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ADVANCED TECHNOLOGY PROGRAM

Understanding Private-Sector Decision Making for Early-Stage Technology Development

A "Between Invention and Innovation Project" Report

National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce

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Acknowledgements

The report summarizes the results of seven months of interviews with dozens of R&D executives representing many of the nation's largest and most influential industrial firms. The interviews, as well as additional supporting analysis, were carried out during the years 2001 and 2002 by Booz Allen & Hamilton (BAH) analysts as a core component of the Between Invention and Innovation (BII) project at Harvard University's Kennedy School of Government. The BII project was led by Lewis Branscomb (Aetna Professor of Public Policy and Corporate Management, emeritus, Kennedy School of Government, Harvard University) and Philip Auerswald (Assistant Professor and Director of the Center for Science, and Technology and Policy, School of Public Policy, George Mason University). Brian Min contributed substantial research and writing to the project. The BAH team was led by Nicholas Demos (Vice President, Strategy Practice), Gerald Adolph (Senior Vice President), Rhonda Germany (Vice President, Consumer and Health Practice), and Raman Muralidharan (Vice President, Consumer and Health Practice).

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President Johnson named him to the President's Science Advisory Committee in 1964, and he chaired the subcommittee on Space Science and Technology during Project Apollo. President Carter appointed him to the National Science Board and he served as Chairman of the NSB during the Presidency of Ronald Reagan.

Branscomb was the co-chairman of the project of the National Academies of Science and of Engineering and the Institute of Medicine, which authored the report *Making the Nation Safer: Science and Technology for Countering Terrorism*, published by the National Academies Press in 2002.

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Executive Summary

Financial market failures create obstacles to the commercialization of science-based innovations originating from inventors and technology entrepreneurs.[1] Such obstacles deny the economy new sources of revitalization and future growth.[2] Studies of this topic have tended to focus on the particular challenges associated with bringing new ideas to market through the creation of a new firm. Start-up firms are particularly appropriate vehicles for more radical innovations (characterized by both technical and market novelty). Established enterprises are typically more successful in pursuing incremental extensions to existing technologies and markets.

But what about radical innovations that fall within the business strategy of larger firms? Since the overwhelming majority of U.S. industrial research and development (R&D) expenditures come from large firms ($180.4 billion invested into R&D by U.S. industrial firms in 2000)[3] surely large firms face fewer financial barriers to bringing radical innovations—including those stemming from their own corporate research—into their businesses. This is the line of reasoning followed by some critics of government-funded research partnerships with large and other size firms.

That large firms have real difficulty creating radical innovations outside the core areas of business to which they are committed is well understood.[4] This report shows that large firms may experience similar failures when trying to exploit high technology innovations that apply directly to markets already served by the firm—what we will refer

1. Lewis M. Branscomb and Philip E. Auerswald. *Between Invention and Innovation: An Analysis of Funding for Early-Stage Technology Development.* Advanced Technology Program, National Institute for Standards and Technology (NIST), U.S. Department of Commerce report, NIST GCR 02–841, November 2002; Bronwyn H. Hall, The Financing of Research and Development, Working Paper 8773, National Bureau of Economic Research (NBER), 2002.

2. William J. Baumol, 1994. *Entrepreneurship, Management, and the Structure of Payoffs* (Cambridge, MA: MIT Press).

3. National Science Foundation, *Research and Development in Industry: 2000* (Arlington, VA, 2003) (NSF–03–318), table A–2, page 19–20. Of this number $110.8 billion of R&D expenditures were in the manufacturing industry. The software industry (counted as non-manufacturing) spent $12.7 billion in R&D in 2000.

4. James McGroddy, "Raising Mice in the Elephant's Cage," in Lewis M. Branscomb and Philip Auerswald, *Taking Technical Risks: How Innovators, Executives, and Investors Manage High-Tech Risks,* (Cambridge, MA: MIT Press, 2001), pp. 87–95.

to as "in-core" innovations. The obstacles to radical in-core innovations are not market failures so much as institutional ones, but they are no less real. The barriers to in-core radical business innovations may include incompatibility of the new product with existing production processes; the need for a radical change in business model; lack of familiarity with key technical knowledge by the product development teams; and concern about "fratricide" of existing products made obsolete by the radical, in-core innovation. Like the abandonment of "out-of-core" innovations, neglect of "in-core" innovations deprives the economy of valuable spillover benefits.

Even given such obstacles, corporate support for early-stage technology development (ESTD) does occur. This study estimates that of the $180.4 billion invested into R&D by U.S. industrial firms in 2000 as much as $13.2 billion or 7.3% was for ESTD activities targeted at bringing disruptive new technological innovations to the marketplace.[5] Such disruptive innovations are distinctive in their capacity to destabilize markets, create new opportunities for learning, and open up entirely new spheres of economic activity. While the portion of R&D funds directed at ESTD may be small, ESTD investments are essential to sustaining long-term economic growth, and corporate funds represent the most significant source of funding for the nation's ESTD activities.[6]

Our research illuminates the varying levels of support for ESTD activities across industries and firms. We find that these inter-industry and intra-industry variations are shaped by several forces, including the increasing sophistication required to develop new technological innovations, mounting pressures on corporate R&D divisions to demonstrate financial value from R&D investments, and the importance of the lifecycle position of specific industries relative to other industries and individual companies relative to their peers.

The report is based upon research and analysis performed by analysts at Booz Allen Hamilton, who conducted 39 detailed interviews with senior executives and investors from 31 large corporations across 8 industry sectors, and 8 venture capital firms. By drawing upon these interviews, we examine trends in management of corporate R&D and how new market realities are affecting the ways corporations manage and support ESTD activities. Among these emerging corporate strategies are an increasing

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5. As is explained in the text below, the industry sample interviewed was relatively more R&D intensive the industry as a whole, and it appears than the more R&D intensive firms tend to have higher ratios of ESTD to R&D. This suggests that total funds actually spent on ESTD are likely to be lower than the estimate of $13.2 billion.

6. Branscomb and Auerswald, *Between Invention and Innovation,* 2002.

formalization of portfolio management approaches to corporate R&D and a growing reliance on acquisitions, alliances, and contracting out to obtain access to and exploit earlier stage technologies, especially where internal barriers are blocking progress. Case studies suggest that government funding may be effective, even essential, in helping larger firms pursue in-core radical innovations (via alliances) that bring economic and social benefits that would otherwise be lost.

I

Introduction

MOTIVATION FOR THE STUDY

Corporations are the largest funders and performers of research and development in the United States. In 2000, U.S. corporations reported to NSF investments in R&D totaling $180.4 billion. According to the traditional three-tiered R&D classification scheme, firms allocated $6.0 billion of their R&D investments to basic research, $36.1 billion to applied research, and $138.3.4 billion to development.[7]

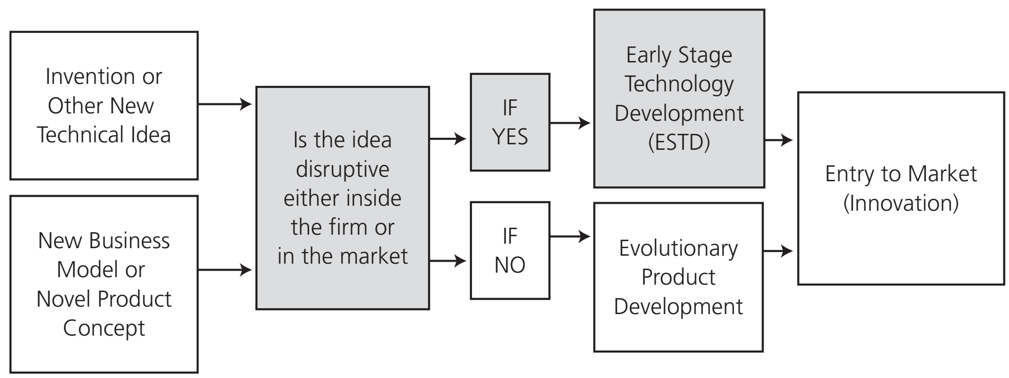
Only a small and unidentified portion of these massive investments is directed at the kinds of early-stage technology development (ESTD) activities that transform lab bench inventions and discoveries into new radical innovations for the marketplace.[8] ESTD investments are critical because they measure the level of support for radical innovations that open up new markets, create new opportunities for learning, and sustain long-term economic growth.

There is extensive literature on related topics. Corporate venturing activity has been examined in detail (most notably by Gompers 2002); however, this body of work only quantifies corporate investment in innovation activity external to the corporation and it does not attempt to distinguish investments in ESTD from other R&D funded by corporate seed venture capital. A vast literature exists on corporate resource allocation methodologies focusing on internal project investment and portfolio management (including such techniques as real options valuation); however, it is difficult to apply these methodologies when assessing allocation of resources toward highly speculative ESTD activity, which by its definition cannot be valued quantitatively. Others, such as Lazonick and O'Sullivan (1998), recognize the limitations of these approaches to the

7. National Science Foundation, *Science and Engineering Indicators 2004* (Arlington, VA, 2004) (NSF–04–01), tables 4–5, 4–9, 4–13, and 4–17.

8. ESTD does not correspond uniquely to any of the three categories used by the National Science Foundation (NSF) and the Organization for Economic Cooperation and Development (OECD) to categorize industrial R&D. In fact, there are no statistical collections of ESTD data in the United States.

Figure 1. Paths from a Creative Commercial Idea to an Innovation



innovation process and prescribe alternative frameworks for corporate governance; however, they do not attempt to quantify the allocation of corporate resources to this type of activity.

