



Between Invention and Innovation

An Analysis of Funding for Early-Stage
Technology Development

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Branscomb was appointed by President Johnson to the President's Science Advisory Committee (1964-1968) and by President Reagan to the National Productivity Advisory Committee. He is a member of the National Academy of Engineering, the National Academy of Sciences, the Institute of Medicine and the National Academy of Public Administration. He is a director of the AAAS and a director of the National Research Council. He is a former president of the American Physical Society and a former president of Sigma Xi.

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Abstract

The purpose of the Between Invention and Innovation project is to support informed design of public policies regarding technology entrepreneurship and the transition from invention to innovation by providing a better understanding of the sources of investments into early-stage technology development projects. National investment into the conversion of inventions into radically new goods and services, although small in absolute terms when compared to total industrial R&D, significantly affects long-term economic growth by converting the nation's portfolio of science and engineering knowledge into innovations generating new markets and industries. Understanding early-stage technology development is important because a national and global capacity to sustain long-term economic growth is important.

The project has sought to answer two sets of questions:

- What is the distribution of funding for early-stage technology development across different institutional categories? How do government programs compare with private sources in terms of magnitude?
- What kinds of difficulties do firms face when attempting to find funding for early-stage, high-risk R&D projects? To what extent are such difficulties due to structural barriers or market failures?

We have pursued two approaches in parallel to arrive at a reasonable estimate of the national investment in early-stage technology development: first, learning from the observations of practitioners in the context of a series of workshops held in the U.S., and second, collecting the data available on early-stage technology development investments from other studies and from public statistical sources. These approaches have been supplemented by four case studies conducted by a team of Harvard researchers and a set of forty-six in-depth interviews of corporate technology managers, CEOs, and venture capitalists conducted on our behalf and with our direction by Booz Allen & Hamilton.

We found that most funding for technology development in the phase between invention and innovation comes from individual private-equity “angel” investors, corporations, and the federal government—not venture capitalists. Our findings support the view that markets for allocating risk capital to early-stage technology ventures are not efficient. Despite (or in response to) market inefficiencies, many institutional arrangements have developed for funding early-stage technology development. This suggests that funding mechanisms evolve to match the incentives and motivations of entrepreneurs and investors alike.

We also found that the conditions for success in science-based, high-tech innovation are strongly concentrated in a few geographical regions and industrial sectors, indicating the importance in this process of innovator-investor proximity and networks of supporting people and institutions. Among corporations, the fraction of R&D spending that is dedicated to early-stage technology development varies both among firms and within industries. The latter variation may be related to industry life cycles. Overall, we found that the federal role in early-stage technology development is far more significant than would be suggested by an uncritical glance at aggregate R&D statistics. Federal technology development funds complement, rather than substitute for, private funds. Decisions made today regarding the nature and magnitude of federal support for early-stage technology development are likely to have an impact far into the future.

Acknowledgments

We are particularly grateful to the members of the advisory committee, as listed at the opening of this report, and to participants in the three Between Invention and Innovation workshops, as listed in Annex III. The collective observations and perspectives of these individuals comprise the most valuable content in this report. We owe special thanks to Ronald Cooper, Paul Reynolds, Hans Severiens, and Jeffrey Sohl for consultations regarding the difficult task of estimating investments by “angel” investors into early-stage technology development. We additionally thank Cooper for providing us with unpublished data relevant to our study. Ambuj Sagar contributed to the report via numerous discussions throughout the process as well as through the writing of the brief company narratives presented in Annex II. Teresa Lawson of Lawson Associates Editorial Consulting ably edited the entire report (including company narratives) and the separately published case studies. Stephen Feinson assisted with workshop organization and project administration.

We would also like to thank Darin Boville, the original contracting officer, formerly of the Advanced Technology Program, for his insights and guidance at the initial stages of the project. Connie Chang, Senior Economist at ATP and the contracting officer for the project, ably managed the work to its conclusion. We benefited from additional comments by reviewers at ATP, including Anya Frieman (Economist), John Hewes (Information Coordinator), Omid Omidvar (Program Manager), and Stephanie Shipp (Director of the Economic Assessment Office.)

Executive Summary

MOTIVATION

Technological innovation is critical to long-term economic growth. Most technological innovation consists of incremental change in existing industries. As the pace of technical advance quickens and product cycles compress, established corporations have strong incentives to seek opportunities for such incremental technological change. However, incremental technical change alone is not adequate to ensure sustained growth and economic security. Sustained growth can occur only with the continuous introduction of truly new goods and services—radical technological innovations that disrupt markets and create new industries.

The capacity to turn science-based inventions into commercially viable innovations is critical to radical technological innovation. As economist Martin Weitzman has noted, “the ultimate limits to growth may lie not as much in our ability to generate new ideas,

Definition of terms:

We use “invention” as shorthand for a commercially promising product or service idea, based on new science or technology that is protectable (though not necessarily by patents or copyrights). By “innovation,” we mean the successful entry of a new science or technology-based product into a particular market. By early-stage technology development (ESTD), 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. Because innovations must be new or novel, we restrict the definition of ESTD in the corporate context to products or processes that lie outside a firm’s core business interests. The technical goal of ESTD is to reduce the needed technology to practice, defining a production process with predictable product costs and relating the resultant product specifications to a defined market.

so much as in our ability to process an abundance of potentially new seed ideas into usable forms” (1998: 333). Understanding the invention-to-innovation transition is essential in the formulation of both public policies and private business strategies designed to convert the nation’s research assets more efficiently into economic assets.

OBJECTIVES

The purpose of the Between Invention and Innovation project is to support informed design of public policies regarding technology entrepreneurship and the transition from invention to innovation by providing better understanding of the sources of investments into early-stage technology development (ESTD) projects.

