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MARKETS FOR TECHNOLOGY AND THE RETURNS ON RESEARCH

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Markets for Technology and the Returns on Research

A variety of scholars have empirically confirmed that investment in research and technology development is crucial to the growth of modern economies (Solow, 1957; Mansfield (1980), Griliches, 1986; Jaffe, 1989). Because of this, signs that large industrial companies in economically advanced countries are cutting back on their research expenditures could be cause for alarm.[1] Explanations for the declining proportion of industrial resources devoted to research have ranged from the end of the cold war,[2] to short investment horizons of managers, to the inescapable problems of technology transfer out of central research laboratories into operating businesses, to management's rational reaction to appropriability problems (Teece, 1986).[3]

This paper proposes a model of the mechanisms that can cause the degree of appropriability of technology to change -- thereby affecting the potential for innovators to profit from their investments in research. The model focuses on the drivers of appropriability at the interfaces between four stages of technological value added:

- Research
- Development & production of materials
- Development & production of components
- Design & assembly of end-use products.

The model asserts that whenever and wherever technological modularity exists (as defined below), it creates sufficient information to enable freely functioning markets to work efficiently across the interfaces between these stages of value added. In particular, the modularization of product designs can create sufficient information to enable markets to emerge between components and assembled products. Modularity occurs in the form of accurate scientific models, to enable such markets to emerge at the interfaces between research, materials and components. These intermediate markets, which this paper labels "decoupling markets," make it difficult for firms that develop new technology in research, to capture its value in the markets for end-use products.

However, when the condition opposite to modularity exists -- which this paper calls technological *integrality* -- then managerial coordination, rather than markets, are the most effective mechanisms to coordinate the interfaces between these stages. Under conditions of technological integrality, companies can much more readily capture the returns from their investments in research.

An important implication of the model is that the strategies that integrated firms need to employ to appropriate the value of the technologies they develop through research, must change in response to increasing or decreasing degrees of modularity at these interfaces. Because technological change and scientific discovery can reverse the nature of product modularity or change the scope of scientific models, we should expect that firms' abilities to appropriate the value they create in research will wax and wane. Technological modularity in certain industries, in other words, may be the deeper, causal factor at work behind the trends in the R&D statistics that we observe. Reductions in research spending may be a rational and possibly temporary response to the modular character of product technology in these industries. It may not necessarily presage a long-term, broad-based trend toward underinvestment in industrial research and advanced technology development that is driven by short-term financial performance goals, as some have feared.[4]

This paper builds upon Gomory's (1989) assertion that the fruits of research are generally embodied in new components and materials, rather than end-use products. In industries such as pharmaceuticals and chemicals, whose marketed products are materials, there are fewer value-added stages at which decoupling markets can emerge. We would therefore expect that capturing the returns to research would be more straightforward in these industries, than would be the case for companies that are integrated further forward into end-use products, such as IBM, Siemens, General Motors, Xerox and the former Bell Telephone system. Because materials and components are the vehicles through which these companies take new technologies from research laboratories into usable products, there are more places where accurate scientific models and product modularity can enable decoupling markets to emerge.

The model is grounded in two sets of case histories, in what Yin (1989) terms a nested, multiple case research design. The first set of case studies, about IBM's work to develop advanced components in the disk drive industry, is part of a larger, detailed research program investigating the patterns of technology development in that industry (see Christensen, 1993, 1997). The impetus for these developments typically originated in forecasts by end-use product designers that certain disk drive components would constitute bottlenecks to performance improvements in the future. These cases suggest that IBM's ability to utilize the technologies its scientists developed, and its ability to prevent other firms from appropriating them, seems to have varied directly with the degree of technological integrality in its products. The second set of cases describes technologies -- advanced ceramics and RISC microprocessors -- whose development was instigated in research laboratories. These cases suggest that because of technological integrality, innovating companies find it difficult to create commercial value from their research unless they integrate forward into developing end-use products that employ their technology.

Because of this research design, the model that emerges from these case studies can constitute only a hypothesis, whose validity and reliability need to be evaluated through further research. The final section of this paper suggests where and how the model's usefulness might be tested.

Definitions

Before proceeding to the case histories, it will be helpful to define several important terms. *Components* are devices fabricated from materials that are the building blocks of intermediate- or end-use products. Components embody the fundamental technological concepts upon which products are based (Henderson & Clark, 1990). For example, the magnetic data recording technology upon which tape and disk drives are based resides in the recording heads, tapes and disks employed in the products. Optical recording products employ different technology, embodied in different components. The *architecture* of products and components defines the working relationship amongst the components and/or materials of which they are comprised. *Research* encompasses the study of fundamental scientific principles and questions, and the application of scientific principles to the development of new materials and functional devices. The knowledge generated from research rarely constitutes a commercial product; rather, this knowledge tends to be embodied in materials or components, from which new products can be made. *Development* refers to the design of new products that provide functionality to end users.

As an example of how these terms are used here, Sony's creation of the portable transistor radio in the 1950s would be termed *development,* whereas the activities leading to Bell Laboratories' fabrication of the first transistor in 1947 would be termed *research*. The transistor itself is a *component*, from which more complex products can be assembled, as defined by the product's *architecture*.

Modularity amongst the materials and components that comprise a product exists when three conditions are met:

1. The designer of a product knows which parameters or attributes of a component or material need to be specified, and to what tolerances, in order to function acceptably in the product;

2. Well-accepted measures of these attributes exist, and the technology to make and verify these measurements is known and available; and

3. It is well understood how variability in the attributes of components and materials interacts with the required design and resulting performance of the other materials, components and subsystems that comprise the product.[5] This knowledge of technological interactions enables designers to model, simulate, or predict the impact that changes in components or materials will have on product performance, without having to build physical prototypes.

When these three conditions are not met, then a technology is said to be *integral*. With integral technologies, product designers do not know which of the many attributes of a component need to be specified to particular tolerances, in order to have the product perform as expected when the components are assembled together. Unambiguous means to measure these attributes may not exist, and engineers are unable to predict or model how variation in the attributes of some components will affect the required design of other elements of the product. Hence, under conditions of technological integrality, optimal component designs and the product architecture can only be defined iteratively and interactively, by an integrated development organization. Pure modularity and pure technological integrality are, of course, extreme boundary conditions. Most products and technologies exist somewhere along a continuum between these extremes.[6]

This definition of technological modularity is a scalable definition. For example, when the above conditions are satisfied in materials science, scientists can model whether and how certain atoms can be combined together, and predict in advance what the resultant material's properties will be. In parts of the pharmaceutical world where modularity reigns, researchers or doctors can substitute one new chemical entity for another in a patient's therapy, and accurately predict the results. In elements of that industry that are characterized by integrality, doctors cannot accurately predict how patients will respond when treated with a different drug compound.

At the other end of the value-added spectrum, we might say that a modular interface between product design and manufacturing exists when clear, explicit design-for-manufacturing rules exist (points #1 & 2 above), and when new engineers can readily be taught how changes in product design affects manufacturing process parameters. Modularity at this interface enables an arms-length relationship between design and manufacturing. It can enable a decoupling market to emerge at this interface (outsourcing manufacturing, for example). Technological integrality exists at this interface when clear design-for-manufacturing rules do not exist, and when the impact of changes in product design on the cost and quality of the manufacturing process can only be discovered through trial and error prototyping.[7]

Section 1: The Disk Drive Technology Case Studies

With these definitions as a foundation, we can now examine the case histories. The first section offers general historical background information about how the need to initiate research in certain aspects of magnetic recording technology was initiated at IBM, the industry leader. The subsequent sections then recount the case histories of three particular new component technologies.

The Instigation of Magnetic Recording Research at IBM

For most of the first three decades in the computer industry's history, IBM was the undisputed leader in developing and manufacturing a range of data storage products based upon magnetic recording technology. In a manner modeled by Abernathy & Utterback (1978), the early years of IBM's magnetic recording technology development were characterized by extensive experimentation with product design. IBM first began using magnetic tape storage with its early computers in 1953. In 1956, engineers at its newly-established magnetic information storage laboratories in San Jose, California completed development of the world's first machine to store data on rigid rotating disks. Named the RAMAC (for Random Access Method for Accounting and Control), the world's first disk drive took the space of two large side-by-side refrigerators; stored data on fifty 24-inch disks mounted on a single spindle; and for all this, packed 5 megabytes (MB) of capacity.

The IBM RAMAC was an *architectural* innovation -- its inventors used known technology and available materials to craft a machine that worked. This is frequently the case in the development of new categories of products -- initial models often employ known technology and commercially available materials and components.