The specific objective of this research was to develop an empirically based estimate of the total level of funding for ESTD activities by US companies, to estimate ESTD funding levels across industry sectors, to better understand differences in ESTD funding levels across firms, and to better understand the drivers of these funding levels.

In addition to the objectives above, this report also covers insights from the interviews on the R&D management processes and priorities within U.S. corporations as they relate to ESTD activities, and identifies emerging strategies that corporations are adopting to deal with changes in the R&D environment and how this relates to ESTD investment.

- What are the major trends in the organization and prioritization of R&D activity and how do these affect ESTD investment?
- What strategies are firms adopting to maintain and strengthen their innovative capacity?
- What variations exist in ESTD activities across industries and firms? Why?
- How do companies obtain value from breakthrough laboratory inventions outside of their core business?

Figure 2. Four Transitions to Innovation; Three Require ESTD

Compatibility with technology, business model	**More disruptive**	**Type B** Market is alien to core business	**Types B + C** Market is outside core business and incompatible with technology
	Less disruptive	**Type A** New technology easily introduced; ESTD not required	**Type C** New technology easily introduced; ESTD not required
		Less disruptive	More disruptive
		Compatibility with core markets	

CORPORATE INNOVATIONS AND THE DEFINITION OF EARLY-STAGE TECHNOLOGY DEVELOPMENT

Early-stage technology development is a subset of corporate innovation activity. Innovations are created from inventions or other ideas whose novelty may trace to new science, to new engineering concepts, or even to new and different business models. Figure 1 on the previous page illustrates the paths through which these new commercial ideas may flow.

There are three kinds of technical innovations that may arise within established firms:

A. Type A innovations address a market within the core business of the firm and, despite their technical novelty, are sufficiently compatible with existing business models and technical capabilities that they are highly likely to be supported by an existing business unit.

B. The intended market for Type B innovations is sufficiently alien to the company's existing business models and technical capabilities that, if the innovations are developed at all, they will be spun off outside the firm.

C. Type C innovations that address a market within the core business of the firm, but face serious obstacles from incompatibilities or displacement of current products, may nonetheless be pursued in a "skunk works" or some other form of protected environment.

Type A innovations take place within the normal functioning of businesses and might be thought of as a more discontinuous kind of progress than is normally characteristic of evolutionary progress. We do not conceive of ESTD as applying to this situation.

Type B innovations may be "excubated"[9] through partnerships outside the firm, but they are rare as J. McGroddy argues. Here the ESTD characteristics are closest to the circumstances surrounding new firm creations based on the ideas of technical entrepreneurs.

An example of a Type C innovation is the IBM PC, which as a computer product certainly lay within the strategic interests of IBM, but had to be developed in a specially formed organization free of the normal business practices of the company.

Our definition of ESTD and the data reflecting it in this paper apply to Type B and Type C innovations but not to Type A. By early-stage technology development we mean the technical and business activities that transform a commercially promising "invention" into a business plan that can attract enough investment to enter a market successfully, and through that investment become a successful innovation.

We define ESTD in the corporate context to refer to early development of fundamentally new products or processes that lie outside of or might be in conflict with the firm's current technology strategy or that deploy current technology outside of the firm's current core businesses. ESTD must address functional specifications, product manufacturability and costs, and the initial market for entry of an innovation must have at least one of the following characteristics:

- its technical novelty promises the possibility of exclusive advantages but poses a significant risk that technical obstacles cannot be overcome;
- the intended innovation either addresses a market that lies outside the core business interests of the firm, or challenges the current business model, the current technical base, or competes with current products.

Thus the concept we advance for ESTD applies to new business activities that have the characteristic of destabilizing markets, if the innovation hopes to create a market not already in existence, or destabilizing customer behavior—posing serious barriers to acceptance—or destabilizing the internal operations of the firm. This last

9. McGroddy, "Raising Mice in the Elephant's Cage," 2001.

obstacle might reflect a novel and unfamiliar business model,[10] a technical incompatibility,[11] or a significant impact on the sale of current mainstream products.[12]

While corporate R&D numbers are regularly reported to NSF and other agencies, these numbers alone tell us little about how companies support and invest in truly radical technological innovations. The traditional categories of 'basic research," "applied research," and "development" do not correspond in any meaningful way to the nature and level of risk or value of commercial investments in new product innovation. A new approach is required, therefore, to track the levels of corporate funding and support for activities aimed at bringing disruptive innovations to market.

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10. H. Chesborough and R. Rosenbloom, "The Dual-Edged Role of the Business Model in Leveraging Corporate Technology Investment," in L. M. Branscomb and P. Auerswald, *Taking Technical Risks* (MIT Press, 2001).

11. John Cocke invented the Reduced Instruction Set Computer (RISC) in IBM Research. Despite its functional advantages as a target for optimized compilers, and despite the best efforts of the company's technical executives, product divisions rejected RISC because of its incompatibility with the IBM 370 architecture. Hewlett Packard produced the first native RISC machine under the leadership of the former head of the IBM computer research group where RISC was developed. Later IBM did sell RISC processors and was successful using them as elements of a super computer.

12. In the 1980s Xerox Corporation suffered heavily from Asian competition at the low end of their copier product line. In the next decade Xerox introduced all digital copiers in the quest to regain lost market share.

II

Historical Background

INDUSTRY R&D: HISTORICAL CONTEXT AND RECENT TRENDS

Rosenberg and Birdzell (1985) document the advent, at the end of the nineteenth century, of the corporate research laboratory. "Until about 1875, or even later, the technology used in economies of the West was mostly traceable to individuals who were not scientists, and who often had little scientific training."[13] The first corporate laboratories were engaged in "testing, measuring, analyzing and quantifying processes and products already in place."[14] Later a small subset (notably Thomas Edison's Menlo Park laboratory) began bringing "scientific knowledge to bear on industrial innovation," producing inventions in pursuit of "goals chosen with a careful eye to their marketability."

The dramatic trend toward the consolidation of American business in the first quarter of the 20th century had a direct impact upon the organization of industrial innovation. As early as 1928, Joseph Schumpeter was to observe that in the new era of oligopolistic markets dominated by large trusts, "innovation is ... not any more embodied *typically* in new firms, but goes on, within the big units now existing, largely independently of individual persons.... Progress becomes 'automatised,' increasingly impersonal and decreasingly a matter of leadership and individual initiative." (Schumpeter 1928: 384–385).[15] Writing in 1959, Jewes, Sawers, and Stillerman reinforce Schumpeter's theme:

> In the twentieth century … the individual inventor is becoming rare; men with the power of originating are largely absorbed into research institutions of one kind or another, where they must have expensive equipment for their

13. Rosenberg and Birdzell (1985: p. 242).
14. Rosenberg and Birdzell (1985: p. 246).
15. This argument was developed more fully, and famously, in Schumpeter (1942).

work. Useful invention is to an ever-increasing degree issuing from the research laboratories of large firms, which alone can afford to operate on an appropriate scale … Invention has become more automatic, less the result of intuition or genius and more a matter of deliberate design." (quoted in Rhodes 1999: 212)

Where industrial innovation in the 19th and early 20th centuries was identified with the work of individuals—Samuel Morse, Eli Whitney, and Thomas Edison—by the 1960s and 1970s it was identified with corporate entities—Bell Telephone Laboratories, General Electric (GE), RCA Laboratories,[16] the IBM T.J. Watson Research Center, and the Xerox Palo Alto Research Center (PARC). In each of these famed research settings, goals were far-sighted. Management focused on attracting the most able researchers, then providing them with a great deal of latitude. The Laboratories' scientific achievements, recognized by several Nobel prizes, brought these companies great prestige.

Despite their great success in advancing scientific and technological frontiers, the great U.S. research laboratories often (one might say, systematically) failed along one critical dimension: the ability to take inventions that were unrelated to core lines of business and translate them into viable commercial innovations within the sponsoring company.[17] While some firms sought to imitate Bell with commitments to basic science—in many instances making a serious effort to incubate within the firm ideas that the product line divisions could commercialize—few firms survived long in this mode. The freedom to take a more creative approach to corporate research was widely welcomed by industry scientists, but it did not address the requirements for commercializing radical innovations.[18]

Inherently transient circumstances contributed to the ability of Bell Telephone, IBM, Xerox, and other leading research corporations to support sustained investments in fundamental science distant from market applications. In the case of Bell Telephone, market dominance was government granted. For other U.S. firms, the capacity to maintain market dominance was artificially enhanced by the crippling of international competition as a result of World War II. Over the last quarter of the 20th century, deregulation and the resumption of international competition contributed to the erosion of the ability of U.S. technology corporations to sustain funding of basic research not linked to core corporate activities. Indeed it was government support of academic research and national laboratories that generated a new and successful mode of high

16. The David Sarnoff Research Center.

17. Smith and Alexander (1988) offer a narrative account of failures to commercialize innovations from Xerox PARC. Chesbrough and Smith (2000) detail the experience of each of the 35 firms that spun out of Xerox research centers from 1978 to 1998.

18. Indeed, Xerox PARC was known for brilliant contributions to the development of personal computers, but the parent corporation was notably unable to exploit these inventions for commercial success.

technology innovation—the start-up further nurtured by angel investment and venture capital and a variety of important public policies.[19]

Trends in the valuation of publicly traded companies also had indirect but significant impacts on corporate R&D. The widely observed phenomenon of "conglomerate discount"[20] indicated a general reversal of the prior trend toward consolidation as a pathway of corporate growth. Corporate managers contended with a Wall Street climate that persistently penalized those that lacked focus. At the same time, especially in the decade of the 1980s, increased international competition in high tech product markets has put tremendous pressure on costs—contributing to agglomeration of firms within well defined lines of business (merger waves), reorganizations, and "downsizing."

