is most openly founded on a belief in achieving outcomes similar to the development of Route 128/Silicon Valley (Peters and Wheeler 1988).

The University Industry Cooperative Research Centers program arose from the idea that fundamental science could be more easily transformed into commercial products when the ties between basic research and the commercial sector were reinforced. The ERC program was related to the perceived lack of adequately trained scientists and engineers for industry. Local state funding was usually provided with the argument that investments in R&D and R&D infrastructure would benefit regional economic development (Peters and Wheeler 1988). Universities in the same science and technological areas can have centers with several of these purposes. In contrast to the 1960s, funding for research centers in the 1980s was largely based on a perception that developing stronger links between science and commercial applications was necessary for research to prosper.

Generally speaking, the motives, actions, and reactions of the various actors involved in funding research and performing research in research centers have grown increasingly complicated. Usually, the way in which a center functions is determined by its interactions with local institutional culture, opportunities seen by scientists in operating collectively, and the interaction of these factors with outside opportunities.

What is the specific relation between these developments and university science? To answer this question, we assume that various factors have shaped the programs and outside initiatives that led to research centers. So external missions were imputed, and adherence to these missions can have a number of more specific impacts depending on the scientific field.[7]

Local Integration of Centers

The manner in which the requirements of MRLs were met as well as their success in setting up modern centers in various universities illustrate quite clearly how development of research programs interacts with premises related to the existing research organization. At Penn State, MRL funding led to the building of an organizationally separate research organization because a well-defined Department of Materials Science and Engineering (DMSE) was lacking. Separate from the MRL, a DMSE was organized in the late 1960s within the usual academic tradition. The MRL already had organizational momentum, which enabled it to acquire an independent and separate status. Its first director only stepped down in 1988 after building it into a large integrated facility operating quite independently of the DMSE. Part of his vision of the function of university research was a fundamental study of materials.[8] External funding was geared to this need. In relation to the DMSE (with a larger effort in undergraduate education and therefore also a need to take industry as an employer in mind), the need to acquire funding arose, and in the 1980s, various thematic centers were founded. Typically, these oriented themselves toward certain product- or materials-related themes; one example is the Center for Advanced Materials, founded in 1986.[9]

At Northwestern University, MRL funding was acquired and used as a source of funding, mainly going to the Department of Materials Science (DMS), but other departments were involved from the start. At Northwestern, the establishment of an MRL coincided with the establishment of a small but fast-growing materials science department (claimed to be the first of such name in the United States). While it is officially an MRL, it mainly functions for funding purposes and as a channel for support for expensive capital equipment and instruments for a variety of clients in the university. In addition, the center provides funding for other purposes, such as the support of graduate students. The MRL is governed by a committee consisting of members of the

DMSE and other departments. Materials science has been structured mainly along a physical approach.

At Cornell University, the MRL functions similarly to Northwestern as a source of funding in materials research, similarly related to the DMSE but also outside of it. Again, support is mainly directed toward funding for expensive facilities and instruments. The funds are governed by a committee that is open for research proposals from the institute and does not have a permanent composition. Comparable to Penn State, the DMSE was a relatively small effort that expanded rapidly in the late 1960s parallel with but, in this case, partially in conjunction with MRL funding.

At the University of Illinois, instruments, facilities building, and source of funding for cooperative research are central to the original MRL. Both a Department of Ceramic Engineering and a Department of Metallurgy existed at the time of the foundation of the MRL, and these remained in existence separately until the mid- 1980s. Both departments already were strong before initiation of the MRL. Scientists from the Department of Metallurgy used the MRL much more than did ceramic engineers. This difference is mainly due to the insistence of the NSF that funding should be used for fundamental approaches. In this institute, the metallurgy-related research was closer to physics and profited much more from the funding than did the ceramic scientists.

In general, the original funding of MRLs stressed fundamental research tied to capital expensive equipment. This led to an emphasis in the first years of the field on fundamental studies close to experimental physics. Facilities that were based on these premises were not beneficial for everybody in materials science, engineering departments, or forerunners thereof. On the other hand, researchers outside traditional materials science and engineering, particularly those in physics, might be supported at a rather high level. Generally, the MRL funds were stable and reliable support as long as original configurations of cooperation and internal coherence were maintained. Interdisciplinary/multi-investigator projects were common; the effect of them on science depended on whether they were merely token change (Illinois) or part of a wider cooperative culture (Northwestern/Cornell). Participants in the field argue that, in general, integration with regular university politics works more successfully in cases where research into the (atomic) properties of materials is central than in those cases where engineering problems are seen as the central mission.[10] Study of properties therefore functioned as the basis of a need for integration separate from the external demand that would occur later and that was based on an (industry) interest in processes and products.