Most of the federal investment into R&D supports basic scientific research carried out in university-affiliated research laboratories. While such investment may lead to science-based inventions and other new product ideas, it is primarily intended to support basic research with potential to generate fundamental advances in knowledge. In contrast, most venture capital and corporate investment into R&D exploits science-based inventions that have already been translated into new products and services, with specifications and costs matching well-defined market opportunities.

The basic science and technology research enterprise of the U.S.—sources of funding, performing institutions, researcher incentives and motivations—is reasonably well understood by academics and policy makers alike. Similarly, corporate motivations, governance, finance, strategy, and competitive advantage have been much studied and are relatively well understood. But the process by which a technical idea of possible commercial value is converted into one or more commercially successful products—the transition from invention to innovation—is highly complex, poorly documented, and little studied. This project aims for a better understanding of this important transition, by seeking the answers to two sets of questions:

- What is the distribution of funding for early-stage technology development (ESTD) across different institutional categories? How do government programs compare with private sources in terms of magnitude?
- What kinds of difficulties do firms face when attempting to find funding for early-stage, high-risk R&D projects? To what extent are such difficulties due to structural barriers or market failures?

APPROACH

We have pursued two approaches in parallel to arrive at a reasonable estimate of the national investment in early-stage technology development: first, learning from the observations of practitioners in the context of a series of workshops held in the U.S., and second, collecting the data available on early-stage technology development investments from other studies and from public statistical sources. These approaches were supplemented by four case studies conducted by a team of Harvard researchers and by a set of thirty-nine in-depth interviews of corporate technology managers, CEOs, and venture capitalists conducted on our behalf by Booz Allen Hamilton.

Participating practitioners in the workshops included venture capitalists; angel investors; corporate technology managers; university technology licensing officers; technologists; entrepreneurs; representatives from the Advanced Technology Program (ATP) and the Small Business Innovation Research (SBIR) program; representatives from federal agencies and private firms engaged in gathering and organizing data on private-sector R&D investments, such as the National Science Foundation, the Census Bureau, and the National Venture Capital Association; and scholars who specialize in the study of technological innovation and entrepreneurship.

The four case studies examined in detail the experiences of selected workshop participants in managing the invention-to-innovation transition.

The thirty-one companies interviewed by Booz Allen Hamilton represent a cross-section of large and mid-size firms from among the 500 U.S. firms with the highest R&D expenditures. Distributed between eight industry sectors—electronics, biopharmaceutical, automotive, telecommunications, computer software, basic industries & materials, machinery & electrical equipment, and chemicals—these companies jointly fund approximately 7% of all U.S. corporate R&D spending. An additional eight interviews were with representatives from leading venture capital firms.

FINDINGS

A. SOURCES OF MOST FUNDING

Most funding for technology development in the phase between invention and innovation comes from individual private equity “angel” investors, corporations, and the federal government — not venture capitalists.

Of \$266 billion that was spent on national R&D by various sources in the U.S. in 1998—the most recent year for which comprehensive and reliable data were available at the time of the research, and probably a more reliable benchmark of innovation funding activities than 2000, when markets were at their historic peaks—roughly 14 percent flowed into early-stage technology development activities. The exact figure is elusive, because public financial reporting is not required for these investments. Our method of arriving at a reliable estimate was to create two models based on different definitions of early-stage technology development—one very restrictive (that is, biased toward a low estimate) and the other quite inclusive (that is, biased toward a high estimate). With this approach we conclude that between \$5 billion (2 percent) and \$37 billion (14 percent) of overall R&D spending in 1998 was devoted to early-stage technology development. The remaining R&D funding supported either basic research or incremental development of existing products and processes.

Although the range between our lower and upper estimates differs by several billion dollars, the proportional distribution across the main sources of funding for early-stage technology development activities is surprisingly similar whether we employ models that are restrictive or inclusive. Given either model, expenditures on early-stage technology development by angel investors, the federal government, and large corporations funding out-of-the-core business technology development are comparable in magnitude (see Figure 1 on page 23.) Early-stage technology development funds from each of these sources greatly exceed those from state programs, university expenditures, and the small part of venture capital that supports early-stage technology projects. Notably—even excluding as we do the impact of government procurement—the federal role in this process is substantial: in our estimates roughly 30 percent of the total early-stage technology development comes from federal R&D sources.

As noted earlier, investments by corporations in advancing established product and process technologies to better serve existing markets comprise a dominant source of national R&D spending. But, as the Booz Allen Hamilton research team found during this project, corporate technology entrepreneurs who create an innovative idea lying outside their firms' core competence and interest face risks and financial challenges similar to those faced by the CEOs of newly created firms. While corporations will indeed spend lavishly on technological innovations that support their core businesses, they are systematically disinclined to support technological innovations that challenge existing lines of business, require a fundamental shift of business model, or depend on the creation of new complementary infrastructure.

Venture capital firms are critical financial intermediaries supporting new high-growth firms. Why, then, is the role of the venture capital industry in funding early-stage

technology development not dominant? Popular press accounts notwithstanding, venture capital firms are not in the R&D business. Rather, they are in the financial business. Their fiduciary responsibility is to earn maximum returns for their investors. They do this through a complex set of activities that can be summarized as buying firms low and selling them high. Venture capitalists do indeed back high-growth new ventures, and in many cases, though not the majority, they support firms that are bringing radical new technologies to market. However, even when venture capitalists do support technology-based enterprises, they prefer to support ones that have at least proceeded beyond the product development stage—that is, firms that have completed the early-stage technology development that is the focus of this study. As the median size of venture capital deals has increased and the pressure to provide attractive returns to investors in mammoth funds has intensified, venture capital has tended increasingly to flow to projects in later stages of development and to already-proven technologies. For all these reasons, trends in venture capital disbursements should not be confused with trends in the funding of early-stage technology development.

B. INEFFICIENCY OF MARKETS

Markets for allocating risk capital to early stage technology ventures are not efficient.