By the end of the 1980s, most U.S. research firms were seeking to link research activities more closely to existing lines of business and new management tools to match the apparent efficiency of the Asian competitors. Richard Lester's analysis of how U.S. firms were able to restore their competitiveness in the 1990s concludes that a broad variety of management tools and practices were invoked.[21] More mature and sophisticated forms of technical management in industry focused on core business interests and, while they expected the corporate laboratory to create commercializable technologies, began to look increasingly outside the firm for innovative components and subsystems. Some (at GE for example) turned to more disciplined priorities, tightly coupled to core business interests. Formal processes of risk management and metrics for tracking progress toward documented goals were introduced.[22] Others (IBM, for example) began to see the central corporate laboratory as an instrument for informing decisions about technology choices, identifying directions for new business opportunities, and evaluating the intellectual assets of competitors and potential partners. Firms also began to outsource more of their needs for component innovation to small and medium-sized enterprises, both at home and abroad, reducing the dependence on corporate laboratories for component innovations.

In the past decade, real increases in U.S. national R&D have all come from industry. Industrially funded R&D has doubled, while Federal R&D has been relatively flat in total. Corporate R&D investments are highly concentrated; the top 500 firms accounted

19. Among these policies were reduced capital gains taxes, ERISA changes allowing pension funds to invest in private equity markets, the Bayh–Dole Act allowing private ownership of patents from government-sponsored research, the Small Business Innovation Research Act and other provisions of tax law favoring startups.

20. See Berger and Ofek (1995) for empirical support.

21. Richard Lester *The Productive Edge: How U. S. Industries Are Pointing the Way to a New Era of Economic Growth,* (New York: W. W. Norton), 1998.

22. Hartmann and Myers, M., "Technical Risk, Product Specifications, and Market Risk," in L.M. Branscomb and P. Auerswald, *Taking Technical Risks,*. pp. 30–43.

for nearly 90% of all corporate R&D expenditures.[23] Industry investments (including those by venture capital backed companies, but dominated by large corporations) continue to be the source of a substantial share of the resources utilizing basic science knowledge in their commercial products. However, these have increasingly been focused on near-term product developments leading to incremental increases in market share, in productivity, and product function.[24] Increases in efficiency come at a price: corporate investment may be decreasingly likely to produce the spin-off ventures and "knowledge spillovers" that have seeded the economic landscape with technology start-ups for over a generation. As Intel founder Gordon Moore recently observed:

> One of the reasons that Intel has been so successful is that we have tried to focus R&D, thus maximizing our R&D yield and minimizing costly spin-offs. But successful start-ups almost always begin with an idea that has ripened in the research organization of a large company (or university). This is a fundamental tension between what is ideal for the individual technology firm, and the phenomenon that builds a dynamic high-technology region. Over time, any geographic region without larger companies at the technology frontier, or sizeable research organizations (either privately, within firms or within academia) will probably have fewer companies starting-up or spinning off, both because of lack of technically trained people and a shortage of ideas.[25]

Research-intensive firms under pressure to focus on core lines of business are also mindful of past corporate failures to commercialize out-of-core innovations. In many cases research-intensive corporations have sought to employ seed venture funding and incubators as tools permitting additional flexibility without loss of focus. Venture funding and technology incubators are used to advance one or more of a variety of only loosely related corporate objectives:

- to move innovations developed "in-house" that are not relevant to core lines of business or encounter disruptive obstacles internally toward commercialization;

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23. C. Shepherd and S. Payson, "U.S. Corporate R&D, Volume I: Top 500 Firms in R&D by Industry Category." National Science Foundation and U.S. Department of Commerce Topical Report (1999). Note that firms with fewer than four persons engaged primarily in R&D are not asked to respond to the survey, and many highly innovative small firms do not have an internal organization for R&D activities and thus do not report in these surveys. Thus R&D in the smallest firms is probably undercounted. In addition the R&D by large firms is heavily focused on D, while smaller high tech firms may focus on more radical technical ideas even though they may not call it "research."

24. For a journalistic account of this trend, see Gina Kolata, "High-Tech Labs Say Times Justify Narrowing Focus," *New York Times* C1, September 26, 1995.

25. Moore and Davis (2001). It is interesting that Intel compensates for this intensity of focus by managing the single largest corporate venture capital investment program—though this program is also focused on core interests, including application development to grow existing Intel market.

- to aid in the retention of talented researchers by providing them with an opportunity to spend some time working outside of the corporation toward commercialization of promising new technologies developed in-house;[26]
- to support the development of new technologies for potential acquisition by the corporations;
- to nurture demand for core products by supporting complementary infrastructure (e.g., a semi-conductor firm supporting software development tailored to its new, high-performance products); or[27]
- simply to earn maximal returns on investment.

While some core business innovations may represent radical advances in the sense that they are based upon fundamentally new technologies, if they do not encounter disruptive barriers either inside the firm or with customer acceptance, they are unlikely to be the sort of *disruptive innovations* that destabilize markets, create new opportunities for learning, and open up entirely new spheres of economic activity.[28] By isolating and examining the narrow slice of corporate research activities that actively support the development of disruptive innovations, we can gain important insights on the ways corporations seek growth and expansion through radical innovation, even as they focus on nurturing and cultivating their core lines of business.[29]

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26. Chrysalis Technologies Inc., supported by Philip Morris, is an example.

27. Intel Capital is a leader in this strategy.

28. Clayton M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail.* Boston, Mass.: Harvard Business School Press, 1997.

29. We recognize that it is very difficult to develop a rigorous distinction between a radical innovation that leads to markets that lie totally outside a firm's experience, a radical innovation that disturbs (or perhaps replaces) and existing firm's business, and a new technology that transforms an existing line of business in a way the firm's customers readily accept.

III

Project Scope and Methodology

METHODOLOGY

Between July 2001 and January 2002, Booz Allen Hamilton researchers conducted detailed interviews with 39 company chiefs, senior executives, technology managers, and venture capitalists to identify emerging corporate trends and strategies for managing early-stage technology development (ESTD) activities. Of the 39 interviews, 31 were with technology companies from across 8 different industries and 8 were with venture capital firms. In total, the interviewed firms account for approximately 7% of total U.S. industrial R&D expenditures.

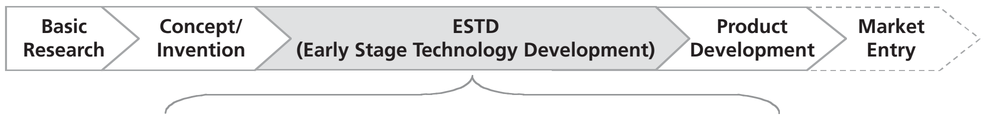
In advance of each interview, respondents were sent materials with background information to familiarize themselves with the concepts and goals of the research. During telephone and in-person interviews, respondents were asked to discuss the R&D management process within their organizations, including investment strategies, funding decisions, and partnership efforts. Specifically, interviewees were asked to discuss their firm's R&D activities leading to research-based disruptive innovations aimed at new markets along the following four-stage invention-to-innovation framework, which are defined below and presented in Figure 3.

- **Basic Research:** Generic research aimed at developing new scientific knowledge

- **Concept/Invention:** Proof-of-concept activities to transform scientific knowledge into a functional prototype and develop belief in integratability and select a target market.

- **Early-Stage Technology Development (ESTD):** Technical and business work required to reduce the needed technology to practice, define a production process with predictable product costs and relating the resultant product

Figure 3. Early-Stage Technology Development (ESTD) Along the Path From Invention to Innovation



- **Research Objective**
  - Develop product requirements and specifications
  - Define production process
  - Identify value creation process
  - Integrate new technology with existing/enabling technologies
  - → Output = Integrated system prototype
- **Economic Value Proposition**
  - Estimate Revenue Stream, identify specific set of costs
  - Prove specific Value Creation
  - Identify specific operational mechanisms
  - → Output = Contingent business model
- **Skills**
  - Entrepreneur (business builder), Engineer B
- **Business Risk**
  - High (significant investment for highly uncertain payoff)
- **Technical Risk**
  - High (uncertain integration)

specifications to a projected market so that a business plan with attractive opportunities despite high risks and disruptive effects can be financially justified.

- **Product Development:** Activities aimed at evaluating market opportunities; establishing logistics and infrastructure for product manufacture and delivery; and finalizing detailed product specifications based on pilot production.

Additionally, respondents were asked to

- Identify what specific criteria were used by the firm to make R&D funding decisions
- Discuss how research projects are evaluated and what goals guide their execution
- Respond to the funding gap hypothesis (i.e. are there structural, cultural, and financial disjunctures that impede the development of radical new technologies along the invention to innovation pathway?)

To gain insight on the levels of ESTD funding across industries, each respondent was asked to provide details of the firm's R&D budget in 2000 along with their bestinformed estimates of how these funds were distributed across the four-stage invention-to-innovation framework.

Once all the interviews were completed, detailed quantitative analysis was performed to derive estimates of corporate ESTD spending. As we were particularly interested in intra-industry variations in ESTD support, all interviewed firms were classified into industry groupings modeled after categories from the North American Industry Classification System (NAICS) classification scheme, which in 1997 replaced the 1987 Standard Industrial Classification and groups together business establishments that use the same or similar processes to produce goods and services. Our industry classifications are presented in the Appendix.

To estimate total corporate ESTD spending across the nation, we summed ESTD funding estimates from across each of the eight sampled industry categories. To achieve individual industry estimates, we added up total ESTD funding in each category of our interviewed firms and compared it with their total R&D budgets to derive an industry-specific weighted average of ESTD as a portion of R&D spending. These weighted averages were then applied to total R&D expenditures within each industry to come up with an estimate of total ESTD funding by industry. The results of these calculations are presented in Table 1.