Modern centers are considered to exert a different influence on university research, in effect reducing the influence of the traditional disciplinary orientation of research.[11] The funding distributed through centers is sizeable. One main element in most of the current centers is that they relate to specific materials or product categories, which is indicative of the economic purposes, or that they are oriented toward specific instruments, placing them on a similar basis to the MRLs. Thus, the new centers cover polymers, which are composites that can be regarded as modern materials; other advanced or applied materials, such as fiber optics; and special facility-oriented centers, such as high-vacuum machines. The modern centers only by exception deal (in their name) explicitly with older industry interests.

Some suggestions by scientists occur every now and then that these centers create a division into haves and have-nots. However, this is countered by the argument that because there are so many centers most scientists that want to work in them can. Local administration of such centers takes very different routes even within similar programs. Original centers, such as the University Industry Center funded by the NSF, and others funded by the Department of Defense can be either concentrated within one department or spread over different departments. For example, high-temperature superconductivity is regarded as a broad problem in which expertise is needed that even extends across the boundaries of institutions; therefore, there are also some interorganizational/multi-institute centers (see Table 1).

It seems obvious that variations in local arrangements have a different impact on the structure of the field of materials science. The size of the centers varies to a large extent, ranging from a couple of thousand to research enterprises that manage funds in excess of $5 million a year (see Table 2).

At the level of the university, research integration of various subfields in materials science and engineering departments has probably benefited from the existence of MRLs. However local organizational factors have shaped outcomes, depending on disciplinary origins. Metallurgy usually changed its hiring practices, including increasing numbers of scientists with other backgrounds, especially ceramists. Typically, departments of mining and metallurgy had lost their mining component in the 1950s. When equally important ceramics efforts existed, they could also be turned into a DMSE in the early 1960s. DMSEs with a larger integrative capacity seem to have been built in those places where only small efforts existed in the 1950s and 1960s (e.g., Cornell and Northwestern). Usually, polymers departments arose out of chemistry or chemical engineering at a much later date; as a consequence of the moment they emerged, they have been included later into a DMSE or they have become separate departments. Integration or formation of a combined

Table 1. Institutional Location

Institution Type	*Number of Research Centers*
University Industry Center	6
Interuniversity	3
University Center	35
School, college, or department	25
Department of Materials Science and Engineering	22
Interdisciplinary	5
Center in center	3
Other	5
Stated aims next to research	
Facility centers	5
Technology transfer facility	3

Table 2. Amount of Funds per Center (in millions of dollars)

< 1.0	19
1.0-2.0	9
2.0-3.0	9
3.0-4.0	2
4.0-5.0	2
> 5.0	5

DMSE is problematic where various original departments have a strong tradition (e.g., Illinois). In general, we argue that such organizational transformations have an effect on the viability of scientific fields, and we now turn to assess these effects.

The Transformatory Role of Centers

A discussion of the role of centers as resource structures that have an impact on the growth of a field must take into account that centers are quite different in character from each other. It is useful to distinguish them in various types, each with a different effect on local conditions for research and external relations of research. The change in university structure shifting both distribution of funds and research choice away from individual reputational assessment by colleagues in the field and educational concerns of departments to centers have changed the relative importance of each of the factors.

For university scientists, centers change the conditions for work. Funds cover staff and director as well as research. Furthermore, competition for grants is no longer among individuals competing with each other but among groups of scientists who come together and formulate a reasonable program (reasonable with regard to external agencies). This change introduces a dynamic in the field that is not well understood by the scientists involved.[12] We suggest that centers differ with regard to each of three elements.

The first type of center is a baseline case: centers are a—sometimes minimal—administrative burden, so there must be some local payoff for scientists to get involved in them. This gives us the first type of center: the administrative center.