These earliest disk drives worked, but rarely worked well. In fact, the earliest customers did not have clear definitions of which attributes of the product would be the most important. This understanding could only coalesce as these early products began to be used.[8]

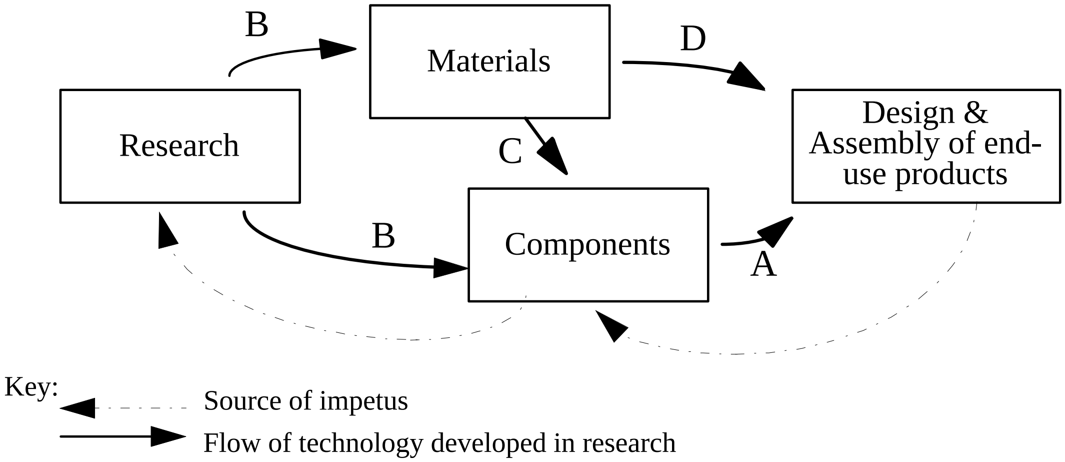
Early Challenges in Managing Technology and Product Development at IBM

Between 1956 and 1964, the dimensions of performance along which customers needed improvement became clear, and innovating firms began to be pressured by customers and competitors to advance along this technological trajectory. IBM initially was able to find these improvements within the network of component suppliers it had cultivated around its San Jose development and manufacturing operations. By the mid-1960s, however, IBM determined that its independent component suppliers could not provide the rate of improvement in component performance that it required, and the company integrated backward into designing and producing many of its components. This required IBM, in turn, to begin *research* activities that would yield the advanced technology to be embodied in those components. This was the genesis, in about 1964, of the company’s research activities in magnetic recording[9] (as opposed to *development*, in which IBM had been active since the early 1950s). As it did this, IBM’s innovative energies shifted away from the architectural creativity that was so important to the establishment of the product category, and focused instead on improving the materials and components employed in the product.[10] This impetus for engaging in research, and the mechanisms through which the fruits of research flowed into the market, are depicted in Figure 1.[11]

These decisions created two management challenges for IBM: First, component development was a very different enterprise than product design, requiring very different resources and time scales. And second, the technological advances emerging from the lab intensified the degree of integrality of disk drive technology. This required a highly interactive, complex product development process -- the design of most of the key components was dependent upon the design of the other components.

Figure 1:

**The Motivations for Research, and the
Pathways by which the Fruits of Research Reach Commercial Markets**



Note: The letters are placed at various interfaces to aid in references made later in this text.

<u>Differences Between Component Development and Product Design</u>

The broadening of IBM’s technological aspirations from architectural design to technology and component development heralded a significant change in the enterprise of development for IBM, because component development and manufacturing were fundamentally different activities than product design and assembly, with respect to scale, scope and feasible targets.

Development of new product architectures is generally an engineering task, not an issue of research and development. Development of the initial RAMAC, for example -- including time to lease a building, recruit a team, bring the engineers up to speed on what was known about magnetic recording, and complete the product design -- took four years. Today, with computer-assisted design and simulation tools, development of new platform products can be completed within a year, at a cost of $5 to $20 million.

In contrast, some of the most important new component technologies, such as thin film heads and disks or magneto-resistive heads, cost hundreds of millions of dollars, and took more than a decade, to develop. This is because component technology development often must start with research on basic scientific questions, and then proceed forward through component development and engineering, manufacturing process development, and manufacturing scale-up. Compounding this long cycle, components or materials then must await being designed into new products, before they generate commercial value. The development of new component technology is often, therefore, extraordinarily expensive, uncertain and time-consuming, compared to the enterprise of product development.

Another factor making the development and manufacture of components a very different enterprise than product design and assembly is the nature of what can be targeted. New product designs are generally targeted to customers' needs. Programs to develop new component technologies, however, can rarely be targeted at customers or markets because of the time and uncertainty involved, and because the attributes of components typically are not the attributes of products upon which end-use customers base their product choices.

Because component developments are difficult to target at customers, they generally are launched in response to what Constant (1980) calls *presumptive anomaly* -- an estimate that the performance trajectory of the present technology will level off at some point in the future, and that another approach will be needed at that time to keep pace with the industry's technology trajectory.[12]

Technological Integrality

IBM was not simply integrated upstream into components and research in order to assure supply. It had to employ highly integrated product development processes as well, because the design of most components depended upon the way other components were designed, and upon the design of the product’s architecture. Designing and manufacturing complete disk drives required the substantial, integrated scale and scope that Chandler (1977) saw had been necessary to create other substantial industries.

As the dominant manufacturer of magnetic recording products in the 1960s and 1970s, IBM was best able to afford the research costs inherent in being in the component business, and had the scale and scope required to manage integal design problems. But *every* firm that wanted to play in the disk drive industry during these years had to incur these costs or exit the industry, because the advanced components required to keep pace with the industry's technological trajectory were not commercially available, and because the technologies were integral. Hence, each of the early participants in the industry -- including Burroughs, Control Data, Univac, Honeywell, Storage Technology, Digital Equipment, Xerox, Ampex, Fujitsu, Hitchi and NEC -- integrated backward into the manufacture of components, and the research required to support their development.

These other firms, which lacked the scale and technical scope of IBM, tried to cope with IBM's advantages in several ways. For example, Control Data, which was the largest supplier of disk drives in the non-captive Original Equipment Manufacturer (OEM) market, established a consortium of smaller computer companies that at various times included Honeywell and Univac, to develop and manufacture components. Others, such as Ampex, sought to offset development costs and achieve efficient manufacturing scale by selling components outside.

The integrality of disk drive technologies was both a blessing and a curse. It was a blessing in that it created a pervasive barrier to entry in the industry. Independent manufacturers of most components could not exist, because their would-be customers were unable to specify what they needed, and the interaction of variability in key component parameters on the performance of other components was not well understood.

But technological integrality was also a curse, in that it made the product design process costly and managerially difficult. It would be far simpler if a project manager could in essence say to one group, "You go off and design the head;" to another group, "You design the disk;" and so on, and then to put the pieces together at the end. They could not do this, however, unless they could specify to each of these groups which attributes of their components they needed to meet, and to what tolerances. They needed to be able to measure these attributes unambiguously; and they needed to understand how changes in the design of one component would affect the required design of other components. In other words, technological modularity could vastly simplify the problems of management, by obviating the need for so much interaction during development (Sanchez, 1996).

IBM took this step toward modular design in about 1964, at the same time that it designed its first modular mainframe computer, the IBM Series 360 (Baldwin & Clark, 1998).[13] Initially, modular designs did not enable decoupling markets for components to supplant managerial coordination across the interface between components and product design, as Christensen (1996) and Baldwin & Clark (1998) suggest may ultimately happen. This is because at the outset, the interface standards amongst the modules were internal and proprietary. Under such conditions of "internal modularity," companies such as IBM could subcontract the design and manufacture of components to third-party suppliers. But until "market modularity" occurred -- widely accepted interface standards amongst components -- vertically integrated companies still held the upper hand. It took several years after IBM and its competitors achieved internal modularity, before market modularity emerged. And as the following case histories show, it happened much faster in disks than in heads.

Modularity brought to IBM and its competitors all of the benefits in speed, flexibility and design cost that Baldwin & Clark describe. But it brought costs as well. The same specifications, measurement technology and understanding of interactions that enabled internal component development groups to work at arms length with product designers, made it possible for external suppliers to produce components that would meet those same specifications.

Development of Advanced Recording Heads and Disks: Three Case Studies

The suggestion that technological modularity enables markets to emerge at the interfaces between any of the steps of value added in technology and product development -- between research, materials, components and product designs -- is key to understanding why companies' abilities to capture the returns from their investments in research are likely to wax and wane. The way in which this can occur is illustrated in the following three brief case studies, about the emergence of thin film head, thin film disk, and magneto-resistive head technologies. These efforts entailed the integration of everything from basic science through end product design, and exemplify the management challenge of coordinating the disparate character of component development and the design of products that can use those components.