Entrepreneurs report a dearth of sources of funding for technology projects that no longer count as basic research but are not yet far enough along to form the basis for a business plan—a scarcity Dr. Mary Good, former Undersecretary of Commerce for Technology, has termed an innovation gap. At the same time, venture capital firms and other investors are sitting on record volumes of resources not yet invested, with over \$70 billion currently undisbursed from funds raised during the boom years. In 2002, several premier venture capital firms have taken the unusual step of prematurely returning money to investors to reduce the size of particularly large funds.

We should not be surprised that technology entrepreneurs experience an apparent shortage of funding while large sums in venture funds remain undisbursed. Whether efficient markets exist on Wall Street may be an open question. However, *efficient markets do not exist for allocating risk capital to early-stage technology ventures*. One often-cited reason for such inefficiency concerns fundamental limits on the ability of investors in early-stage technology ventures to fully appropriate returns from their investments. We focus on a second reason: serious inadequacies in information available to both entrepreneurs and investors. Early-stage development involves not only high quantifiable risks, but also daunting uncertainties. When the uncertainties are primarily technical, investors are ill equipped to quantify them. For new technologies that have the potential to create new product categories, market uncertainties are also high

and similarly difficult to quantify. The due diligence that investors in venture capital funds require of managing partners and that angel investors require of themselves is intrinsically difficult—and getting more so as both technologies and markets become increasingly complex.

Up to a decade is required for the transition from invention to innovation. Given technical and market uncertainties, venture capitalists, angels, and bankers prefer to wait to see the business case for a new technology rather than funding speculation. The technical content of the business proposal must be sufficiently well established to provide reliable estimates of product cost, performance, and reliability in the context of an identified market that can be entered in a reasonable length of time. It is the funding of this technical bridge—from invention to innovation—that is the focus of this study and is the basis for the notion of an innovation gap.

Do government agencies that fund R&D provide the support required to bridge this gap? As noted above, most such agencies fund broad-based basic research aimed at increasing the stock of publicly available knowledge. Thus, the technology entrepreneur who finds it difficult to obtain early-stage funding from venture capital firms may also find it difficult to obtain funding from federal agencies to support the resolution of technical issues required to define and justify a business case.

C. INSTITUTIONAL ARRANGEMENTS FOR FUNDING

Despite (or in response to) market inefficiencies, many institutional arrangements have developed for funding early-stage technology development. This suggests that funding mechanisms evolve to match the incentives and motivations of entrepreneur and investors alike.

Champions of early-stage technology projects make use of a wide variety of funding options to keep their projects alive. These include not only successive rounds of equity offerings, but also contract work, income from licensing patents, the sale of spin-off firms, and old-fashioned cost-cutting. While each of these options is associated with its own costs and benefits, entrepreneurs do not play favorites among them when it comes to keeping their projects moving forward.

In contrast to institutional sources of equity and debt capital for advancing existing businesses incrementally, the transition from invention to innovation is financed by a great variety of mechanisms, with new ones being created every day, including angel networks and funds, angel investments backed by bank debt, university and corporate equity investments, seed investments by university and

corporate venture capital programs, and certain experimental R&D programs run by federal and state agencies.

A report from the National Commission on Entrepreneurship notes that “the substantial amount of funding provided through informal channels, orders of magnitude greater than provided by formal venture capital investments and heretofore unknown and unappreciated, suggests some mechanisms for filling the gap may have developed without recognition” (Zacharakis *et al.* 1999: 33).¹ Yet, the proliferation of institutional types is as much an indication of the particular informational challenges and structural disjunctures that define the innovation gap as it is one of a resolution to the challenge.

D. CONDITIONS FOR SUCCESS

Conditions for success in science-based, high-tech innovation are strongly concentrated in a few geographical regions, indicating the importance in the process of innovator-investor proximity and networks of supporting people and institutions.

If early-stage technology development investments from all sources are distributed as non-uniformly as venture capital investments, then they are concentrated in a few states and a few industries. This would be expected, for our research results suggest that angel investments are even more locally focused than venture capital. Furthermore, theory suggests that the quality of social capital in the locality where inventions are being exploited is an important determinant of success. Where the social capital is strongly supportive, in places like Route 128 in Boston or Silicon Valley near San Francisco, one might expect not only strong venture capital and angel investments, but a concentration of federal support for early-stage technology development and industry-supported high-tech ventures as well.

While the scope of this research project has not generally focused on funding patterns at the regional and industry sector level, some important trends are apparent (Part II below offers a highly aggregated presentation of early-stage technology development funding flows at the national level).

Geographic Distribution. The geographical distribution of early-stage technology development activity mirrors that of innovation-related activity in general. In particular, early-stage technology development is concentrated in geographical regions that invest heavily in R&D, that possess developed risk-capital networks and related

1. Full text available at <<http://www.ncoe.org/research/RE-018.pdf>>.

complementary infrastructure (such as specialized law firms and other suppliers), and that otherwise benefit from strong university-industry linkages.

Angel Investors. We found that angel investors provide the most significant source of early-stage technology development funding for individual technology entrepreneurs and small technology startups. Since angel investors make the vast majority of their investments close to home, early-stage technology development activities, particularly those of smaller firms, are likely to be concentrated in regions with active communities of tech-savvy angels.

Role of State Governments. State governments, while providing a relatively small portion of total early-stage technology development funding, play a critical role in establishing regional environments that help bridge the gap from invention to innovation. State governments facilitate university-industry partnerships, leverage federal academic research funds by providing both general and targeted grants, build a technically educated workforce through support of public colleges and universities, and ease regulatory burdens to create a more fertile ground for technology startups. While Route 128 and Silicon Valley arose with little local- or state-level political support (in part because they had developed the needed networks, stimulated by defense funding, in the 1950s), a number of states have created many of the environmental features needed for successful innovation. Research Triangle Park in North Carolina, for example, was conceived and initiated by Governor Luther Hodges.