LIMITATIONS OF DATA AND METHODS

In planning our interviews, efforts were made to target a qualitatively diverse sample of firms along dimensions of industry, firm size, and lifecycle stage. In the end, we relied heavily on established relationships and contacts between members of the research team and industry leaders to select our interviewees. No effort was made to create a random statistically significant sample, as this was outside the scope of our study. The small number of firms in our study sample allowed us to conduct in-depth interviews with each of our respondents but does place serious limitations on our ability to assess the accuracy of our extrapolations to industry sectors as a whole.

Table 1 compares the R&D expenditures and sales of interviewed firms aggregated by industry with industry totals. These data indicate that the firms interviewed are more R&D intensive than the average firm in every industry analyzed. Furthermore, for all industries with the exception of computer software, the interviewed firm with the

30. To maintain confidentiality, the names of interview respondents and their respective companies are omitted from this report.

TABLE 1. R&D Expenditures and Sales: Companies and Industry Totals in 2000

	R&D Expenditures ($ million)			Sales ($ million)			R&D/Sales (%)	
Industry	**Surveyed Companies**	**All Industry**	**Surveyed/ All Ind**	**Surveyed Companies**	**All Industry**	**Surveyed/ All Ind**	**Surveyed Companies**	**All Industry**
Surveyed Industries								
Electronics	1,039	30,408	3.4%	7,655	387,956	2.0%	13.6%	7.8%
Biopharmaceutical	509	17,722	2.9%	1,096	160,252	0.7%	46.4%	11.1%
Automotive	6,800	20,389	33.4%	170,064	612,644	27.8%	4.0%	3.3%
Telecommunications	157	13,085	1.2%	514	399,607	0.1%	30.5%	3.3%
Computer Software	273	18,761	1.5%	1,099	104,176	1.1%	24.8%	18.0%
Basic Industries & Materials	1,078	21,215	5.1%	87,356	1,870,478	4.7%	1.2%	1.1%
Machinery & Electrical Equipment	540	10,642	5.1%	13,000	337,049	3.9%	4.2%	3.2%
Chemicals	2,000	8,548	23.4%	30,000	224,992	13.3%	6.7%	3.8%
TOTAL	12,395	140,770	8.8%	310,784	4,097,155	7.6%	4.0%	3.4%

Source: BAH Analysis, Interviews with Corporations, National Science Foundation, Research and Development in Industry: 2000, Arlington VA, 2003 (NSF-03-318)

highest level of R&D intensity was also that with the greatest share of ESTD activity. To the extent that a firm's overall R&D intensity affects the *share* of R&D dedicated to ESTD activities, this difference may imply that our results overstate the share of corporate resources dedicated to ESTD activities.

In our interviews, we made an important distinction between incremental improvements in a firm's core products and processes and disruptive innovations as defined earlier. As we define it, only early stage research that is disruptive because its market lies outside that of the firm's core products or core business model, or because the introduction of the new product disrupts the firms current technology or impacts current products qualifies as ESTD. This distinction is subtle, however, and in many cases, deciding what technologies and products lie within a firm's core business and what lies outside is a subjective judgment. To facilitate this discussion we often used a framework represented in Figure 2 on page 7. Early development within the context of familiar technologies and familiar markets was not considered to be ESTD. Early development work oriented to new products using familiar technologies but focussed on new value propositions, using new technologies deployed against a familiar value propositions, or new technologies focused on new value propositions were all considered ESTD. When using this framework most of the interviewees recognized that most of their ESTD activity was in fact focused in the upper left or lower right hand quadrants. These interviewees also observed that they would generally not allocate funds to activity in the upper right hand quadrant.

Moreover, the operational definition of R&D process terminology like "exploratory research" and "process development" varies widely across industries and firms. While we made efforts to ensure consistency in the way terms were defined and used in our interviews, some variation in the way our respondents categorized their research activities was expected. In a few exceptional situations, there were clear discrepancies in the way respondents decided what portion of their R&D investments to characterize as ESTD work. In these cases, we made slight adjustments to the categorizations to be more broadly consistent with our set of definitions.

IV

Findings: Corporate ESTD Investments and Activities

Early-stage technology development (ESTD) investments are critical to sustaining long-term economic growth, and corporate funds represent the largest source of funding for the nation's ESTD activities. The results of our interviews reveal, however, that despite recognition of the value of early stage research, ESTD investments are rarely a corporate priority, market incentives to fund ESTD are low, and ESTD budget flows are under constant pressure. The quickening pace of technological change, the increasing efficiency of capital markets, and the continual demand for profits has forced a shift from a technology-forward to a market-back paradigm within many corporations. These pressures have created a heavy bias towards product development research activities at most firms, at the expense of a more long-term inventive focus. In addition, companies earmark the vast majority of their R&D funding to support existing business lines rather than to research new technologies that could enable entry into new markets. Increasingly, it is the market that drives innovative activity, not the other way around.

ESTIMATES OF CORPORATE ESTD INVESTMENTS

Our research indicates that of the $180.4 billion invested into research & development by U.S. firms in 2000, an estimated $13.2 billion funded the kinds of ESTD activities that are targeted at bringing radical technological innovations to the marketplace. This works out to about 7.3% of total corporate R&D budgets that is dedicated to ESTD activities. As noted earlier, this may be an over estimate, since the firms interviewed were somewhat more R&D intensive than the average firm in each sector, and ESTD expenditures appear to be correlated with R&D intensity. The majority of R&D

spending, 86%, is for product development; and the remaining is for concept/invention. The results of our research are summarized in Table 2 and Figure 4.

There are significant variations in ESTD expenditures across industries and between firms within specific industries. These inter- and intra-industry variations are shaped by several forces including the increasing sophistication required to develop new technological innovations, mounting pressures on corporate R&D divisions to demonstrate financial value from R&D investments, and the importance of the lifecycle position of specific industries relative to other industries and individual companies relative to their peers.

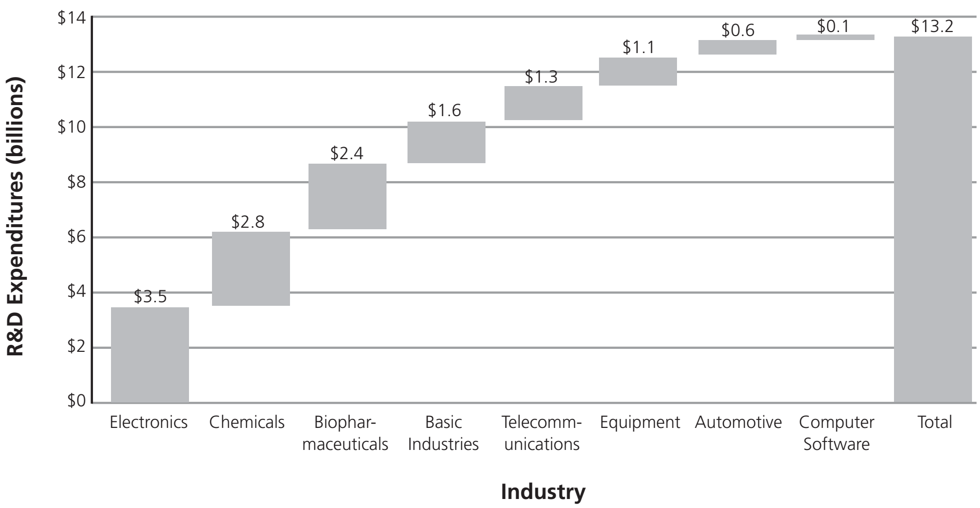
TABLE 2. Estimated ESTD Spending by U.S. Corporations in 2000

	Average R&D Spending Allocation (%)				R&D Expenditures ($ million)		ESTD Expenditures by industry (est. in $million)	% Range of R&D funding for ESTD
	Basic	Concept/ Invention	ESTD	Product Development	Surveyed Companies	Industry		
Surveyed Industries								
Electronics (8)	0%	5%	11%	84%	1,039	30,408	3,463	0%–40%
Chemicals (2)	3%	28%	33%	38%	2,000	8,548	2,778	25%–40%
Biopharmaceutical (5)	0%	0%	13%	86%	509	17,722	2,373	0%–40%
Basic Industries & Materials (3)	0%	5%	7%	87%	1,078	21,215	1,547	0%–15%
Telecommunications (5)	0%	0%	10%	90%	157	13,085	1,305	0%–35%
Machinery & Electrical Equipment (1)	0%	0%	10%	90%	540	10,642	1,064	10%
Automotive (1)	1%	3%	3%	93%	6,800	20,389	612	3%
Computer Software (6)	0%	0%	0%	100%	273	18,761	71	0%
Subtotal	0%	4%	9%	86%	12,395	140,770	13,213	
Non-Surveyed Industries								
Trade						24,929	n/a	
Services						10,545	n/a	
Aircraft, missiles, space						4,175	n/a	
Subtotal						39,649	n/a	
TOTAL						180,419	13,213	7.3%

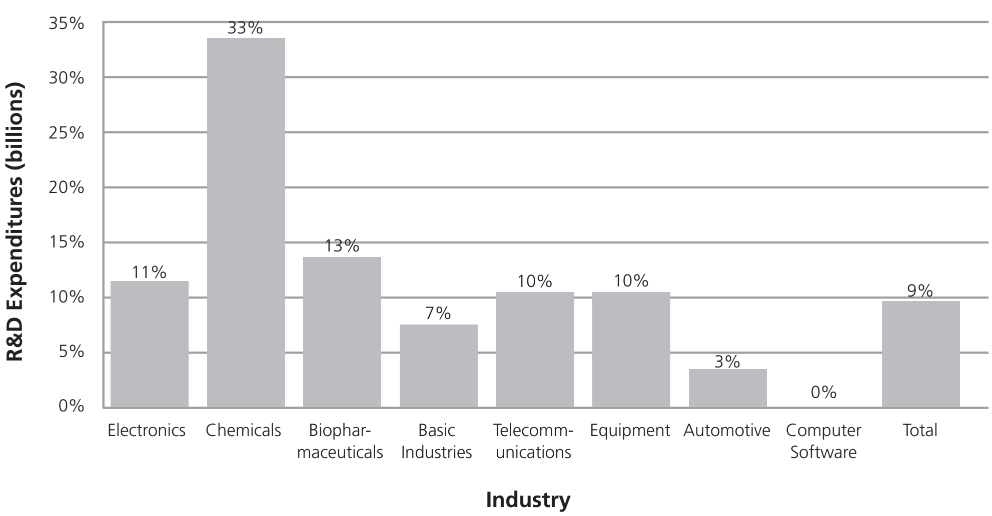
Note: *Numbers in parentheses indicate quantity of interviews in each industry category.
Source: BAH Analysis; Interviews with Corporations; National Science Foundation, Research and Development in Industry: 2000, Arlington VA, 2003 (NSF–03–318). See Appendix for map of source document industry classifications to industry categories above.