Thin Film Heads

IBM's original recording head design, called ferrite heads, consisted of an electromagnet formed by coiling fine copper wire around ferrite (iron oxide) cores. By the mid-1970's, recording head technology had become modular enough that a market for standard-design heads had emerged. These were supplied by independent manufacturers such as Applied Magnetics.

A primary factor limiting recording density was the size and precision of these electromagnets. Ferrite heads had to be ground mechanically to achieve desired tolerances, and by the mid-1970s, many felt the performance limits of ground ferrite heads were being approached. As early as 1965, researchers posited that by sputtering thin films of metal on the recording head and then using photolithography to etch electromagnets on the head's surface, smaller but more powerful electromagnets could result, enabling more precise orientation of smaller magnetic domains on the disk surface. Starting in about 1965 in its Yorktown Heights, NY research center, IBM alone wrestled with understanding basic scientific issues in the physics of magnetic recording and the properties of new materials -- issues that needed to be better understood before the feasibility of thin film head development could be realistically assessed. This phase of foundation-building scientific inquiry lasted about 6 years. By 1971, no thin film heads existed, but the *concept* -- the technological feasibility -- had been worked out through theory and general experimentation.

Once IBM had established the feasibility of the technological concept, the news spread to other firms through published scientific papers and the trade press. Statements by respected IBM scientists that the technology was important and the components were conceptually feasible *greatly* reduced the risk perceived in undertaking the project amongst the broader group of vertically integrated manufacturers mentioned above. IBM had established that it *could* be done. These competitors then initiated their own development efforts to figure out *how* it could be done. In a sense, this awareness of the feasibility of the technology constituted an important leakage of proprietary technology -- without any drawings, know-how or secrets passing from IBM to its competitors.

Development of prototype thin film heads began in these other firms roughly in 1971. Although thin film photolithography was well-established in the semiconductor industry, its application to recording heads proved extraordinarily difficult. Read-write heads required much thicker films than did integrated circuits; the surfaces to be coated were often at different levels, and they could be sloped. This phase ended in 1976-78, after each of these firms had spent between $30 and $60 million.

Once working prototypes had been made and tested (by about 1976), a manufacturing process engineering effort was initiated, and the tortuous process of designing the component into a new disk drive model was begun. This was tortuous because the thin film head was an integral technology -- the design of the head depended upon the design of other components in the system, and upon the architecture of the system itself. And the designs of these other elements of the product were predicated on the design of the head. Product development teams intending to employ thin film technology therefore had to do their work in a tightly integrated manner, because of these complex technological interactions. And because of the modularity of earlier designs, none of them had a practiced process for doing this.

Burroughs was the first disk drive maker to announce a model employing thin film heads, in 1976, but it was never able to ship the product. Its failure was not because it coldn’t make the thin-film heads. It was because Burroughs was unable to account for the new, complex technological interactions inherent in thin film technology. They couldn’t make the *product* work

IBM shipped its first product that used thin film heads in 1979 -- 14 years after the underlying scientific research had been initiated, and 8 years after purposeful component development had begun. The cost of IBM's total thin film head effort has been estimated at over $300 million. Despite this magnitude of investment, the vertical integration and investments in research that supported advanced component development paid off handsomely for IBM. It was able to capture the proprietary value of the technologies it developed because of the technologically integral character of the disk drive. Even if proprietary technology had leaked out of IBM embodied in an engineer or a document, competitors could not directly use it, unless they also possessed the integrative design capability to design simultaneously the other components as they designed the head, and the product architecture. A leading market researcher commented as late as 1986 that:

> Very high entry costs combined with a veritable mine field of technical traps has kept the number of independent thin-film head suppliers down to a handful; even IBM, developer of the technology, had formidable problems in bringing this technology to market.[14]

The Case of Thin Film Disks

In contrast to the way in which the developers of thin film heads were able to capture the fruits of their investment in technology, the case of thin film disk development illustrates how modularity enables other firms to appropriate technology.

Recording disks originally were made by coating flat aluminum platters with microscopic particles of iron oxide. By the mid-1970s, engineers sensed that this technology was approaching two insurmountable barriers to improvement. By nature, there were unusable interstitial spaces amongst even the most tightly packed of the needle-shaped oxide particles. These spaces could not store magnetic information. The second problem was that variation in the height of the particles limited engineers' ability to fly heads closer to the disks. The technological solution to these constraints, thin film disks, consisted of plated aluminum platters that were sputter-coated with thin films of a magnetic metal a few angstroms thick. Thin film disk development was initiated in about 1976 in IBM's research center and at Xerox's Palo Alto Research Center (PARC).[15] Thin film disk development is estimated to have cost each of these firms between $50 and $100 million.

Despite the fact that the design and manufacture of thin film disks was radically difficult technology on a number of dimensions, incorporating thin film disks into new product designs was much simpler than for thin film heads -- because the new disks were *modular* in character. Specifically:

1. Product designers knew what attributes of thin film disks needed to be specified, and to what tolerances. For example, the definition of what constituted a surface defect, and the flatness and diameter of the disks, could be specified quite precisely to an independent group that would design and manufacture the disks.

2. Standard metrics for each of these attributes existed, and the technology to perform reliable measurements was available; and

3. The science underlying this technology was well enough understood that the interactions between the thickness of the sputtered metal layer, the coercivity of the media, and other elements of the disk drive design could be modeled. This meant that variation in these key parameters could be accounted for, and designs ultimately could be made robust to such variability (Clausing and Taguchi, 1990).

Leakage of Thin Film Disk and Head Technology from IBM and Xerox

The thin film head and the thin film disk were both substantially new component technologies, as defined by Henderson & Clark (1990). Yet the integral character of the head, and the modular character of the disk, made the first technology very difficult for other firms to appropriate, and the second relatively easy (Teece, 1986).

IBM's introduction of its new thin film heads and disks in a limited number of high-end models stimulated demand for the new componentry amongst certain independent, non-integrated disk drive manufacturers. These independent firms, such as Maxtor and Micropolis, were those that pushed, through innovative (some would say "daring") system design, what was called in the industry "the bleeding edge" of performance -- a much more aggressive posture than the vertically integrated manufacturers were typically inclined to adopt. These “bleeding edge" manufacturers that most needed the advanced componentry were, more or less directly, competitors of IBM. But IBM viewed its proprietary access to advanced componentry as its primary competitive advantage, and was reluctant to sell its components in the external marketplace.[16]

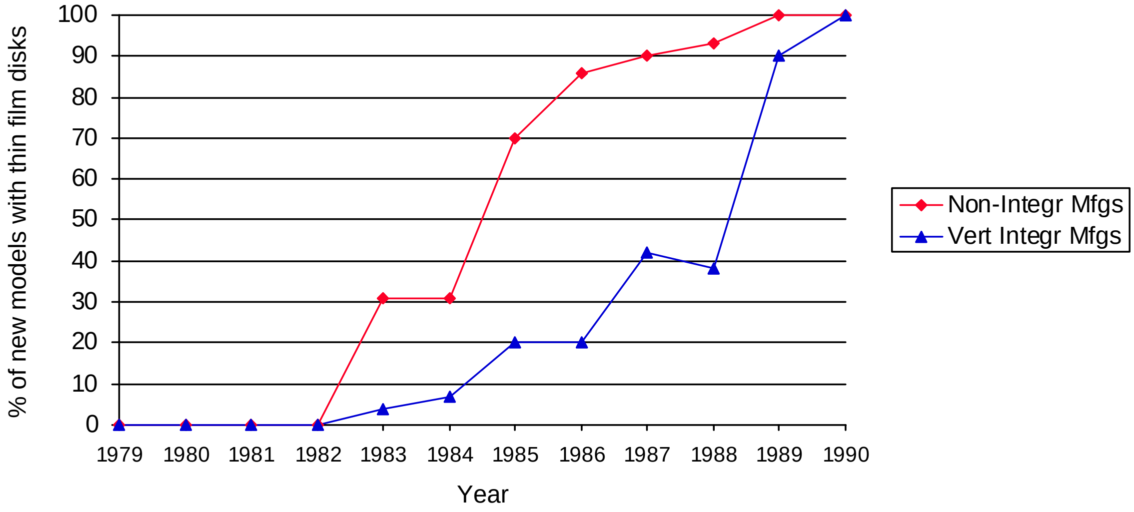
Sensing this demand for advanced components, venture capitalists recruited key IBM and Xerox engineers into new start-up firms to produce and sell the new-technology components to bleeding-edge disk drive makers in the OEM market. The industry's leading thin-film disk manufacturer, Komag, and the leading thin film head manufacturer, Read-Rite, both started in this manner, in 1983. [17]