An administrative center is founded either as a consequence of a concerted effort on the side of faculty or university administration or as a requirement of an external audience. The formal center that is organized has little impact on internal operations. It is used as a mere letterhead for external relations with regard to interested audiences. Such centers may function as a mere extension of existing departmental commitments, so we call this type administrative.

A second type of center is a based on the provision of increased resource availability if and when it operates as a focal point for external funding, but it leaves the relations with the scientific field intact or reinforces them with some modification in problem choice because of labeling. This type of center can be called an amplifier.

The third type embodies changes in operating procedures internally, such as grouping of faculty members, and externally with regard to problem selection by audiences. This type of center can be called a brokerage house.

The fourth and last main type is the situation in which faculty members are integrated formally into a laboratory structure and where one or more function in a formal organizational role to ensure both internal and external coordination—a form that can be called the laboratory type center.

The external complexity of the funding for materials science and engineering is one element that favored setting up centers for research; thus, various ways for government funding both from ministries as well as the NSF and industry could be combined. Moreover, the combination of forces in centers allows for the funding of dedicated management functions involved in raising larger grants. Materials science and engineering was one of the first areas in which new forms of funding in university research were introduced that significantly differed from traditional NSF project funding. The effect of a reorientation in research funding (preference for programs and centers) is vividly demonstrated by the growth of the number of centers in materials science and engineering (Dresser and Hill 1989;[13] Wood 1998).

Figure 3 shows two marked periods of fast growth; the early growth is based on the ARPA program for interdisciplinary research laboratories. Subsequently, in the late 1970s and the early 1980s, a new center's growth takes off again, related to initiatives for which two NSF programs discussed above served as examples, in addition to local search for organizational forms to attract research funding from a variety of sources. Thus, the evolution sketched around the two periods discussed above is clearly demonstrated.

It is difficult to assess the outcomes of these various types in themselves. In the sections on the various phases in the development of centers, it became clear that there is a direct relation with research practice. The outcomes are very well illustrated by an important indication of scientific identity, graduate education. We charted the type of Ph.D.s produced in a number of relevant subfields of materials science. In Figure 4, it is clear that the number of Ph.D.s with a materials science and engineering degree has increased in the past decades. This is a trend that builds on the changes before 1970. Similarly, while the number of Ph.D.s in solid-state physics remained more or less stable, those in metallurgy declined in the same period. The limited growth at the same time of Ph.D.s with a degree in polymer science or ceramics illustrates that the main tendencies in the field coincide with the changes in organizational forms. The patterns with a strong growth of materials degrees in the early 1990s and a similar growth from 1986 to 1987 corresponds with a time lag to the periods in which the organizational changes at the university level took place.

Discussion and Conclusion

Some wider ranging conclusions can be drawn. Previously, the American research university—with regard to research—basically operated as an umbrella organization for the individual knowledge entrepreneur. The emergence of centers led to a more complex organizational structure; the effects of such new arrangements might be far reaching. The system of dual control of research through funding, on one hand, and employment, on the other hand, might be breaking down. This would lead to a diminished influence of the elite of the scientific field. But short of dissolving scientific fields per se, well-aimed investments in research centers, such as MRLs, affects the balance of efforts within the field. The integrative effort of outside forces, such as the funding of MRLs, might be unique for materials science and engineering.

In the creation and change of scientific fields, this changes the meaning of (and beliefs about) science's role in the world. Building on the social goals and organizational model of the Manhattan Project, outside culture changed