These geographical concentrations create additional challenges to champions of early-stage technology development projects located outside of favored geographical or market spaces. Such challenges may be of considerable importance to public policy. The implications for public policy will depend heavily on whether the federal government attempts to compensate for such tendencies toward concentration, or chooses instead to accept them as reflecting the flow of resources to geographical and market areas in which expected economic returns are highest. In subsequent work, we will further explore the causes and implications of inter-regional and inter-industry differences in funding for early-stage technology development projects.

E. CORPORATE R&D SPENDING

Among corporations, the fraction of R&D spending that is dedicated to early-stage development varies both among firms and within industries. The latter variation may be related to industry lifecycles.

Support levels for ESTD vary widely by industry, and by company within specific industries. The Booz Allen Hamilton team estimated (by extrapolation from reports

from interviewed firms) overall corporate spending on early-stage technology development to be approximately \$13 billion annually, or 9 percent of total corporate R&D spending. Spending was found to differ widely by industry, as well as by company within specific industries. For example, ESTD investments in the computer software industry is essentially zero, while for the biopharmaceutical industry, the rate is 13 percent. Software companies use existing technical tools to help expand functionality. These are not technical innovations, strictly speaking: even in the midst of the massive Internet boom (according to respondents in the Booz Allen Hamilton survey), few true technical innovations emerged out of the computer services sector. Indeed not all of the investments Booz Allen Hamilton reported in other industries are based on new science, nor are all of them outside of core business areas. Within the biopharmaceutical industry, ESTD spending ranged from 0 percent to 30 percent of R&D at the companies interviewed.

A key driver of ESTD support levels appears to be life-cycle position of the industry and the individual company. More mature industries, such as the automotive sector, tend to invest a smaller percentage of R&D into earlier stages such as ESTD than do industries at an earlier stage of evolution, such as biotechnology.

However, individual companies may make disproportionate investments in early-stage R&D compared to their peers in an attempt to break out of their existing positioning or to rejuvenate their innovation resource base. Several companies interviewed by Booz Allen Hamilton described how they reached a deliberate decision to rebalance their investments toward ESTD and earlier stages 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 making a temporary movement backwards out of a product development focus and into a strategy emphasizing basic and ESTD research.

The distinction we draw between the speculative research most firms pursue to advance the performance of existing products and research on high-risk new technologies that lie outside the firm's core business area (ESTD) is admittedly not a crisp one. It is much easier to identify ESTD investments by governments at state and federal levels, and to recognize university forays into new business ventures based on faculty research. In those cases the motivation of the investor is unambiguous. However, for public policy reasons, it is critically important to quantify the modest fraction of corporate R&D that is invested in new business areas outside the core. Some research does suggest that radical innovations are most likely to be successfully launched by new ventures

formed with the specific objective of new product development, as opposed to large corporations. Yet in absolute terms the assets of established firms—their financial resources, skill and market experience—are substantially greater than those of other major sources of ESTD funding. Consequently, policies to encourage ESTD may be most effective when directed in part to encouraging successful out-of-core innovations by established firms.

CONCLUSION

As investors stampeded first into, then out of the public market for equity in technology-based firms, the assertion that U.S. economic growth is led by entrepreneurial, venture capital-backed firms became almost an article of faith among politicians, pundits, policy makers, and the general public. The number and diversity of institutions specialized in supporting the commercial development and marketing of new technologies have expanded dramatically—a trend unlikely to reverse itself.

Funds available to high-growth technology ventures appear at first glance to have grown accordingly. In particular, the overall growth in the size of the venture capital industry during the past decade suggests to many observers of the U.S. innovation system that private funding is available for high-technology projects. Yet, even in an environment where large sums committed to venture capital funds remain undisbursed, practitioners report that the process of translating a basic science invention into a commercially viable innovation is extremely difficult and getting more so.

The economic and technological factors driving this trend are not new. Markets, technologies, and their interrelation are becoming increasingly complex, further complicating the challenge of converting inventions into innovations. The rapid advance of the scientific frontier and the increasing breadth and depth of knowledge available across all scientific fields have contributed to the acceleration of technological complexity. Today, even the large corporations with the largest R&D budgets have difficulty putting together all the elements required for in-house development and commercialization of science-based technologies.

A core finding of this project is that the federal role in early-stage technology development is far more significant than may be suggested by aggregate R&D statistics. In general, we find that federal technology development funds complement, rather than substitute for, private funds.

National investment into the conversion of inventions into radically new goods and services, although small in absolute terms when compared to total industrial R&D, significantly affects long-term economic growth by converting the nation's portfolio of science and engineering knowledge into innovations generating new markets and industries. Understanding development of technologies in the phase between invention and innovation is important because a national and global capacity to sustain long-term economic growth is important. Decisions made today regarding the nature and magnitude of federal support for early-stage technology development are likely to have an impact far into the future.

Introduction: Motivation and Approach

The ultimate limits to growth may lie not as much in our ability to generate new ideas, so much as in our ability to process an abundance of potentially new seed ideas into usable forms.

—Martin L. Weitzman (1998: p. 333)

1. MOTIVATION

In the field of economics, fewer relationships are more broadly supported by both theory and empirical evidence than the relationship between technological innovation and long-term growth.² Yet prior to the mid-1980s, economists undertook little detailed study of the process by which ideas are transformed into new goods and services, or how new industries and sectors of economic activity arise.³ As Nobel Laureate Kenneth Arrow observed in 1988: “Innovations, almost by definition, are one of the least analyzed parts of economics, in spite of the verifiable fact that they have contributed more to per capita economic growth than any other factor” (Arrow 1988: p. 281). Similarly, public policies aimed at enhancing science and technology-based economic growth were based on the assumption that leadership in basic science and military R&D would automatically and indefinitely translate into broad economic benefit.⁴

2. Lively debates do exist over the effects of specific innovations on human and environmental welfare, but the central role of technological innovation as a driver of conventionally measured (GDP) growth is undisputed. Jones and Williams (1998) provide a survey of both models and evidence.