Figure 4. Estimated ESTD Spending by U.S. Corporations

ESTD investments are concentrated in a handful of industries…



…But the share of ESTD funding as a portion of total R&D varies widely by industry.



Source: BAH Analysis, Interviews with Corporations, National Science Foundation, Research and Development in Industry: 2000, Arlington VA, 2003 (NSF–03–318)

In 2000, the two firms we interviewed in the chemicals industry invested on average 33% of their R&D dollars on ESTD activities, the highest proportion for any group of industry firms that we interviewed. These high ESTD expenditures were driven by a common corporate emphasis on new technology and market development and by market expectations for frequent innovation. The fact that the chemicals industry seemed to have the highest ratio of ESTD to all R&D may seem counter-intuitive, given the significant amount of bulk industrial chemicals manufactured in this industry, but it is important to observe that the R&D to sales ratio in this industry is only 3.8%. Thus the industry is not nearly as R&D-intensive as biopharmaceuticals or electronics, but the R&D that they do perform is often aimed at fundamental research to spur the development of new product innovations, and thus tend to spend a larger fraction of their modest R&D investments on early stage research than do other industries.

In sheer dollar terms, the largest ESTD spender was the electronics industry. The results from our interviews suggest that the electronics industry spent $3.5 billion, or 11% of its R&D, on ESTD activities in 2000. Among the firms we spoke with in this highly competitive industry, many insisted that while the incentives to exploit and extend existing product lines are powerful, such a short-sighted strategy could be perilous. Given the rapid pace of technological change in electronics, investments into new lines of research and the pursuit of an innovation-led growth strategy are the most viable paths to long-term survival.

On the opposite end of the spectrum, the computer software industry showed no evidence of substantive ESTD activity — a result that may be surprising to some. We found that almost all software releases, creative as they may be, are built using well-established technologies and programming languages. They are rarely based on truly novel technological innovations—indeed, most were business model or market innovations. Numerous software industry executives provided corroboration for this finding.

Overall, we found that ESTD spending is concentrated in industries based on quickly developing technologies, like electronics, specialty chemicals and materials, and biopharmaceuticals. Mature industries based on well established technologies, like the automotive and computer software industries, typically spend less on ESTD and focus more of their resources on product development.

Within individual industries, significant firm-level variations in ESTD spending also exist. A firm's relative lifecycle position, for example, is a key driver of intra-industry differences in ESTD investments. Companies in the early stages of their lifecycle are more likely to invest more heavily into ESTD than more mature companies who focus instead on promoting existing product lines through heavy spending on product and market development. As companies grow, their technology investments become increasingly targeted and disciplined processes are put into place to evaluate all research projects.

Another critical driver of ESTD spending is related to broader corporate strategies. Technology-centric companies for whom new technology is seen as a source of growth are more likely to invest heavily in ESTD than product-based companies for whom technology is a cost center. On the other hand, companies seeking to break out of their existing market positions or to rejuvenate their innovation resource base may make disproportionate investments into early stage R&D relative to their peers.

KEY TRENDS SHAPING CORPORATE R&D AND ESTD INVESTMENTS

1) R&D PROCESS EVOLUTION: INCREASING COMPLEXITY OF TECHNOLOGY DEVELOPMENT

Most interviewees generally agreed with the classification of R&D into the four-phase innovation framework used in our discussions (Basic, Concept/Invention, ESTD, Product Development). However, many respondents resisted the linear simplicity of our idealized framework. They noted that the actual innovation pathway is frequently much more complicated. The development of any innovation can require multiple parallel streams of research, iterative loops through any of the four stages, and linkages to developments outside the core of any single company.

Even when all the technical challenges are solved, there are still external risks that can significantly alter the development path of an innovation. The chief technology officer of a large machinery manufacturer states: "New product development is based on technologies that are largely believed to be proven, but there are still significant risks related to market, channel, and other infrastructure development. Companies are sometimes surprised when they find out that some technologies turn out to be less developed than anticipated."

Rapid advances and the increasing breadth and depth of knowledge available across all scientific fields have also contributed to the acceleration of this complexity in recent decades. To many, the pathway from scientific invention to commercial innovation has reached the point where the process is more web-like than linear. Consequently, the ability of any one company to develop all of the technological elements required to deliver significant advances alone has rapidly diminished. According to a disk drive industry executive we interviewed, "As technology advances, it costs more to solve successive problems. At some point, solving a new problem is beyond the capabilities of any one company." There are simply too many potential ideas and too few resources to go it alone. There was a strong sense among our interviewees that the scale of research required to create new innovations has increased as technology becomes more complex. But a firm's ability to capture the full benefits and exploit the full potential of new research has not kept pace, making ESTD investment decisions more difficult than ever before.

2) PRESSURE FOR MEASURABLE RESULTS AND FINANCIAL RETURNS

Increased pressure on R&D to deliver measurable results was also cited as a key force that has driven corporations almost entirely away from basic R&D, making it difficult to justify many activities that do not directly support existing lines of business. One interviewee dubbed this trend the "Larry Bossidy approach," after the famed CEO for whom he worked at Allied Signal. "Bossidy was very uneasy with our basic research work because he could not measure the expected return of his investment in financial terms." Projects that did not have clearly demonstrable financial benefits were not funded, and the R&D portfolio shifted dramatically toward product development.

Increased pressures to deliver near term financial results and manage profits to expectations have resulted in an increased bias towards the more predictable and more immediate payoff of product development, at the expense of earlier stage investment. This increased emphasis on predictability of earnings also has created a bias toward a fast follower technology strategy. These trends were evident throughout our interviews, regardless of firm size and industry.

While general investment into earlier stages of R&D has faded, corporations will still opportunistically invest in earlier stage development in a more reactive mode, either in response to significant threats, or to meet aggressive growth objectives.

3) INDUSTRY AND COMPANY LIFECYCLE INFLUENCES

The final major influence we observed was differences in R&D investment related to industry and by company that are in part linked to lifecycle positions. Support levels for ESTD vary widely by industry, and by company within specific industries. While the average ESTD investment is about 9% of corporate R&D spending for all firms, ESTD investments in the computer software industry is essentially zero, while for the biopharmaceutical industry, the rate is 13%. Within the biopharmaceutical industry, ESTD spending ranged from 0% to 30% of R&D at the companies interviewed.

We believe that the key driver of these differences is the lifecycle position of the industry and the individual company.[31] More mature industries such as the automotive sector tend to invest a smaller percentage of R&D into earlier stages of research than industries at an earlier stage of development such as the biotechnology sector.

However, individual companies may make disproportionate investments in early stage R&D compared to their peers as an attempt to break out of their existing positioning or to rejuvenate their innovation resource base. Several companies that we interviewed described how they reached a deliberate decision to rebalance their investments toward ESTD after recognizing that they were not positioned for growth. In some cases they have managed complete transformations out of an historical line of business and into high-tech sectors in which they did not participate a decade ago. Monsanto's move into genetics in the 1980s is a successful example of a company temporarily moving out of a product development focus and into a strategy emphasizing basic and ESTD research.

SELECT INDUSTRY ANALYSIS: DETAILS FROM THE INTERVIEWS

COMPUTER SOFTWARE

Few industries experienced the unprecedented expansion enjoyed by the software industry throughout the 1990s. Driven by the proliferation of the Internet, whole new types of software products and services were introduced and new markets were created. Yet despite this remarkable growth, none of our software industry respondents were prepared to state that growth in the software industry was fueled by truly new technical innovations.

Based on our interviews, we found that the incentives and opportunities for invention in the software industry have been tempered in recent years. Throughout 1998 and 1999, for example, Y2K issues siphoned a significant portion of industry resources away from inventive research. More importantly, the emergence of the Internet has required the industry to respond to changing customer needs and expectations. Demand for web-enabled software has created opportunities for software vendors to generate revenue by selling web-enabled versions of existing products.

31. It might seem that software is early in its life cycle, not late. However, at the time of this survey, most software firms were relying on conventional software engineering tools and on Internet and web technology as if these were mature, expecting to evolve the underlying technology later if needed.

The proliferation of new web-based services, while generating important economic value, represents a new class of market innovations, relying upon unique value propositions and business models to reach customers in new ways, rather than on new technical inventions.