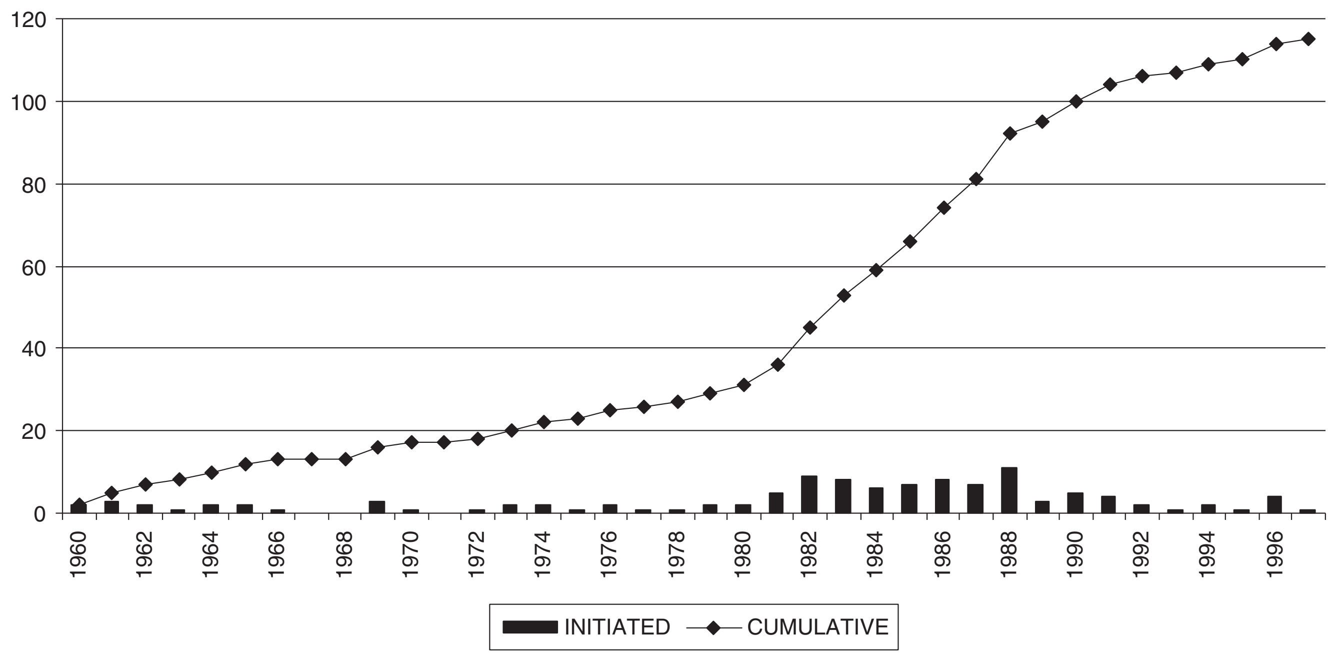

Figure 3. U.S. research centers in materials science and engineering.