3. Important exceptions include Griliches (1963, 1979), Arrow (1962), Shell (1966, 1967), and Nelson and Phelps (1966).

4. Alic *et al.* (1992).

Strong political support for funding of basic research allowed U.S. research universities to achieve international pre-eminence and supported the establishment and growth of the National Institutes of Health (NIH) and the National Science Foundation (NSF).

During the 1980s, however, this linear model of innovation with its associated *laissez-faire* policy implications came into question. Japanese firms successfully challenged formerly dominant U.S. companies in a range of high-tech industries. Industry in the United States was widely perceived to have failed to give high enough priority to manufacturing efficiency and consumer satisfaction.⁵ Leading U.S. technology companies were embarrassed by widely publicized failures of commercial development of market-transforming technologies invented in their own research laboratories.⁶ At the same time, the “new growth” or “endogenous growth” theories associated with Romer (1986, 1990), Grossman and Helpman (1991), and Aghion and Howitt (1993) refocused economists’ attention on the manner in which micro-economic incentives affect the transformation of ideas into long-term growth. Work by Young (1991) and Lucas (1993) in particular emphasized that, although incremental technical change accounts for most observed increases in productivity, sustained long-term growth requires the continuous introduction of new goods and services. For this reason, national investment into the conversion of inventions into radically new goods and services, although small in absolute terms when compared to total industrial R&D, significantly affects long-term economic growth by converting the nation’s portfolio of science and engineering knowledge into innovations generating new markets and industries.

In the 1990s, the U.S. economy experienced a remarkable resurgence driven by dramatic gains in industrial productivity. Scholars have produced a solid body of knowledge about innovation systems;⁷ economic behavior in the face of technological risk, uncertainty, and incomplete information;⁸ and social capital, regional agglomeration, and industry clustering.⁹ We now know that the early development of a novel technology depends on academic science, which generates the ideas that drive the innovation process;¹⁰ on the magnitude and geographical localization of knowledge spillovers;¹¹ and on the social returns from investments in R&D, including those made by the federal

5. Dertouzos, Lester and Solow (1989).

6. See, for instance, the Smith and Alexander (1988).

7. See Nelson (1993), Branscomb and Keller (1998), and Branscomb, Kodama, and Florida (1999).

8. See Aghion and Tirole (1994), Dixit and Pindyck (1994), Zeckhauser (1996), and Branscomb and Auerswald (2001).

9. See Krugman (1991) Glaeser *et al.* (1992), Branscomb (1996), Gaspar and Glaeser (1997), Fountain (1998), Glaeser *et al.* (2000).

10. See Rosenberg and Nelson (1994), Henderson, Jaffe and Trajtenberg (1998), Jensen and Thursby (1998), and Branscomb, Kodama, and Florida (1999).

11. See Jaffe *et al.* (1993), Feldman (1995), and Fogarty and Sinha (1999).

government.¹² The roles played by large corporations, new firms (in particular, those backed by private-equity financing), research and development alliances, and partnerships of various types, and federal and state governments have been described.¹³

As investors stampeded first into, then out of, the public market for equity in technology-based “new economy” firms, the assertion that U.S. economic growth is led by entrepreneurial, venture capital-backed technology firms became almost an article of faith among politicians, pundits, policy makers, and the general public. The volume of traffic along the path from Palo Alto’s Sand Hill Road¹⁴ to Wall Street came increasingly to represent not merely an indicator of the vibrancy of a single economic sector, but a scorecard for the economy as a whole. The number and diversity of institutions specializing in supporting the commercial development and marketing of new technologies have expanded dramatically, in a manner unlikely to be reversed. These include venture capital firms, corporate venture funds, incubators of various types, niche law firms, university and government offices of technology transfer, and networks of individual private-equity angel investors.¹⁵

Funds available to high-growth technology ventures appear at first glance to have grown accordingly. In particular, the overall growth in venture capital suggests to many observers of the U.S. innovation system that private funding is available for high-technology projects. Indeed, at present, by some measures, the supply of such funds seems to exceed the demand. Venture capital funds disbursed to firms reached a peak of over \$100 billion in the year 2000, before dropping off to \$37 billion in 2001. As of February 2002, the magnitude of commitments from the limited partners that invest in venture capital funds (such as pension funds, banks, endowments, and wealthy individuals) exceeded industry-wide disbursements by a total of \$75 billion—more than the cumulative total of venture capital investments from 1990 to 1998.

Yet, even in such an environment, practitioners report that the process of translating a basic science invention into a commercially viable innovation is extremely difficult and getting more so.¹⁶ The economic and technological factors driving this trend are not new. Four years ago, then Undersecretary of Commerce Mary Good testified before the Senate Committee on Governmental Affairs: “As the competitive pressures of the global marketplace have forced American firms to shift more of their R&D into shorter

12. See Mansfield *et al.* (1977), Griliches (1992), Jones and Williams (1998), Borras and Stowsky (1998).

13. See Acs and Audretsch (1988), Alic *et al.* (1992), Scherer (1999), Bidhé (2000), and Kortum and Lerner (2000).

14. Located in Palo Alto, Sand Hill Road is the Wall Street of the venture capital industry in Silicon Valley.

15. The term “angel investor” comes from the theater—see also Part I, section 3C, of this work. [please note: all this material also appears verbatim later in the text.]