Software companies use existing technical tools to help expand functionality. These are not technical innovations, strictly speaking. Even today's most creative software packages are mostly built using well-established programming languages and tools. While the configuration of programming code in a new software release may be unique and the abilities provided to the user may be novel, the fundamental technological basis of most software applications is not extremely innovative.

The introduction of Java, led by the Sun Corporation, is seen by many as one of the few true technical innovations in recent years. In contrast, XML (eXtensible Markup Language) is an extension of existing web coding standards and is not based on a new invention. In any case, Microsoft, Sun, and Oracle were not among the firms interviewed, thus suggesting that in this category the estimated ESTD in the entire software industry may have been to some extent an underestimate.

According to our respondents, the incentive to create new inventions in the software industry is small. One software executive explains, "The moment you introduce a software product to market, you need to start providing customer support. So a part of the team that developed the product has to be dedicated to support." Another manager states, "The industry itself demands that new versions of old products be introduced into the market at least every two to three years. Customers also demand numerous minor enhancements and changes to a product after purchase."

Within the quickly evolving enterprise resource planning (ERP) market, significant resources are still focused on developing interoperability standards between various ERP suppliers that deliver products to help companies integrate and automate business practices associated with the production or operation of a company. According to one senior ERP executive, "within the Enterprise Software space there are so many little problems that can be solved at so many different organizations, that we don't have to worry about being in this business for the next fifteen to twenty years."

With little incentive for invention or technical innovation, we conclude that even though the software industry has created huge economic value in recent years, there is essentially no significant ESTD activity being funded internally by the industry at the moment; virtually all R&D dollars in the software industry are dedicated to product development (see Table 3).

TABLE 3. Breakdown of R&D Dollars by Interviewed Software Companies

Basic Research	Concept/Invention	ESTD	Product Development
• **0% of R&D is spent here**	• **0% of R&D is spent here**	• **0% of R&D is spent here**	• **100% is spent here**
• None of the interviewed companies are involved in basic research	• Our interviewees suggest that new invention in the software industry is "non-existent"	• Many companies do some prototyping when creating a brand new software product.	• All R&D activity takes place at this stage
• If there is any basic research going on in the software industry, it is being performed by academia, government institutions or at large corporations	• Characteristics of software could explain the lack of inventions	• While prototyping makes up about 9% of total R&D, it is not included as ESTD since prototyping is mostly based on new product ideas (driven by customer needs), not new technological inventions	• Activities may include – New software development – Software testing – Bug fixing – Prototyping new functions for a product – Technical customer services

TELECOMMUNICATIONS

Firms engaged in relatively "new" areas of telecommunications, such as optical networking and wireless infrastructure must spend considerable amount of R&D dollars in ESTD to keep up with technological change. But firms outside these new areas focus their resources heavily on product development. Overall, only 10% of R&D dollars in the telecommunications industry is spent on ESTD and 90% on product development (see Table 4).

Deregulation of the telecommunications industry has escalated industry competition and quickened the pace of technological change. With the emergence of whole new classes of competitors to the industry, a proven capacity to innovate has become a prerequisite for any firm to remain competitive. But given tighter profit margins and shorter product development cycles, firms cannot afford to spend lavishly on unfocused R&D.

At one representative telecommunications firm, only 5 of 270 engineers were charged with researching and developing new technologies. Rather than fund expensive

TABLE 4. Breakdown of R&D Dollars by Interviewed Telecommunications Companies

Basic Research	Concept/Invention	ESTD	Product Development
• **0% of R&D is spent here** • None of the interviewed companies are involved in basic research.	• **0% of R&D is spent here** • Only one company we interviewed funded research at this stage, related to its collaborations with Navy and Air Force labs	• **10% of R&D is spent here** • The above number is the weighted average of ESTD spending across all companies interviewed. However, there was significant variance across companies • The company that was the most active in this phase was a wireless infrastructure technology company that spent 35% of its R&D budget on ESTD – The company was not yet profitable and was in a rapidly developing technology based sector	• **90% is spent here** • Once again, a majority of activity takes place in the Product Development and later stages • Activities in this phase revolves around – Designing and testing network equipment, – Designing new development processes – Making the equipment fast and more reliable • Many companies that are in established areas of the telecommunications market spend ALL their R&D dollars in this stage

in-house early stage research labs, many of the firms we spoke with relied on other strategies, including company acquisition, technology licensing, and aggressive recruiting of industry experts, to acquire already proven technologies and reduce market risk.

"Most of the time, the proof of concept work has already been done by these acquired companies or hired personnel," says the chief technology officer of a midsize switching and transmission equipment manufacturer.

The rapid pace of change in the industry requires short-term planning horizons. One mid-sized telecommunications manufacturer reported the need to develop one new marketable idea per quarter in order to stay competitive. Another mid-sized telecommunications firm stated that R&D goals are limited to a one-year time horizon, while a third noted that any product idea requiring more than five years to be commercialized is usually abandoned.

Academic collaborations also play a significant role in the telecommunications sector. Such partnerships are almost always with institutions residing close to firm offices or located in key target markets. These cooperative efforts focus on basic research and serve as idea generators for industry, as well as a talent feeder into in-house corporate labs.

AT&T funds research sites at Cambridge University and UC-Berkeley focusing on network, multimedia, and mobile communications. Other examples include the Center for Wireless Communications at the UC-San Diego, a cross-disciplinary research and education program sponsored by industry participants, and GCATT, a local R&D initiative at Georgia Tech University linking local Georgia industry, state government, and academic partners. One telecommunications executive spoke of the challenges facing joint ventures with academic partners. "We would prefer to do less ground-breaking and risky work, but most professors are not interested in partnering with us unless we are doing cutting-edge research."

CHEMICALS

According to our interviews the chemicals industry invested on average 33% of their R&D dollars on ESTD activities, the highest proportion for any group of industry firms that we interviewed. We believe that this is a function of the chemicals industry's position in the overall value chain. Chemicals are an input into other manufacturing industries and are rarely a final product in and of themselves. Therefore there is less onus on the chemicals industry to make the kind of engineering related or consumer related product development investments associated with industries such as manufactured goods. Basically the activity related to adapting the product to specific consumer and market requirements happens down stream. If we were to include the chemicals inputs into an analysis of the entire value chain supporting any given product we would expect that the proportion of ESTD to product development expenditures would look more like that of the other industries analyzed.

A high priority in the chemicals industry is growth through invention. Unlike other industries we interviewed, the chemicals industry has a large portion of R&D expenditure funded centrally and performed in central corporate labs. There was an explicit allocation in these companies of 30–40% of research activity to markets where the companies had no current position, therefore the role of corporate "incubators" was important for these companies (see Table 5).

TABLE 5. Breakdown of R&D Dollars by Interviewed Chemical Companies

Basic Research	Concept/Invention	ESTD	Product Development
• **3% of R&D is spent here** • Interviewed companies identified market based approach to R&D investment. There is little science for the sake of curiosity. • Occasionally fundamental research is required (such as in the field of computational chemistry) • Other basic research only occurs on the margins	• **28% of R&D is spent here** • Invention of new products is a critical goal and sustaining activity of both companies interviewed • Invention activity is generally centrally funded and performed in corporate labs	• **33% of R&D is spent here** • ESTD activity is often transferred to business units… • …or to an "incubator" for inventions in areas where the company does not currently have any market activity	• **38% is spent here** • Extent of product development activity varies across product lines and the chemical company's position in the value chain within that product line. • Products which are inputs to manufactured goods industries tend to have lower product development expenditures • Products which are marketed directly by the company tend to have higher product development requirements

In addition to centrally funded invention activity, both companies cited partnerships with downstream companies as a source of invention activity. In these instances the company would work with downstream partners to develop materials that would solve a problem for the downstream company or enhance the downstream company's product. This brings up one of the complications in the vocabulary used in discussing these issues. The development of a new to the world material by the chemical company would be considered in our vocabulary an ESTD. The application of this material to incrementally enhance an existing product would be considered product development on the part of the downstream company. However, radical innovations for use in manufacturing by established firms often encounter serious barriers due to the cost and uncertainty the customer experiences when considering a basic change in design or production processes. Thus, such projects may qualify as ESTD even though the final product differs only in cost and quality, not in product function.[32]

32. An example would be the penetration, now underway, of advanced adhesives, replacing welding, in the assembly of door panels and other parts of automobiles.

TABLE 6. Breakdown of R&D Dollars by Interviewed Electronics Companies

Basic Research	Concept/Invention	ESTD	Product Development
• **0% of R&D is spent here** • None of the interviewed companies are involved in basic research.	• **5% of R&D is spent here** • Only one of the interviewees (an audio equipment manufacturer) conducts research at this stage. – The type of activity includes research into understanding how people judge subjective experiences such as audio quality. – Then the firm will focus on finding and understanding algorithms from other fields that may enhance the audio experience. – "At this stage you are not selling anything and you cannot foresee selling anything."	• **11% of R&D is spent here** • There is considerable ESTD in the industry – In the case of the audio equipment manufacturer, ESTD activity includes converting new algorithms into hardware and proving that audio quality can be improved with its use. – In another example, a company used existing technologies from other firms to ensure that it can improve the graphical quality of its flight simulation products	• **84% is spent here** • Most activity takes place in this and later stages • Companies that have established products spend most of their R&D dollars here, and make incremental improvements

ELECTRONIC COMPONENT MANUFACTURING

According to our interviews, early stage research activity in the electronic component manufacturing industry is relatively robust, driven by high consumer demand for innovation and intense industry competition. That being said, the vast majority of research activity in the electronic components industry is focused on improving existing electronic components or using existing technology to create components for new devices — not on groundbreaking new innovations that disrupt old markets and create new ones. Only 11% of R&D dollars in the electronic component manufacturing industry is devoted to ESTD and 5% to concept/invention, while the balance is dedicated to product development (see Table 6).