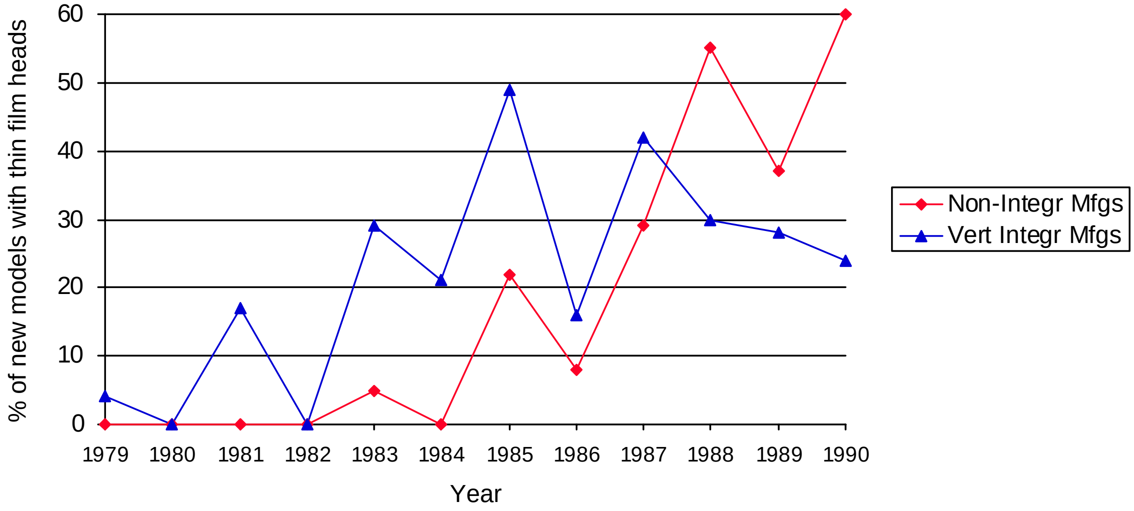
Komag was much more successful in selling its thin-film disks than Read-Rite was in selling its thin film heads. The technological modularity of disks constituted sufficient information for a decoupling market to emerge between Komag as supplier, and non-integrated designers and assemblers of drives, such as Maxtor. All three elements of modularity existed: Komag’s customers could specify what they needed; clear metrics allowed supplier and customer to communicate expectations and confirm results; and the ability to predict how variation in disk attributes would interact with the performance of other elements of the system, facilitated the buying and selling of disks in the open market. As the top chart in Figure 2 shows, this decoupling market was so much more effective than managerial coordination at the component/product design interface that the non-integrated firms were much more aggressive in adopting the new disks than were the integrated firms, even though it was the integrated firms that had paid to develop the technology. For example, in 1986 85% of the products introduced by non-integrated disk drive makers used thin film disks, whereas only 20% of the models introduced by integrated drivemakers that year used thin film disks.

The bottom chart in Figure 2 shows a different story for thin film heads, however. It was the *integrated* firms that led in their development and use. A few non-integrated firms attempted to employ thin film heads in fits and starts between 1983 and 1986, but their attempts were frustrating. Complaints from both sides of the transaction typified the challenge. One disk drive design engineer said, “The (independent) thin film head suppliers just aren’t reliable. We tell them what we need, and they ship heads to us that just won’t work.” And the head supplier lamented, “The customers just don’t know what they want. They give us a spec, and we deliver exactly what they ask for. Then they call us and complain that the heads won’t work.”

In our assessment, this problem was not an issue of the reliability of the head supplier. It was an issue of technological integrality. Drive makers did not know which attributes they needed to specify; clear measurement methods did not exist; and variation in certain attributes of the heads interacted with the performance of the disk drive system in unpredictable ways. This is why the disk drive makers concluded that the heads they had received “wouldn’t work.” Between 1979 and 1986, therefore, the integral nature of the technology essentially kept thin film heads proprietary to IBM and its integrated competitors. Hence, in 1986, while 85% of the drives introduced by non-integrated companies were using thin film disks, only 8% of those models used thin film heads.

Figure 2: Impact of Modularity on the Ability of Integrated and Non-Integrated Firms to Exploit New Thin Film Technologies





Starting in 1987 the situation changed, however. With eight years of experience with the technology under the belts of industry engineers, the uncertainties about attributes, tolerances and interactions that had kept thin film heads an integral technology became resolved -- and as thin film heads acquired a modular character, their use by non-integrated companies mushroomed. It then became straightforward for non-integrated designers and assemblers of disk drives to procure the heads from non-integrated suppliers like Read-Rite. While Komag, the disk maker, had been financially viable from its inception, Read-Rite struggled to stave off bankruptcy until 1988, when it finally turned its first profit on $28 million in sales. Enabled by modularity, its revenues then rocketed 86% per year, to $345 million in 1992.

In summary, these two case studies suggest that under conditions of technological integrality, effective decoupling markets cannot emerge at the interfaces between research, materials, components, product design, and manufacturing. Only management can coordinate these activities, as Chandler (1977) suggests. Modularity, however, brings sufficient information for decoupling markets to operate across these interfaces. And for reasons discussed next, markets appear to do a better job at this coordination than managers, once modularity exists.

Modularity and the Markets for Technology

One puzzle unanswered by the analysis above is why, in the case of thin film disks, the integrated companies were so much *slower* than the non-integrated ones in adopting the technology they had developed. The following paragraphs suggest a reason.

Although the characteristics and economics of the new component technology development process differed greatly from the product design process, the technological integrality that characterized disk drives through the 1960s and 1970s gave IBM such control over the market that it could effectively dictate both the slope of the technological trajectory and the pace at which it introduced new products. There was not a well-developed market for new components technology during this period. This made it possible for IBM to coordinate the emergence of a new component technology from its lengthy development, with the design of the product system in which it would be used.

Beginning in about 1980, enabled by the increasing modularization of product designs and abundant venture capital, over 50 non-integrated firms entered the industry to design and assemble disk drives (Christensen, 1993). The most successful of these companies employed an entry strategy of using a new design architecture, incorporating standard, available components, with a product targeted at an emerging market segment (Christensen, Suarez & Utterback, 1998).

The entry of these non-integrated competitors changed the basis of competition, particularly at the low end of the market. Whereas earlier, integrated manufacturers had been able to rely on access to proprietary advanced componentry as a source of competitive performance advantage, the non-integrated entrants could not. Competition amongst these manufacturers forced them to excel at product design.

Enabled by the flexibility of product modularity, the product design cycle accelerated dramatically. Whereas IBM had introduced new product generations every four years in the mid-1970s; the cycle had accelerated to two years by 1980, and to one year by 1985. Through intense competition amongst non-integrated producers to beat each other to market with products that incorporated the latest and best components, the market wrested control of the product development cycle from IBM.

At the highest-performance end of its product line -- drives whose disks were 10 and 14 inches in diameter -- product designs continued to be integral in character, and development cycles were longer. In these instances, IBM was able to coordinate the emergence of new thin film heads with the design and introduction of products in which they would be used, very effectively.

The pressure from the non-integrated designers and assemblers occurred almost exclusively in smaller disk drives, most of which were sold to makers of desktop personal computers and engineering workstations. Responsibility for these products at IBM resided in its divisions in Rochester, Minnesota and Fujisawa, Japan. To remain competitive in smaller desktop products, these divisions had to implement product development strategies that responded to a very dynamic and competitive customer environment. There was no time to carefully coordinate the positioning of a product in the market with the capabilities of new component technologies that were emerging from the lab.

Just as product modularity enabled the emergence of an open, OEM market for components, IBM's response to these decoupling forces in its low-end disk drives was to evolve towards an *internal* "free market" system for new component technologies as well. When new component technologies were developed, they were made available to (but not forced upon) product design engineers. The designers of new disk drive systems were free to pick and choose whatever component technologies IBM had in its arsenal to meet the performance objectives of their products. This internal "market" for components allowed IBM to accelerate its product development cycle in pace with the external marketplace by avoiding any delays caused by force-fitting inappropriate componentry into new product designs.[18]

In this free market system, IBM's market position, rather than management dictums, determined the pace at which it could employ the advanced component technologies in its desktop models. This is illustrated in Figure 3, which charts on its vertical axis the market positions (average megabytes of all new models introduced each year in the 5.25-inch architecture) of Micropolis, Maxtor and IBM.[19] It shows that in 1984, Maxtor's average 5.25-inch model sported 125 megabytes; Micropolis's was 64, while IBM's was 16.5. There is nothing normative about this observation -- these firms were simply serving different markets. Maxtor was selling to the memory-starved engineering workstation market, while IBM was making 5.25-inch drives for its XT and AT personal computers.[20] The percentage number near each line in each year denotes the percentage of all of that firm's 5.25-inch models introduced that year which employed thin film heads (in the left-most chart); thin film disks (in the center chart); and Run Length Limited (RLL) recording codes (in the right-most chart).[21] All of these technologies were developed initially by IBM, and came to be disseminated in the industry through the mechanisms noted above. Note that in 1984, none of these technologies was used in the IBM or Micropolis product lines, while Maxtor used thin film disks in all of its models, with ferrite heads and MFM codes.[22]

Insert Figure 3 about here.