16. See also Preston (1993, 1997), Chertow (2001), Hall (2002), and the Introduction to the February 2002 report from the Secretary of Commerce, “The Advanced Technology Program: Reform with a Purpose.”

term product and process improvements, an ‘innovation gap’ has developed.... Sit down with a group of venture capitalists. The funding for higher risk ventures ... is extraordinarily difficult to come by.”¹⁷ Entrepreneurs in many settings consistently report difficulty in raising funds in the range of \$200,000 to \$2 million.¹⁸ The current environment was summed up by Bill Joy of Sun Microsystems, who observed in July 2001, “A couple of years ago, even the bad ideas were getting capital. Now we have gone too far in the opposite direction, shutting down investment in good ideas.”¹⁹

Markets, technologies, and their interrelation are becoming increasingly complex, further complicating the challenge of converting inventions into innovations. The rapid advance of the scientific frontier and the increasing breadth and depth of knowledge available across all scientific fields have contributed to the acceleration of technological complexity. Today, even the largest corporations and the most deep-pocketed venture capital firms have difficulty putting together all the elements required for in-house development and commercialization of truly novel science-based technologies.

2. PROJECT OBJECTIVES

Investments in basic and applied research support the development of both science-based inventions and entrepreneurial talent, the dual prerequisites for commercial innovation. The purpose of this study is to provide comprehensive analysis of investments into early-stage, high-technology ventures to support informed design of public policies regarding invention, technology entrepreneurship, and innovation.

The focus of the project is on early-stage technology development—the difficult transition from (science-based) *invention* to (commercial) *innovation*. We use the term “early-stage technology development” (with the abbreviation ESTD) to describe the technical and business activities required to develop a nascent technology into a clearly defined product or service whose specifications and business plan are matched to a particular market. ESTD and invention-to-innovation transition are equivalent in our usage. The premise of the project is that some degree of quantification of the

17. Cited in Gompers and Lerner (2000, p. 2). These authors quite accurately point out an apparent contradiction in the quote from Dr. Good, which appears in its edited form to suggest that venture capitalists are reluctant to provide risk capital. Of course, this is not the case. As Gompers and Lerner describe, the venture capital mode of finance is precisely that which is specialized in providing finance in contexts where uncertainty is high and information asymmetries severe. At the same time, however, as Morgenthaler (2000) and other venture capitalists report, the risk/reward ratio for seed-stage technology-based ventures is not as attractive to venture capital firms as it is for ventures at a slightly later stage. We develop this argument further below.

18. The hypothesis of such a capital gap in seed-stage funding for new ventures is discussed by Sohl (1999), and consistently corroborated by practitioners (see, for instance, comments by participants at a Senate Small Business Committee Forum, <www.senate.gov/~sbc/hearings/internet.html>).

19. *BusinessWeek*, July 2001.

magnitude and distribution of investments in early-stage technology development is a prerequisite to determining the appropriate role of government in supporting science-based innovation and technology entrepreneurship.

As noted above, many technology entrepreneurs, investors, and policy makers have noted what is called a funding gap that faces science-based, new enterprises seeking seed-stage funding. On an anecdotal level, assertions of the existence of a funding gap have been remarkably persistent.²⁰ How can we directly test the validity of these assertions? A series of rigorous studies at the level of the U.S. economy have consistently estimated that social returns to research and development investments substantially exceed private returns.²¹ Unfortunately, because such studies characteristically lump into undifferentiated R&D all basic research expenditures together with all phases of investment in technology development, they neither support nor refute the notion of a funding gap between a basic science breakthrough and the development technological prototype linked to a market. The existence of a funding gap, in the textbook economics sense of a shortfall from a social optimum, would be extremely difficult to establish empirically; to do so would require at minimum not only reliable data on both the demand and supply for ESTD funding in particular (as opposed to all R&D expenditures), but also computation of project-level marginal social benefits of such funding.

In a similar vein, boilerplate statements regarding the existence of market failure in the context of ESTD have little content without elaboration regarding specifics. As argued first by Arrow (1962), market failures—rigorously defined—abound in the market for new ideas and technological information. Generically, perfect competition may fail to achieve optimal resource allocation whenever products are indivisible (marginal cost pricing rules apply imperfectly), economic actors are unable to appropriate the full returns from their activities (social and private benefits diverge), and/or outcomes are uncertain (future states of nature are unknown). Clearly, all three of these attributes characterize basic research as well as ESTD projects. Of the three, it is instructive to note that the discussion in Arrow (1962) begins not with inadequate incentives to innovate due to imperfect appropriability, but rather with contracting problems due to uncertainty. In particular, Arrow points out that the activity of invention has particular characteristics that complicate the ability of economic actors to relieve themselves of risks due to uncertainty. Arrow notes that success in “highly risky business activities, including invention” depends on “an inextricable tangle of objective uncertainties and

20. See, for example, accounts from participants at a 2001 Senate Small Business Committee Forum, <www.senate.gov/~sbc/hearings/internet.html>. The phenomenon is not restricted to the United States. The U.K. Department of Trade and Industry published a report in 1999 titled “Addressing the SME [small and medium-size enterprises] Equity Gap.”

21. See Mansfield *et al.* (1977), Griliches (1992), and Jones and Williams (1998)

decisions of the entrepreneurs and is certainly uninsurable. On the other hand, such activities should be undertaken if the expected return exceeds the market rate of return, no matter what the variance is. The existence of common stocks would seem to solve the allocation problem... But then again the actual managers no longer receive the full reward of their decisions; the shifting of risks is again accompanied by a weakening of incentives to efficiency."²²

Elaborating upon Arrow (1962) and Zeckhauser (1996), we observe that every high-technology innovation, by its nature, calls for specialized technical knowledge; and every radical innovation that expects to create a market that does not yet exist, can only be evaluated by someone with experience in new market creation in that segment of the business world. Talent at this level to assess both technologies and markets is scarce. Furthermore, the value of a technical idea close to commercial application depreciates rapidly. Consequently, as Zeckhauser (1996) argues, technological information (TI) is not, as is widely assumed in the economics literature, a public good. Indeed, "excessive focus" on the public good character of technological information has led economists "to slight the major class of market failures associated with TI that stems from its amorphous quality."²³

From the standpoint of data, our objective thus is not to test directly the hypothesis of a funding gap. Rather, more modestly, our objective is to estimate the sources of funding for early-stage technology development. In this sense we seek not to offer conclusive results regarding the *appropriate* distribution of input, but instead to suggest some underlying parameters and definitions to set the context for debate over public policy and for future academic research.