In areas where scientific knowledge and technology are well established, early stage research is low, as in the case of a producer of board-level I/O products for computers. According to its VP of engineering, "Point to point signal delivery is a very fundamental science, and since the format of the signals does not change even if the devices at the end points change, our firm does not have to do major research to stay in business."

A leading manufacturer of graphics processors notes that it is able to rely on academic research to provide the inputs for many of the advances in its new products. Its research engineers get most of their ideas sourced from public domain papers presented at annual academic conferences and work on developing 3–D rendering algorithms based on these concepts.

For most electronic component manufacturers, industry competition and diminishing gross margins place enormous pressure on R&D budgets, necessitating new strategies to distribute research costs and minimize risk while capturing the fruits of early stage research.

According to the CEO of a large company with R&D expenditures in excess of $500 million, "The traditional corporate model of R&D is dead. The centralized Edison and GE labs model was efficient when technology was less complex. But today, technology is too complex to justify development for use by just one firm. As a result, industry labs have become product development and enhancement labs, with less emphasis on developing truly innovative technologies."

Even a large computer equipment manufacturer with revenues of $2.0 billion cannot afford to do all of its own research. The company's senior vice president noted, "[W]e are 'virtually vertically integrated.' We work closely with our supplier network to identify technologies to be pursued or science to be developed. We also share costs of developing new technologies."

An executive in the highly competitive disk drive industry said, "The products we sell are highly commoditized in today's market and gross margins are too small to allow any one company to drive the R&D effort alone."

AUTOMOTIVE INDUSTRIES

Because of the relatively high initial investment required to purchase an automobile, most consumers are slow to adopt new automotive technologies. As a result, automobiles have evolved slowly through waves of incremental technological improvements, punctuated by the occasional radical innovation. Over 90% of R&D dollars in the

TABLE 7. Breakdown of R&D Dollars by Interviewed Automotive Companies

Basic Research	Concept/Invention	ESTD	Product Development
• **1% of R&D is spent here** • A portion of basic research spending funds long term research grants to universities • The auto company we interviewed has 5 major laboratories that employ scientists with doctoral degrees and engage in basic research that has immediate relevance to the auto industry – An example is research to understand and predict properties of basic materials	• **3% of R&D is spent here** • According to our interviewee, basic research often yields concepts useful to the core auto business. Spending in this stage goes toward trying to build a lab version of the product	• **3% of R&D is spent here** • Only a small portion of R&D is targeted at bringing radical inventions into the automobile. – An example cited here is the conversion of a vehicle's structure from steel to aluminum – Another example is building and testing methods of driving engine valves with electromagnetic waves instead of conventional tools	• **93% is spent here** • The majority of dollars is spent on improving existing technologies, including enhancing vehicle design, and streamlining development and engineering activities. Design and development of manufacturing plants are also included here.

automotive industry are devoted to product development and the balance is distributed across the earlier stages of R&D (see Table 7).

The surplus of power created by the development of the high-compression engine allowed vehicles to grow in size and weight and encourage a broad new set of technologies. Some of these incremental improvements included the introduction of automatic transmission, air conditioning, electric seats and windows, dual headlamps, and wider, softer-riding tires.

The advent of the microprocessor, imported from the electronics industry, created the next major wave of technological upgrading. Some key developments that emerged were the development of sophisticated engine control modules and the ability to integrate engine control with power train and chassis electronic systems.

According to an executive at one of the Big Three automobile manufacturers, their large revenue base allows significant R&D investments across the spectrum, including at the early concept and invention as well as ESTD stages. "But we do not do nearly as much basic science research as we did when our company's original central research lab was created in the 1950s," he says. Motivated by a growing focus on more reliable and profitable products, the vast majority of their research is targeted at product development. Also, given the importance of design and form in the automotive industry, a significant portion of R&D efforts is driven by design-related needs. Still, he notes, the large number of patents and licensed technologies owned by the company is indicative of the company's commitment to early stage research.

The time horizon for new R&D initiatives is also significantly longer in the automotive industry than in other industries. According to our interviewee, long range projects have timelines of about 10 years to production, while short range projects often have timelines of 3 to 5 years. Research projects are assessed against measures of risk and opportunity, with most projects being medium risk, medium opportunity. In recent years, research goals have focused on environmental regulation and fuel economy issues. Fuel cell research, for example, is a high risk, high opportunity project for the firm.

BIOPHARMACEUTICALS

The biopharmaceutical industry spends 11% of sales on research and development activity, more than any other industry in the United States except for the computer software industry which spends 18% of sales on development (the equivalent of manufacturing expense for this industry).

Biopharmaceuticals include all companies that are involved in biotechnology research, gene mapping, and genomic-database building to identify and characterize the expressed genes of the human genome as well as companies engaged in the discovery, development, and production of drug and drug-related technologies.

The process of drug discovery itself is well understood and has been fine-tuned over many years. Incremental improvements are targeted primarily at reducing the fall-off rate of drug candidates at each stage of the discovery process. Very long product development cycles, high upfront development costs, and an unpredictable rate of success limits the ability of maturing firms in the biopharmaceutical industry to spend on ESTD work to develop new products. For many young firms, bringing their one core founding idea to market is the only goal that matters.

The companies we interviewed were relatively small companies, founded around a single product idea (or a handful of closely-related products). Early on, significant

TABLE 8. Breakdown of R&D Dollars by Interviewed Biopharmaceutical Companies

Basic Research	Concept/Invention	ESTD	Product Development
• **0% of R&D is spent here** • None of the interviewed companies are involved in basic research.	• **0% of R&D is spent here** • None of the interviewed companies are involved in invention at present.	• **13% of R&D is spent here** • ESTD activity is concentrated in companies that have perfected a product or technique and are trying to extend it to new products and situations. – In the case of the inhaleable drug manufacturer, ESTD activity is focused on creating other inhaleable molecules. "Molecules are all different. Even if you get this to work on one molecule, getting it to work for another is really tough." Therefore the technical uncertainty of the research is sufficient to classify it as ESTD	• **87% is spent here** • The majority of the spending in this stage is on clinical trials for new drugs

resources were targeted at proof-of-principle and reduction-to-practice activities. They stated that a considerable amount of R&D money was devoted to ESTD work in the years immediately following the founding of the company. Today, these firms are focused on developing their products for clinical trials and market introduction, with almost 90% of R&D dollars devoted to product development (see Table 8).

The chief scientific officer of a young developmental stage biotech firm told us, "We spend the vast majority of our research money on product development as opposed to ESTD type work. But two to three years ago, that ratio was reversed." After developing the initial concept for a novel vaccination treatment, the idea had to be proven at the manufacturing level. Logistics had to be worked out for complicated procedures ranging from procuring uncontaminated diseased tissue samples from around the world to developing economical manufacturing processes for the vaccinations. With many of these operational and logistical challenges worked out, the firm is now heavily focused on developing the product for clinical trials.

The firm's R&D budget has reached 25% of their burn rate, with nearly all of that targeted at developing their vaccination products for market entry. With no profitable revenue streams yet, R&D investments must be consistent with the firm's very sharp focus. There is little money for new "blue sky" research and no latitude for high-risk early stage research out of the firm's core business.

V

Emerging Corporate Strategies and Responses

While the fraction of corporate R&D dollars devoted to ESTD investments is small, the market pressure to innovate weighs heavily on the backs of all technology firms. During our interviews, we discovered emerging responses and strategies being used by corporations to strengthen their innovative capacity, even in the face of systemic pressures that bias corporate focus away from long-term, early-stage research.

PORTFOLIO MANAGEMENT MODELS

Most of the companies we interviewed used a formalized R&D portfolio management process to select, balance, and manage R&D investments. According to many of our respondents, these portfolio management strategies often favored projects that met near-term research and product delivery goals. Only occasionally were managers required to reassess the balance of projects within their R&D portfolios, particularly as they hit discontinuities in the expansion of their core businesses.

Several respondents described deliberate efforts to restructure their R&D portfolios by increasing the allocation of funding to earlier stage basic and ESTD work after discovering that they had allowed their technology portfolios to swing too far towards the product development end of the spectrum. The vice president of R&D for a $30 billion chemicals company noted, “In the mid-1990s, our R&D portfolio was skewed heavily towards value preservation and product development investments. These made up two-thirds of our R&D spending.” Recognizing the danger of not investing in projects that would open up new markets and rejuvenate its innovation base, the firm took action to reverse the trend. Today, 40% of R&D is targeted at ESTD activities, and another third is aimed at earlier stage concept/invention work.

While no two companies used the same approach to managing their R&D portfolios, several common elements were apparent. These include the definition of a set of technical core competencies to guide investment decisions, the splitting of funding control between business units and a central corporate organization, and the discretionary allocation of limited funds to foster new ideas (e.g., senior scientists with slush funds, central investment fund dedicated to long term investments). Many also had established dollar or percentage spending targets for specific types of investments and used a classification system similar to the four-step model in Figure 1 or other original classification schemes. Overall, the companies that appeared most active in investing in earlier stages of R&D appeared to have more formal mechanisms in place to sustain this type of funding. No company interviewed was able to cite a formal analytic process which justified allocation of funding to ESTD activity. Instead companies recognized the necessity for growth and the importance of ESTD activity to their growth objectives and used funding target levels as a means of sustaining investment in this difficult to quantify activity.