In 1985, Micropolis adopted thin film disks on 100% of its new models, and Maxtor and Micropolis converted completely to RLL codes. But IBM still did not use these technologies -- it could still support its market position with established technologies. In 1986, Maxtor and Micropolis both began using thin film heads, while IBM was still able to satisty its requirements with conventional technology. Finally, when its average 5.25-inch drive approached the 80-100 MB range in 1987, IBM began using RLL codes in 88% of its new models (note that Micropolis had adopted RLL codes when its products had penetrated this same range two years earlier).

When its 5.25-inch drives reached even more demanding territory in 1988, IBM adopted thin film disks on 62% of its new models. Note that although this was done four years after Maxtor had adopted thin film disks, it was done when IBM's drives reached the *same capacity territory* which Maxtor and Micropolis had occupied when *they* first used thin film disks. Although IBM had first used thin film heads in high-end 14-inch drives as early as 1979, and although bleeding edge suppliers such as Maxtor began using them in 1986, IBM did not use thin film heads in any of its modular 5.25-inch models until 1990.

By drawing horizontal lines across Figure 3, one can see that there seem to have been product performance zones which mandated that particular component technologies be used. IBM's personal computer business had devolved to a performance position far from the market's leading edge by the mid-1980s, and it had not yet entered the zones requiring the components IBM had developed. On this basis, it would be difficult to argue that IBM's failure to utilize more broadly the component technologies it had paid so dearly to develop was due to conservative or inept technical management. Simply put, in a modular world the firms that needed the new component technologies used them. The firms that didn't need them didn’t use them.

A manager of IBM's thin film head development program commented during our interview that it had turned out that IBM's thin film head was ahead of its time; that conventional technology had progressed so far beyond what IBM had felt would be its limit, that the desktop personal computer market really didn't *need* the thin film head when its development was complete. When assessed in light of Figure 3, however, this statement is not completely accurate. Given that the technological forecast was made in 1965, it was *remarkably* accurate -- Maxtor snapped up thin film heads as soon as they were available and modular. The forecast which was *not* accurate was the one which said that *IBM's* required product performance would be limited by ferrite head technology.

IBM didn't miss the market. Other companies profited from the technology that IBM developed because IBM missed IBM, and because IBM chose to make its components available only within its internal technology market, and not the external one. Indeed, given the turbulence and variety within the modular product market and the necessity of IBM's product strategy to evolve in response to developments in those markets, it would have been far more profitable for IBM to find *external* customers for its component technologies after thin film heads and disks had become modular, than to have predicted accurately what componentry would be needed within IBM itself. In other words, the strategy that might have maximized IBM’s return on its investments in advanced component technologies would have been to use its components internally as long as the technologies were integral; and then to aggressively sell in the external marketplace after they had become modular.[23]

A hypothesis that might be investigated in further research is that while there are steep economies of scale and scope in a world of integral technology, the scale economies of designing and assembling modular products are much flatter. In contrast, the leading companies that supply components to modular assemblers often continue to enjoy steep scale economies and the protective entry barriers of integral technology required to design and build their components. Hence, in the computer industry, for example, the most profitable companies in its eras of integrality were the integrated designers and assemblers of computers, such as IBM and Digital Equipment. In its modular eras, the most profitable companies were those that made components, such as Intel and Komag. (Christensen (1995) explores this hypothesis more completely.)

As a side note, decoupling of stages in the vertical value-added chain as a response to modularity has been attempted with varying degrees of success in other industries as well. Once standard interfaces amongst the elements of telecommunications systems emerged, for example, AT&T was gradually forced to become a vertically de-coupled company. General Motors, in fits and starts, vertically decoupled itself in response to the modularization of the automobile.[24] Its components devisions were charged to sell their products to other auto makers, and its car divisions were chartered to source components from the most cost-effective suppliers in the market. IBM has also began selling some components from its other businesses into the OEM market. Each of these companies, however, probably decoupled their component and product operations many years after technological modularity would have enabled -- endeed mandated -- that they do so.

New Integral Technologies and the Resurgence of the Value of Research

The third case study, about the development and adoption of magneto-resistive heads, suggests that despite the advantages of technological modularity in product design, it is not necessarily a stable end-state. Markets can shift substantially in both directions along the extremes between modularity and integrality (Chesbrough & Teece, 1996).

The advent of modularity in product designs greatly affected the ability of IBM to capture the proprietary fruits of its investments in research, through two mechanisms: modularity enabled non-integrated companies to enter as component suppliers and as product designer-assemblers. And it de-coupled IBM's upstream technology and component development activities from its downstream product development activities, making it more difficult for IBM to use its own advanced technologies.

Recent developments in the disk drive industry suggest, however, that this process might indeed work in reverse as well. In 1992, IBM announced that its researchers had developed a very different new recording head technology, called *magneto-resistive* (MR) heads, which held the promise of increasing the recording density of disk drives by a factor of 10. The MR head was an intensely integral technology -- significantly more so than was the case with thin film heads -- in that the design of the disks, actuator mechanisms, and read-write channels depended upon the design of the head -- and vice versa. IBM's OEM market sales of disk drives, all of which employed MR heads, grew from nearly zero in 1992 to over $2 billion by 1997. Non-integrated companies such as Western Digital, Maxtor and Quantum struggled mightily, working with independent head suppliers such as Read-Rite, to keep up with the pace of density improvement that IBM forged, but all fell behind.

Statements by non-integrated designers and assemblers of disk drives, and by executives of read-write head manufacturing companies, echo almost verbatim the statements made twelve years earlier about thin film heads. Disk drive designers complain that the independent head suppliers just aren't reliable -- that most of the heads they deliver won't work. And the head suppliers complain that they give their customers exactly what they specified -- the problem is that they don't know what they need. It is not an issue of being reliable. It is an issue of integral technology. And try as they might, for at least the first five years after IBM announced its MR head, nobody but IBM had the integrated perspective required to utilize the MR head effectively.

Quantum and Seagate, the largest OEM drive makers, were each subsequently forced to integrate into making their own MR heads, and to engage in the research and technology development efforts required to support advanced componentry development, integration, and manufacturing. Even Komag, the leading thin film disk maker, had to acquire Dastek, a struggling head manufacturer with a fledgling MR capability, so that it could design disks that would work with MR heads. Between 1992 and 1998, the market share of vertically integrated disk drive manufacturers had rebounded from 55% to 80%, and IBM's research capability once again became the envy of the industry.[25]

Hence, there is some evidence from these case histories of thin film heads, thin film disks, and magneto resistive heads, that a company's ability to capture the proprietary fruits of its investments in research, is linked closely to whether the technology has a modular or integral character as it is incorporated into new product designs.

Section 2:

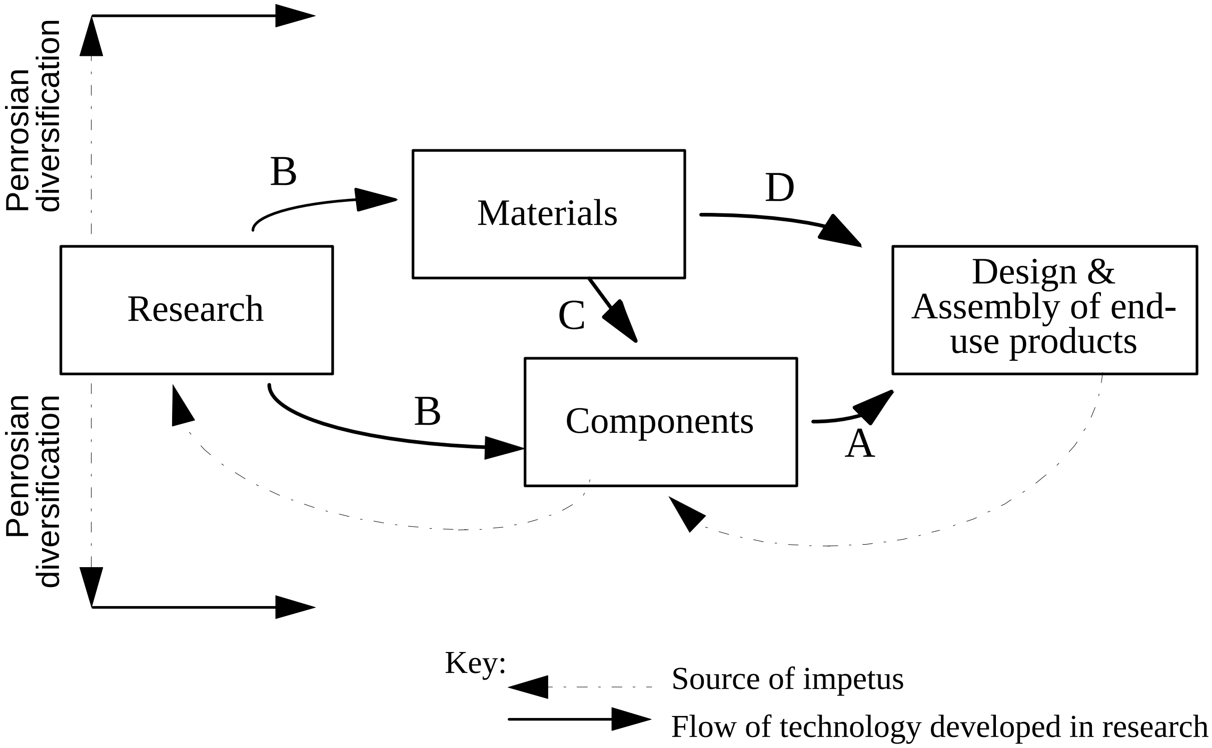
The Penrosian Diversification of Research and Development