We begin by articulating a set of definitions of the ESTD process that are focused on the technology project (driven by a specific champion and team). We then employ these definitions to develop useful qualitative and quantitative comparisons of ESTD

22. Hellman (1998) describes the manner in which control rights in venture capital contracts mitigate the sorts of risks described by Arrow (1962).

23. To emphasize this point, Zeckhauser offers the following illustration: "A thought experiment might task what would happen if information remained a public good, but were susceptible to contract. Fortunately, there are public goods that offer relatively easy contracting, such as songs or novels, which offer an interesting contrast with information. Such goods appear to be well-supplied to the market, with easy entry by skilled low-cost songwriters and novelists." Zeckhauser identifies five distinguishing characteristics of technical information that complicate contracting:

- Technical information is difficult to count and value.
- To value technical information, it may be necessary to "give away the secret."
- To prove its value, technical information is often bundled into complete products (for instance, a computer chip or pharmaceutical product).
- Sellers' superior knowledge about technical information makes buyers wary of overpaying.
- Inefficient contracts are often designed to secure rents from technical information (1996, 12746).

projects and investments across institutional settings, including new firms, corporations, universities, and government labs.

Investments by government, corporations, institutions, and individuals in basic and applied research support the development of both science-based inventions and entrepreneurial talent, the prerequisites for commercial innovation. Corporate and venture capital investors are effective in exploiting scientific and technological advances when such advances are embodied in new products and services whose specifications and costs match well-defined market opportunities. However, this conversion of inventions into commercial innovations is a process fraught with obstacles and risks. Despite the apparent abundance of funds available for the marketing of readily commercializable technologies, many technologists, investors, and public- and private-sector decision makers argue that significant institutional and behavioral barriers continue to impede technology development after invention.

A huge amount of academic research effort has been dedicated to understanding the U.S. research and invention enterprise, which includes non-profit universities, government laboratories, and those companies that engage in the more basic end of the research spectrum.²⁴ At the other end of the innovation spectrum, a considerable amount of effort (most of it centered in business schools) has been dedicated to understanding how businesses are managed once they have a core set of products and are incrementally innovating. Considerably less effort has been devoted to understanding what goes on between the point at which research has defined an economic opportunity and the later stage when a champion can make the business case that the opportunity will be a predictable source of revenue. This is our focus. More specifically, our inquiry is organized around two sets of questions:

- What kinds of difficulties do firms face when attempting to find funding for early-stage, high-risk R&D projects? To what extent are such difficulties due to structural barriers or market failures? These questions are examined in Part I.
- What is the distribution of funding for ESTD from different institutional categories? How do government programs compare with private sources, in terms of magnitude? How does distribution of funding for early-stage technology-based innovations vary across industries, and by geographical region? These questions are addressed in Part II.

24. Leading contributors to this literature include Harvey Brooks, Wesley Cohen, Michael Darby, Paul David, Maryann Feldman, Christopher Freeman, David Mowery, Richard Nelson, Keith Pavitt, Nathan Rosenberg, Donald Stokes, and Lynne Zucker.

We emphasize the inputs into the innovation process, rather than outputs or outcomes. From a public policy perspective, inputs are only interesting to the extent that they relate to socially desired outcomes. However, before one can begin to discuss the relationship of inputs to outcomes, one must first arrive at a coherent picture of the process, the institutional participants, and the basic definitions that allow for comparison of roles and contributions.

3. APPROACH

We pursued two approaches in parallel: first, learning from the observations of practitioners in the context of a series of workshops held in the U.S., and second, collecting the largely fragmentary data available on ESTD investments from other studies and from public statistical sources. These studies were supplemented by four case studies and a set of thirty-nine interviews of corporate technology managers, CEOs and venture capitalists conducted by Booz Allen Hamilton.

A. WORKSHOPS

Two practitioner workshops were held: at the Carnegie Endowment for International Peace in Washington, D.C., on January 25, 2001; and at the Xerox Palo Alto Research Center (PARC) in Palo Alto, California, on February 2, 2001. An analytic workshop was held at the Kennedy School of Government (Cambridge, Massachusetts) on May 2, 2001. The workshops brought together representatives from the following groups (see Annex III for a workshop agendas and biographies of participants):

- venture capitalists and angel investors;
- corporate technology managers;
- university technology licensing officers;
- technologists;
- entrepreneurs;
- representatives from the Advanced Technology Program (ATP) of the National Institute for Standards and Technology and the Small Business Innovation Research programs (SBIR);
- representatives from both federal agencies and private firms engaged in gathering and organizing data on private-sector R&D investments, including the National

Science Foundation (NSF), the Census Bureau, and the National Venture Capital Association (NVCA); and

- academics specializing in the study of technological innovation and entrepreneurship.

The workshops were particularly helpful in two ways: refining our operational definition of the invention-to-innovation transition, and providing guidance in the interpretations of and, where necessary, extrapolations from the available data. Participants in the practitioner workshops included past ATP awardees; participants in the International Business Forum (IBF) Early-Stage Investing Conference;²⁵ firms and individuals nominated by leading angel investors and venture capitalists engaged in seed-stage funding of technology-based firms; firms and individuals affiliated with the MIT Entrepreneurship Center; and the investigators' personal contacts. The three workshops are the source of all direct quotations in the document, unless otherwise noted.