ALLIANCES, ACQUISITIONS, AND VENTURE FUNDS

Corporate innovation strategies are increasingly extending beyond traditional corporate and industry boundaries. On numerous occasions, alliances, acquisitions and other external ventures were cited as a common way of maintaining access to a steady flow of new technologies and ideas, while holding back research infrastructure costs and risk. A senior executive at a $16 billion consumer products company told us, “We see no need to re-invent good research. We are always prepared to acquire technology from external sources, when it makes sense.”

The companies interviewed also indicated that they have become increasingly focused and methodical in their selection of partners and technology rights. Adopting a market-like approach to acquiring new innovations as opposed to developing them internally helps limit the scale of R&D required to sustain their organization while allowing them to pay for only the portion of the ESTD activities they intend to use.

Several different types of partnership are typically pursued, each with differing objectives. Most outright acquisitions or licenses of earlier stage technologies result from interactions with other corporations or start-ups. An alternative is to form some form of alliance, such as a joint venture with these types of partners.

Most interviewees also indicated that they had partnerships with university laboratories. These interactions can be somewhat broader than an outright alliance, but are generally targeted at providing a window into more basic or concept-level research in specific fields of interest. Several interviewees indicated that they have become much more targeted in these investments, and tend to be more interested in establishing relationships with specific professors or scientists rather than an academic department or entire school. Government laboratories also occasionally serve as partners, but they typically lack the infrastructure to partner effectively with corporations. According to one senior executive we spoke with, "Scientists at government labs have good intentions, but no real business support. This tends to result in unrealistic expectations and makes the process of negotiating an agreement difficult."

Another form of alliance that was frequently mentioned was relationships with venture funds. In some cases, an internal venture fund was formed to help profit from and foster start-ups in fields of interest to the company. Alternatively, companies invested in established private funds, securing the rights to actively benefit from offerings of potential commercial benefit.

OUTSOURCING OF EARLY STAGE R&D: ESTD ENGINES FOR HIRE

An alternative strategy used by corporate R&D managers to mitigate risk and maintain firm focus while continuing to explore new opportunities is a growing reliance on outsourcing of early stage research.

The chief technology officer of a large machinery manufacturer told us, "as a result of the de-emphasis of earlier stage R&D investments and the move to a more conservative investment posture by most established firms, the responsibility for developing breakthrough technological advances rests disproportionately on the shoulders of start-ups and universities." This trend was noted by many of our respondents. A senior machinery industry executive cautioned however, "Sourcing ESTD and earlier stage R&D from the outside works well for discrete technologies and small, very-focused inventions. But coordination becomes enormously difficult with larger projects requiring infrastructure or business model changes."

We spoke with one firm that specializes in contract R&D work for other large firms. The company had been the corporate R&D arm of a Fortune 500 firm, but was spun out as a private entity and now concentrates on early stage research work on behalf of other firms. Nearly 80% of its R&D expenditures are allocated to ESTD type research. Essentially, it has become an ESTD engine for its client companies. According to the CEO, "Our strategy is to leverage our capabilities in electronics, optics, and other high-tech areas by linking development and taking them to a wide range of markets." Since it is not captive to the same narrowly tailored business priorities of its individual clients, it can exploit benefits of scale and scope of its ESTD work by structuring its relationships to maintain rights in fields that are not of interest to its clients. The CEO explains why ESTD work is so attractive to the firm: "The apparent commercial potential for ESTD projects is often not large enough to attract VC or corporate support. But what looks like a very narrow market niche at the ESTD level can become broadly applicable as the implications of the research unfold." As it develops new technologies through its research, the firm then either licenses or commercializes products in these new areas to other firms looking to acquire new technologies.

VI

Conclusions

Our research supports the view that large, industrial corporations continue to play an important role in converting new science into market ready innovations, especially when the innovations fit within the firm's core business strategy and can be exploited within the basic manufacturing and marketing capabilities of the firm. At the same time, large firms are hesitant to support technology development projects that have the potential to be internally disruptive, even when the project would be compatible with core business goals. Yet today, even the largest firms cannot maintain all the capabilities internally—including research capabilities—required to compete at the technological frontier. Furthermore, even the most technologically dynamic regions, such as Silicon Valley and Boston's Route 128, do not contain all of the talent locally—including research talent—to compete at all of the most interesting technological frontiers.

The results of our survey of select high-tech firms, while limited in coverage, suggests that the more R&D intensive firms are spending an estimated $13 billion a year on early-stage technology development (ESTD)—funds specifically directed to projects that face barriers from internal disruption or barriers from the limited scope of the firm's established lines of business. This works out to about 7.3% of total corporate R&D budgets ($180 billion invested in 2000) that are dedicated to ESTD investments. When internal development is resisted, excubation and partnering with others may be the answer. Or internal organizational structures such as "skunk works" may be used. Finally, joint ventures with firms that offer complementary capabilities may provide a way around the internal barriers that inhibit the development of some innovations.

We found that spending on ESTD is concentrated in industries based on quickly developing technologies, like electronics, specialty chemicals and materials, and biopharmaceuticals. Mature industries based on well established technologies, like the automotive and computer software industries, typically spend less on ESTD and focus more of their resources on product development. Within individual industries, significant firm-level variation in ESTD spending also exists given the firm's lifecycle position. Companies in the early stages of their lifecycle are more likely to invest more heavily into ESTD in order to establish a comparative advantage than more mature companies that focus instead on protecting existing product lines through heavy spending on product and market development. As companies grow, their technology investments become increasingly targeted and disciplined processes are put into place to evaluate all research projects. Another critical driver of ESTD spending is related to broader corporate strategies. Technology-centric companies for whom new technology is seen as a source of growth are more likely to invest heavily in ESTD than product-based companies for whom technology is a cost center. On the other hand, companies seeking to break out of their existing market positions or to rejuvenate their innovation resource base may make disproportionate investments into ESTD relative to their peers.

Finally, and more importantly, many respondents reported that the ability of any one company to develop all of the technological elements required to deliver significant advances alone has rapidly diminished. According to a disk drive industry executive we interviewed, "[a]s technology advances, it costs more to solve successive problems. At some point, solving a new problem is beyond the capabilities of any one company." There are simply too many potential ideas and too few resources to go it alone. There was a strong sense among our interviewees that the scale of research required to create new innovations has increased as technology becomes more complex, but a firm's ability to capture the full benefits and exploit the full potential of new research has not kept pace, making decisions to invest in ESTD more difficult than ever before.

In our opinion, government can promote economic growth by encouraging the development of disruptive innovations. Depending entirely on high-tech startups to develop disruptive innovations and introduce them to market—waiting for small technology firms to mature into, or merge with, larger firms, thereby transforming industries from the bottom up—is a strategy that is both slow and uncertain. Our research suggests that large firms increasingly also have a need for external partners to help them overcome internal, as well as external, barriers to the development of disruptive innovations. Government programs directed at promoting high-tech innovation across the economy that are "size" neutral may be the best strategy for encouraging firms and leveraging resources in pursuit of investments in ESTD to advance the technological frontier and promote long-term growth of our nation.

Appendix: Industry Classification of Interviewed Companies

Computer Software
Prepackaged software
Multiple & miscellaneous computer and data processing services

Telecommunications
Communications services (phone, satellite, cable)
Computer networking communications equipment
Modems & other wired telephone equipment
Radio, TV, cell phone & satellite communication equipment

Electronic Component Manufacturing
Computer boards, cards and connector products
Test and measurement instruments
Semiconductors

Automotive Manufacturers
Transportation equipment

Biopharmaceuticals
Pharmaceuticals and medicines
Medical equipment and supplies

Basic Industries & Materials
Beverage and tobacco products
Textiles, apparel, and leather
Wood products
Paper, printing and support activities
Petroleum and coal products
Plastics and rubber products
Nonmetallic mineral products
Primary metals
Fabricated metal products
Furniture and related products
Mining, extraction, and support activities
Utilities
Construction
Transportation and warehousing

Machinery & Electrical Equipment
Machinery
Electrical equipment, appliances, and components

Chemicals
Basic and other chemicals
Resin, synthetic rubber, fibers, and filament

Note: "Scientific R&D Services" was distributed proportionally across the above classifications.

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ABOUT THE ADVANCED TECHNOLOGY PROGRAM

The Advanced Technology Program (ATP) is a partnership between government and private industry to conduct high-risk research to develop enabling technologies that promise significant commercial payoffs and widespread benefits for the economy. ATP provides a mechanism for industry to extend its technological reach and push the envelope beyond what it otherwise would attempt.

Promising future technologies are the domain of ATP:

- Enabling technologies that are essential to the development of future new and substantially improved projects, processes, and services across diverse application areas;
- Technologies for which there are challenging technical issues standing in the way of success;
- Technologies whose development often involves complex "systems" problems requiring a collaborative effort by multiple organizations;
- Technologies which will go undeveloped and/or proceed too slowly to be competitive in global markets without ATP.

ATP funds technical research, but it does not fund product development—that is the domain of the company partners. ATP is industry driven, and that keeps it grounded in real-world needs. For-profit companies conceive, propose, co-fund, and execute all of the projects cost-shared by ATP.

Smaller firms working on single-company projects pay a minimum of all the indirect costs associated with the project. Large, "Fortune 500" companies participating as a single company pay at least 60% of total project costs. Joint ventures pay at least half of total project costs. Single-company projects can last up to three years; joint ventures can last as long as five years. Companies of all sizes participate in ATP-funded projects. To date, more than half of ATP awards have gone to individual small businesses or to joint ventures led by a small business.

Each project has specific goals, funding allocations, and completion dates established at the outset. Projects are monitored and can be terminated for cause before completion. All projects are selected in rigorous competitions which use peer review to identify those that score highest against technical and economic criteria.

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