There is another reason why the returns from industrial research laboratories may appear to be declining in some industries, in which the concept of integral and modular technology again plays a key role. This is investigated, in a more exploratory manner, in this section.

It is generally much less expensive to develop new technology in research laboratories than it is to build commercial businesses around those technologies. As a result, most companies' capacity to generate technology far exceeds their capacity to use it.[26] Hence, the breadth of the project portfolios in many laboratories today extends far beyond the original motivation for engaging in research, which was to develop the components and materials required to fuel improvement along the technology trajectories of current products. The scope of these laboratories has subsequently grown organically, in the manner Penrose (1959) described: when the labs' capabilities to develop new technologies were not fully taxed by the downstream product organizations, the labs initiated additional activities to utilize their capabilities (Helfat, 1997).[27] Often these expansions in scope have been encouraged by corporate management, in the view that technological innovation might be a source of new business opportunities.[28] This second mechanism by which research programs can be initiated is depicted in Figure 4, which is a more complete process description than Figure 1.

The abilities of companies to capture the returns from their investments in research programs that are initiated in the laboratory, rather than being initiated in response to performance bottlenecks in downstream product or component operations, appear to be driven by the same factors: integrality and modularity -- but the mechanism works in reverse. As noted above, most new technologies are embedded in new components or materials. They generally are *integral* in character. And when a new component or material emerges from a research laboratory, it is only one element of the end-use products in which it might be used. If it has a technologically integral character, it simply cannot be modularly incorporated or plugged into an existing product: the product's architecture, and the design of other components and materials of which it is comprised, often need to be changed.

Figure 4: Penrosian Diversification to Leverage Excess Research Capacity Creates Additional Challenges in Value Capture, which Are also Affected by Technological Integrality



Utilizing integral technologies whose development originated in research laboratories, therefore, requires the innovator to integrate vertically into the end-use products that utilize the components or materials in which the technologies are embodied. Or it requires that the innovating laboratories make the components or materials available in the open market, and then wait until a downstream product developer decides to tackle the integral challenge of incorporating the new technology in its products. In either case, capturing the value of technology whose development was instigated in research laboratories is an issue much more complex than “technology transfer.” It often requires change in fundamental strategic direction.

As in the section above, these propositions are grounded in two case studies, of advanced ceramics technology and Reduced Instruction Set Computing (RISC) technology.

The Case of Advanced Ceramics

Because of their technological expertise in metal oxides, in the early 1980s Alcoa and a host of other materials companies initiated significant laboratory research programs in advanced ceramic materials. Calculations showed that because they were lighter in weight, harder, and maintained rigidity at higher temperatures than metals, they would be attractive alternative materials for internal combustion engines. Despite their attractiveness on a component-by-component basis, however, a significant market for ceramic engine components has not materialized -- because using a ceramic component creates extensive and poorly understood interactions with many other elements of the engine system.

For example, a number of capable manufacturers, such as Ceramics Process Systems, Norton, and Kyocera and NGK, were able to make silicon nitride ceramic piston pins and pins whose strength-to-weight ratio was four times better than steel. Because reducing the reciprocating mass in an engine component has great value in terms of engine efficiency, materials scientists were able to calculate that it made powerful economic sense for engine designers to substitute silicon nitride for steel in their piston pins. It turned out, however, that engines have been designed with mass distributed at various places in the engine, to counter-balance the reciprocating mass of steel pistons and pins. Using ceramic components would therefore mandate a very complex, integrated re-design of the entire engine.

When innovators in research do not integrate forward to “make a market happen” for a new, integral technology, the wait for a market to materialize can be long indeed. None of the ceramics laboratories had the integrative scale or scope to resolve these issues. Only in a company that was integrated across the activities of developing and producing materials, components and engines -- as IBM was with its early disk drives -- could management proactively coordinate all of the initiatives required to have made ceramic engines a reality.[29]

RISC Technology

A second case illustrating the difficulty of commercializing a technologically integral component technology whose genesis was in a research laboratory comes from Ferguson & Morris’s (1994) account of how Reduced Instruction Set Computing (RISC) technology was developed over a long period and at great expense at IBM. There were difficult, technologically integral issues between RISC processors, and the operating systems and hardware designs of IBM’s products: RISC chips could not “plug and play” in the IBM architectures. IBM managers and engineers worked very hard to use RISC technology, but the integrative design compromises required to accomplish this eliminated the performance advantage of RISC. RISC technology was therefore shelved.

Key engineers on IBM's RISC project, convinced that markets existed for RISC components, subsequently left IBM. One founded MIPS, which became a leading OEM manufacturer of RISC chips, sold largely to the engineering workstation market. Another left to lead a group at Hewlett Packard to make RISC chips for HP's engineering workstation division. Workstation manufacturers, not constrained by IBM's installed base, faced simpler technology integration problems than IBM. It was not until IBM had launched its own line of engineering workstations, that it was able to use its own RISC technology. As in the case of thin film heads, the problem was not that IBM's technology planners missed the market. IBM simply constituted a much narrower target. And because IBM conceived of its scope, or sphere of activity, in terms of its current computer customers, it was unable to utilize technology that had extensive commercial value. Using this technology was not an issue of technology transfer. It required a fundamental strategy change.[30]

In related work, Christensen & Bower (1996) and Burgelman & Sayles (1986) have shown that when the technology doesn't address current customers' needs or fit a firm's strategic context, the impetus required to mobilize the organization's resources behind the technology rarely materializes. The same phenomenon seems to govern firms' abilities to commercialize integral technology developed in corporate labs. When IBM developed RISC technology, we did not see a mobilization of efforts to integrate forward to create a new engineering workstation business, in order to utilize the new technology. Rather' we saw sustained efforts to tailor the technology to fit the needs of IBM's existing customers. There was ample impetus for the latter sort of effort, and little for the former possibility.

Hence, when corporate research laboratories develop new, integral technologies that can only be used in businesses into which they have not vertically integrated, it is nearly impossible for them to reap the fruits of their research. Unless they integrate forward, their technologies will either languish in the laboratory, or leak to companies whose strategic direction gives them reason to perform the required technology integration.

Companies whose business is the sale of molecules (such as pharmaceuticals), materials or components are less likely to find as much difficulty commercializing technologies whose development was instigated in their laboratories. These companies still face downstream technology integration issues, but wrestling with them generally entails less strategic change. Hence, we might expect senior managers in such companies to continue to see strong rationale in financing aggressive research activities.

The Factors that Affect the Appropriability of Technology: Summary Propositions

At the end of this historical narrative, it might be helpful to summarize some of the propositions about how the position of a technology along the spectrum from integral vs. modular affects companies' abilities to capture the returns to their investments in research and advanced technology development. As noted above, because these are grounded in a limited set of case studies these proposals can only constitute hypotheses, which need to be evaluated through further research.

1. Most entrants into what are often regarded as technology-intensive industries actually employ little new technology. Their initial products are built upon innovative architectural concepts that employ existing component and materials technologies.

2. These pioneering firms may subsequently integrate vertically into the production of materials or components, if they cannot find suppliers of components whose performance can serve as engines for keeping pace with the trajectory of product performance improvement in their industry. This can subsequently entail a commitment to engage in research, to develop the technologies to be embodied in these materials and components.