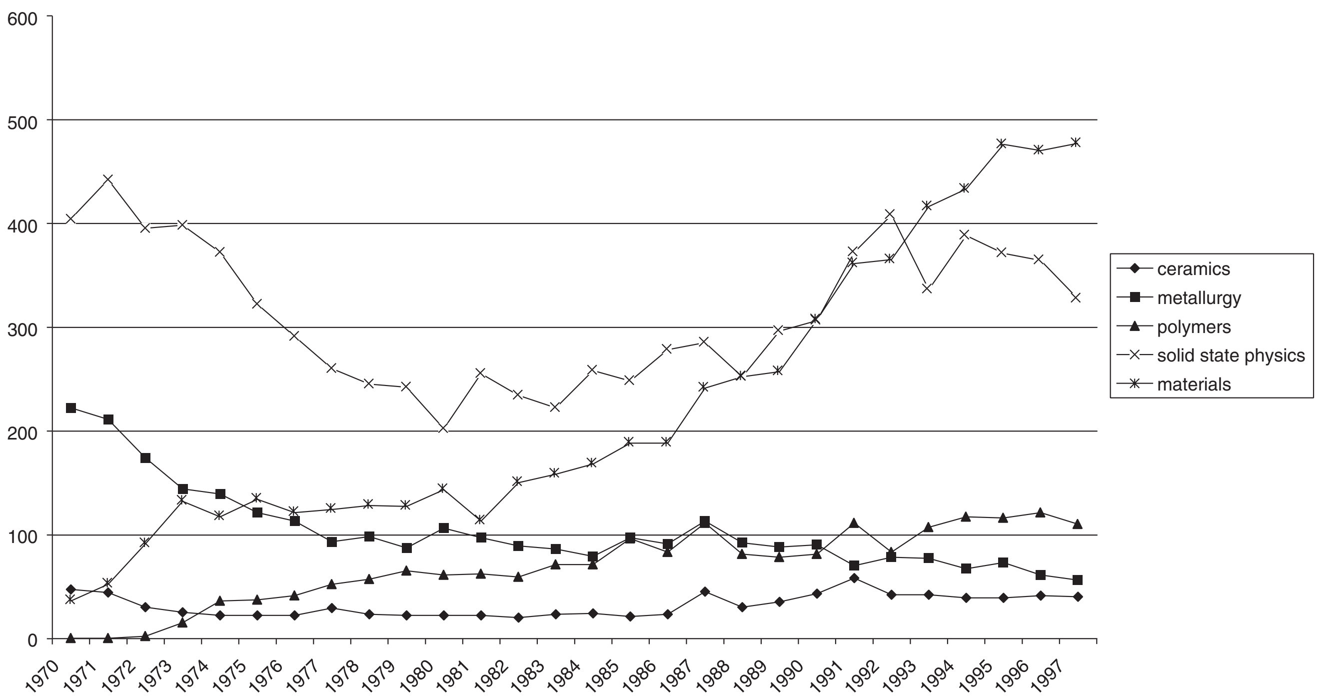

Figure 4. Ph.D.s awarded in the United States.

in such a way as to expect useful products of science in return for the proper instruments to unveil nature's secrets. The internal science project running from enlightenment onward got an increasing, particular meaning that was mediated by this possibility for scientists to exploit the changed cultural meaning of science for direct support. Such support was necessarily connected to fundamental science support because this would lead to exploitable results automatically. It did not make sense to exploit the nature of metals, polymers, or ceramics. The underlying nature of such areas of science needed to be exploited to find broadly applicable theories and methods. Therefore, the MRLs were connected to the fundamental exploitation of the nature of materials and not to the experimentation on actual problems that connected processing with structure and properties. In the first instance, materials science was only legitimated by this rather abstract belief. But when resources (instruments and funds in the MRL) became tied to this abstract commitment, it confronted scientists active in the constituent areas with organizational options that conflicted with mainstream thinking in academia. The availability of the new resources and this conflict is reflected in the assessment and feeling of crisis in the early 1970s. The essential steps that followed were, on one hand, apparently logical and, on the other hand, were only possible through the concurrent change of meaning of the constituent elements and the independent change in the resource mix.

Reasons for external audiences and scientists alike to prefer center funding are various. Bringing scientists together in one center occurs for different reasons. A first reason—and one applicable to large-scale science, such as radioastronomy and high-energy physics—may reside in the basic technical requirements of the specialty (instruments, technical staff). Second, external opportunities or resource agencies might foster the idea of centers. Third, centers can be an effect of a combination of each of these elements in addition to a change within a scientific field.

Notes

1. Probably, it could be argued that only for this period shortly before and more so directly after the war, the ideal type of scientific fields were born that have so governed the approaches of sociologists of science.

2. The following information was collected in a series of in-depth interviews with materials scientists responsible for materials research centers at Massachusetts Institute of Technology (MIT), Cornell University, Northwestern University, University of Illinois, Rensselaer Polytechnic Institute, University of Washington, and Pennsylvania State (Penn State) in 1989, followed up with a couple of brief telephone interviews with other materials scientists in 1990 and 1992. At MIT, Penn State, and the University of Illinois, scientists in traditional departments were interviewed in addition to research center directors.

3. A similar process has taken place in the neighboring field of solid-state physics in the 1940s and 1950s (Weart 1988).

4. Some of the interviewed scientists mention developments that reflect this point. Interview with Professor Th. Stoube, Department of Materials Science and Engineering, State University of Washington, Seattle, 21 August 1989.

5. The information in this section was acquired in the interviews mentioned in note 2, combined with secondary material published before or around 1990.

6. Interview with Professor M. Glicksman, Department of Materials Engineering, Rensselaer Polytechnic Institute, 29 September 1989.

7. The argument in this and subsequent section is based on extensive interviewing in the summers of 1989 and 1990 with most of the universities mentioned in the text and subsequent data collection.

8. Interview with Dr. R. Roy, Penn State, 10 May 1989.

9. Interview with Dr. R. Tressler, Penn State, 11 May 1989.

10. Interview with. Dr. C. Alstetter, University of Illinois, 16 October 1989.

11. We left purely mechanical and engineering centers out of our sampling of these centers for the growth figure together with materials outside the ceramic-polymer-metal applications, such as wood.

12. Interview with M. Glicksman; see note 4.

13. Founding dates unknown: nine; prior to 1960, five.

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