3. Materials and component technology development activities can span the spectrum from basic research to process engineering. And by their nature, proposals to develop new component technologies must be benchmarked against available component technology -- whereas the objectives of product development efforts can be specified in terms of product-market positions. The processes of developing materials and component technologies therefore can constitute a very different enterprise than the processes for developing new products.

4. In the early years of an industry's development, dominant firms such as IBM, RCA, AT&T and Xerox have sufficient scale and scope that they not only can dictate the slope of the industry's technological trajectory and the cycles by which new products are introduced, but they can account for and manage the technological integrality within the products they develop, manufacture and market. They can coordinate the development of technology, materials, components and products, despite the inherently different natures of these enterprises. Indeed, none except such integrated companies can perform this coordination.

5. The complexity of these efforts, however, creates an impetus to modularize the product system, and to standardize the interfaces amongst materials, components and architectures. Modularity inherently creates the information that effective decoupling markets require to emerge and operate, and lowers the barriers to entry in the industry. This makes it difficult for firms whose scope spans across research, materials and/or components, and product development, to continue the complex coordination of these disparate activities. When

modularity reigns, markets are a more efficient mechanism than managerial oversight for handling this integration.

6. Competition amongst non-integrated designers/assemblers wrests control over the product development cycle and the slope of the technological trajectory from the dominant, pioneering firms. To remain competitive, these firms must decouple their operations in materials and components, from their operations in product design and assembly -- either through creation of an internal market, or participation in the external one.

7. Research activities and vertical integration become competitively less critical, and even disadvantageous, and firms begin reversing their commitments to these elements of value added.

8. If new, integral technologies again emerge in the industry, this process will reverse itself, shifting competitive advantage again toward integrated firms that engage in the development and manufacture of materials and/or components, and the commitments to research that this entails.

9. Modularity at the interface between any of the steps of value-added in developing new technologies and products -- research, materials, components, product design, and the manufacturing of both components and materials -- can enable markets to emerge at those interfaces. In these instances, companies that are not vertically integrated at that interface will gain the upper hand. For example,

    - If design-for-manufacturing rules are well defined, product design and manufacturing can be efficiently "out-sourced" to different firms;

    - Markets for technology *per se* -- before it has been embedded in new materials and components -- can also emerge in the form of licensing, if the conditions of modularity are met.[31]

10. When technological modularity decouples adjacent steps in value-added by enabling a market to emerge, vertically integrated companies can continue to capture the value of the technology they developed in research, if they de-couple upstream from downstream operations. For example, when product designs become modular, vertically integrated companies can sell components into the market, and source components from the market.

11. The conditions of modularity can disappear as readily as they can appear, when new, integral technologies emerge. Hence, companies that have enjoyed the advantages of flexibility, speed and cost that stem from modular designs, can suddenly find themselves uncompetitive. Companies that have been unable to transfer technology effectively from their laboratories to their markets, once again can find that their research activities constitute a key competitive advantage.

Notes:

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[1] The exact extent of these cutbacks is hard to measure, because conventions in financial reporting lump together very different classes of activity -- spanning from research, consisting of efforts to improve understanding of fundamental scientific issues, to product development, comprised of engineering and design activities that often involve no new technology development at all. [Hounshell (1996) offers clear definitions for what comprises research applied research, development, etc.] While it appears that in aggregate, industry spending on development remains vibrant, spending on research indeed seems to have been reduced markedly, in many industries (See Rosenbloom and Spencer, 1996; Mowery & Rosenberg, 1989; Bridenbaugh, 1996; Moore, 1996).

[2] David Hounshell (1996), in what is a remarkably clear and concise historical overview of industrial research in western economies, noted that during the cold war, military objectives pre-empted the vast majority of government funding of research conducted in corporate laboratories. With the end of the cold war, much of this funding has simply stopped, rather than being re-directed toward research with more direct commercial applicability.

[3] Gordon Moore (1996), co-founder of Intel Corporation, has noted, "The large, central research laboratories of the premier semiconductor firms probably have contributed more to the common good than to their corporations. Bell Labs, for example, did contribute much to AT&T, but its greater contribution seems to have been to the economy as a whole. Fairchild's large research organization, particularly in its later years, probably contributed more to the many spin-off companies (such as Intel) that exploited the ideas that surfaced within it than it did to its parent company. More recently, Xerox corporation's Palo Alto Research Center made some tremendous contributions to the community at large, notably in the area of local area networks and the graphical user interface that became the basis of the Macintosh computer. Xerox itself, however, did not benefit nearly as much as it might have from these developments.

[4] Because public accounting conventions lump together research and development costs, it is difficult to measure accurately the extent of any decline in research activities. Abelson (1994) estimated that in the United states in 1994, $83 billion was spent in industrial research & development. This was comprised of $60 billion spent in development, $20 billion in applied research, and $3 billion in basic research. Rosenbloom & Spencer (1996) provide a thoughtful, though anecdotal, sense of the extent to which spending on research may have been reduced in recent years.

[5] A number of outstanding scholars -- particularly Baldwin & Clark (choose which citations) and Ulrich & Eppinger (1995) have defined and employed concepts of integrality and modularity. This is our attempt to simplify and synthesize their definitions.

[6] Baldwin & Clark (1998) recount an example that illustrates that modularity is a matter of degree, rather than an absolutely defined condition. An automobile manufacturer designed a new model that employed thinner-gauge sheet steel for certain body parts. When the automobile was assembled and tested, the thinner steel made an annoying, vibrating buzz -- even though the team had followed all the proven design rules. Ths had never occurred before. But in reducing the steel's thickness, the design team discovered an interaction between steel thickness, engine mount design, and vibration. They had thought the design was modular, but by varying a parameter that previously had not been tested, they discovered an additional interaction.

[7] The definitions of modularity and integrality offered in this section are very similar to the concepts of *autonomous* and *systemic* innovations employed by Chesbrough and Teece (1996). I have used the terms modularity and integrality in this paper because the term *modularity* seems to have found more widespread use (Henderson & Clark, 1990; Christensen, 1995; Sanchez & Mahoney, 1996; Baldwin & Clark, 1999).

[8] Rosenberg (1982) has shown that this is common: what constitutes good performance, although obvious in retrospect, is rarely apparent as new product-markets emerge. Because the products simply were not available, customers rarely thought insightfully about how they would be used. This convergence amongst a group of customers toward a rank-ordering of important performance attributes defines what Dosi (1982) calls a technological paradigm. **Cite Ramstrom & Rhenman, from Abernathy & Utterback paper).** Christensen & Rosenbloom (1995) have shown that after such a paradigm has been established in a particular market, manufacturers establish a trajectory of performance improvement within that paradigm in their competitive efforts to make products of higher value. In disk drives, this paradigm was capacity per cubic inch of disk drive volume, and its trajectory improved 50% each year. Year after year, 35% of this came from increases in recording density on the surface of disks, while

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the other 15% of improvement came from system design improvement, often of a mechanical engineering nature -- as engineers figured out how to fit more disks within a given space.

[9] Hounshell (1996) suggests that the search for better materials and components from which to assemble better products was a relatively common motivation for manufacturers of end-use products to integrate backwards into research. Hence, General Electric's motivation to set Charles Steimtetz to work in GE's first research laboratories was to find a better filament material (they found tungsten) for light bulbs (see also Reich, 1985). DuPont's research was instigated in order to find better materials (e.g. smokeless explosive powder); and Kodak's motivation was to develop better photographic chemicals. Morone (1993) saw a similar initial motivation for research in General Electric's medical equipment business. Its initial CT scanning products were architectural innovations, using available materials and components. Relatively quickly, however, it was forced to focus its research and development efforts on improved componentry. In a private conversation, Professor Jonathan West noted, "People think of the role of research as knowledge creation. That is rarely its role. Its role in the real world is solving problems when companies have bumped against technology frontiers.

Hounshell's (1996) history also suggests that the initial motivations for engaging in research were pronouncedly *defensive* in character. The mission of the initial research organizations often was to create or extend patent protection for the firms' most valuable commercial products.

10 Utterback's (1994) work on the dynamics of innovation suggests that in the initial stages of most industries' evolution, the rate of product innovation is high. This rate ultimately subsides when a dominant design emerges. This enables an increase in the rate of process innovation. Other work suggests that within the product innovation phase of Utterback's model, there are really *two* stages -- a period of architectural innovation, followed by a period in which the focus is on component-level product innovation. This phase may last for an extended period, well after the emergence of dominant designs. This is a principal finding of Henderson & Clark (1990), who also found that firms' initial focus on architectural innovation shifts toward a subsequent component focus. They point out that as a result, firms' abilities at architectural innovation atrophy through disuse, while their abilities to innovate in certain types of componentry are enhanced. Iansiti (199x) has also shown that underneath what appears to have been a steady, incremental pace of improvement in an assembled product (mainframe computers), are an array of component-level innovations over time, some of which are quite radical in character. Christensen, Suarez and Utterback (1998) show that the dominant design of disk drives was defined long before several important component-level innovations such as thin film and magneto-resistive heads, as discussed later in this paper.

[11] Argyres (1996) notes that the comparative capabilities of in-house supply vs. external suppliers is an important driver of the decision to integrate or not.

[12] Many of the concepts in this section build upon Dosi (1982). He introduces the concept of *technological paradigms*, which are a "pattern of solution of selectect technological problems," and *technology trajectories*, which chart the path of improvement in the parameters relevant to the paradigm.

[13] IBM's competitors quickly followed IBM's lead in developing modular products.

[14] Waid, Dennis, *Rigid Disk Drive heads and Media: A Technology and Marketing Report*. Saratoga, CA: The Technology Assessment Group, 1986.

[15] Xerox had entered the disk drive industry shortly before, through a sequence of acquisitions that included disk drive makers Diablo, Shugart Associates, and Century Data. Control Data and Digital Equipment also developed their own thin film disks, though they started a few years later.

[16] As shown below, it turned out that if IBM *had* tried to sell its components to these competitors, it could have sold its disks successfully, but not its heads, in the early years.

[17] The leading technical founder of Komag, Tu Chen, was employed at Xerox's Palo Alto Research Center (PARC) doing research in thin film magnetic media, in support of a group of disk drive companies Xerox had acquired -- Diablo, Shugart and Century Data. These firms, in turn, supported Scientific Data Systems, a mid-range computer manufacturer Xerox had purchased in the late 1960s. It turned out that none of these companies was able to use thin film disk technology and eventually Chen left, joined other engineers from IBM and elsewhere and launched Komag. Read-Rite was founded by entrepreneurs who defected from Memorex, an independent maker of tape and disk drives, and engineers from IBM's operation in San Jose. LinData, another thin film disk maker, was founded by another former IBM employee. LinData was later purchased by Nashua Corporation, which had been a leader in manufacturing particulate oxide disks.

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[18] Although creation of this internal market was a managerially tractable way to resolve the problem, it did not enable IBM to capture the profit from those technologies that languished with little demand in this internal market, even while they were in hot demand externally.

[19] The 5.25 inch architecture is relevant for this analysis because through most of this period, over 80% of the new disk drive models developed by IBM were of the 5.25 inch form factor. The lines drawn on each chart represent the best fit regression equation through annual data for each of the companies' new models. The scatter of each firm's annual data around these gets-fit lines was minimal.

[20] In the earliest stages of the personal computer industry, IBM sources the 5.25 inch drives for its desktop personal computers from Seagate Technology, Miniscribe, and other independent firms and then marketed them as IBM products with the contract manufacturer's label on them as well. As the company moved through through the 1980s, it began supplying an increasing proportion of its own 5.25 inch drives. This does not affect the conclusions of Figure 5 however. The point is that the drives IBM was supplying with its desktop machines did not need to incorporate the components it had developed.

[21] Run Length Limited codes were a technique for marking the beginning of new pieces of information on the disk, which took up less recording space than the predecessor marking technology, called Modified Frequency Modulation (MFM). RLL cosec took disks from what were called double density to triple density.

[22] Note that during this time, IBM was using thin film heads in its high-end, technologically integral 14-inch drives.

[23] My colleague Hank Chesbrough has noted that although IBM lost an opportunity to profit substantially from its investments to develop thin film head technology, by refusing to sell them into the external OEM market after they had become modular, the company most recently has begun aggressively selling modular components, with great impact. For example, although its own market position in notebook computers is rather weak, IBM began selling 2.5-inch disk drives (a modular component of a computer) very aggressively in the OEM market beginning in about 1993, and in 1997 generated over $3 billion in sales. The 2.5-inch drive itself is technologically integral, since it uses magneto-resistive heads. Our contacts in the disk drive industry suggest that IBM is earning 40% gross margins on its sales of these drives (when average margins in the industry hover between 15% and 20%) -- supporting the observation made in the next paragraph of the text that companies that design and assemble technologically integral products generate attractive profits. As the magneto resistive head began its transition toward modularity in 1998, IBM appeared to have begun decoupling sales of the head from sales of assembled drives, through deals with Western Digital and NEC to manufacture drives of IBM's design, using IBM heads. Chesbrough (1997) has noted that the major integrated Japanese electronics manufacturers historically have operated in much more of a vertically decoupled fashion.

[24] Wright (1979) describes the difficulty General Motors management experienced in actually implementing an effective de-coupling of component and assembly operations.

[25] Doctoral candidate Michael Raynor of the Harvard Business School offered the following comment about the waxing and waning of the value of research, as the pendulum swings between modular and integral technologies: "There is something here about the second-best nature of internal markets. Companies may choose internal markets in order to sustain some vestige of their research infrastructure, if the cycling through stages of integrated and modular technology states is sufficiently fast. As in Hannan and Freeman (1977), companies have the choice of attempting to "wait out" comparatively hostile environments rather than adapting to them where there is sufficient reason to believe that soon enough, the winds of creative destruction will be at their backs again. Adaptation is costly. Companies should evaluate the costs of adaptation vs. the costs of simply waiting it out. Or they might "sort-of" adapt, by implementing internal markets such as IBM has done, for example.

[26] A rule of thumb that is used in advanced materials technologies is that for every dollar spent in a research laboratory to develop a new material at the lab bench scale, it takes seven dollars to build and operate a pilot plant. And for every dollar required to build and operate a pilot plant, it takes an additiona seven to build and operate a full-scale commercial plant. In other words, even before accounting for marketing and administrative costs, scaling to commercial volumes is about 50 times more expensive than generating the technology to begin with. For an example of these costs of scale, see Hounshell, David A., "DuPont Kevlar Aramid Industrial Fiber," Harvard Business School case study 9-391-146, 1992.

[27] Intel's co-founder, Gordon Moore (1996), recognized the impact that Penrosian diversification could have on a firm's ability to capture the returns to its investments in research. "Intel operates on the Noyce principle of minimum information: One guesses what the answer to a problem is and goes as far as one can in an heuristic way. If theis

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does not solve the problem, one goes back and learns enough to try something else.... There is another advantage to operating on the principle of minimum information: the company generates few spin-offs. Because it does not generate a lot more ideas than it can use, Intel's R&D capture ratio is much higher than Fairchild's ever was.

[28] Gomory (1989) urges caution with this view, noting that it is *product development*, rather than technology development, that generates revenue growth.

[29] Another example of the obstacles that technological modularity creates against efforts to commercialize technology whose development was instigated in research laboratories occured in DuPont's efforts to commercialize its miracle fiber, Kevlar. Kevlar was initially targeted at the tire cord market. But because of technological and cost interactions between Kevlar's properties and the design and manufacture of tires and automobiles, which neither DuPont or the tire makers were able to foresee, that market never materialized. Other markets for Kevlar ultimately emerged, but only gradually, as product designers learned to grapple with the integral nature of Kevlar (see "Tough Fiber - Dupont's Difficulties in Selling Kevlar Show Hurdles of Innovaton," *The Wall Street Journal*, September 29, 1987, p. 1). Freeze and Leonard-Barton (1991) recount how General Electric, which has built a very successful, research-driven advanced plastics business, addressed the challenge of coming to market with one part of a technologically integral system by integrating forward. It built the technological capability in materials development, mold design, molding equipment design, and part design, that were required to make usable products. GE's design center essentially performed the technological integration function for its customers.

[30] The history of the commercialization of transistor technology which originated at Bell Laboratories in the late 1940s is similar in concept to the RISC and thin film head stories, though different in detail. In this case, the early technology was not sophisticated enough to be useful within the Bell System: transistors could not handle the levels of power that were required in Western Electric equipment, and Western Electric had no choice but to continue using vacuum tubes. Transistors initially could only be employed in completely different markets in which AT&T did not participate. The first was a germanium transistor hearing aid, developed by an independent company in 1953. The next application was the transistor radio made by Sony in the mid-1950s. The technology improved rapidly in such markets, until finally the performance is solid state devices was adequate to address the needs of the Bell System, many years later. AT&T could not have appropriated the returns on its investments in transistor technology unless it had been prepared to integrate forward into the design, assembly and marketing of the end-use products that used its transistors.

[31] In some markets in the chemical industry, for example, scientific models are well enough established that independent research organizations such as Halcon, UOP and Chevron Research can exist independently, profitably pricing their intellectual capital. Pisano (1997) has shown that modularity does not yet exist -- and efficient markets therefore do not yet exist -- at the interface between pharmaceutical research and clinical trials to prove the safety and efficacy of new compounds. Hence, integrated pharmaceutical companies that conduct their own research still have an advantage.