The two practitioner workshops included methodological, data, and case-based panel discussions. Participants in the methodological and data panels were asked to describe the organizational and institutional context underlying their publicly reported figures on R&D investments. Of particular interest were panelists' estimates of the distribution of firm expenditures at each stage of the innovation process. The case-based panel discussions focused on two technology areas: amorphous silicon technology and bioinformatics. Each of the case-based panels traced the history of the development of the technology, highlighting the role of different funding sources at each stage and the particular challenges encountered. The separately published case studies on Caliper Technologies and GE Medical Devices further explore the process of early-stage technology development in the context of these two technology areas.

B. MODELS FOR INTERPRETING THE DATA

Our analysis is based upon examination of both published and unpublished data sources, and on insights from extensive conversations with survey managers, industry analysts, and practitioners. Our purpose is to achieve a new perspective on the level of funding that is applied to ESTD. We focus on the six most important sources of funding for ESTD identified in Part I: corporate, venture capital, angels, federal government, state governments, and universities. Beginning with an aggregate figure for support of scientific and technological innovation from each funding source, we develop a rationale for more realistic estimates of the fraction of funding flows to research and development that are directed into ESTD.

25. See <www.ibf.com>.

Given the lack of rigor in the definitions used in much of the available data and its fragmentary character, we present our findings in the form of two models. One model takes a very restricted view of what constitutes ESTD, so that the inferences based on this model are almost certainly lower than the most realistic value. The second model takes a more expansive view, using source data that almost certainly overestimate investments in ESTD. Both models are defined by a set of assumptions that are in some cases subjective, but are based on the insights of informed practitioners. It must be recognized, however, that a more accurate model might represent different choices, some from the model based on less restrictive definitions and others from the model based on more restrictive definitions. Our intent here is to create plausible upper and lower estimates for ESTD funding.

The results from the use of these two models are summarized in Table 1 in Part II (page 62 of this report). Table 1 is then used to calculate the relative magnitude of ESTD expenditures from the different sources considered. This method does not allow the precise determination of a best or most probable estimate. Furthermore, the range between the upper and lower range estimates is very large—a factor of six in the total ESTD flows. However, by combining those percentages from the two models, we see that the relative importance of different sources of investment is similar. This finding is more relevant for supporting some of the public policy conclusions that we seek. As Figure 1 indicates, the distribution of ESTD funding is relatively independent of the model used.

The observation year for this study is 1998, except as noted in a couple of cases. Due to reporting lags inherent in most large-scale surveys, we have relied upon 1998 as the most recent year for which comprehensive and reliable data are available. While the selection of this observation year was motivated chiefly by the absence of more recent data, it is also a sensible choice for other reasons. Given the size of market fluctuations affecting the technology sector from 1999 through 2001, 1998 is a more reliable benchmark of innovation funding activities than 2000, when markets were at their historic peaks.²⁶

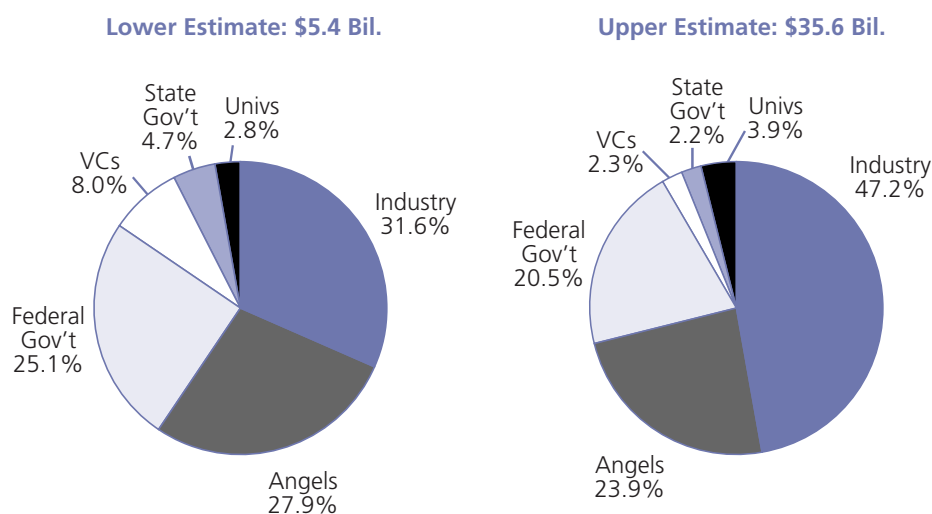
C. ASSUMPTIONS AND LIMITATIONS

Limitations inherent in the data and the magnitude of the extrapolations and subtractions we carry out demand that our findings be interpreted with caution.

Our results are in the form of two sets of estimates, based on the upper and lower models and on assumptions that are broadly consistent with the full range of data sources available to us. The funding range we present for each category is large, but

26. Illustratively, venture capital funds disbursed to firms reached a peak of over \$100 billion in the year 2000, before dropping off to \$37 billion in 2001. In 1998 (our reference year) total venture capital disbursements were \$17 billion.

FIGURE 1. Estimated distribution of funding sources for early-stage technology development, based on restrictive and inclusive criteria



Note: The proportional distribution across the main funding sources for early-stage technology development is similar regardless of the use of restrictive or inclusive definitional criteria.

as a first approximation, these initial estimates provide valuable insight into the overall scale and composition of ESTD funding patterns and allow at least a preliminary comparison of the relative level of federal, state, and private investments.

To build our lower estimates, we applied a narrowly defined lens to develop a conservative estimate of innovation activities in different institutional settings. Our aim was to develop a baseline minimum amount of funding that sets a reasonable and defensible floor for estimated total ESTD funding in the United States.

To derive our upper estimates, we attributed basic and applied research funding more generously to ESTD. These allocation estimates varied by institutional setting and were significantly informed by conversations with practitioners and analysts in the field. We deliberately aimed to choose allocations that were as large as reasonable in order to determine an upper limit on the nation's potential ESTD funding.

We have made extensive use of large-scale R&D surveys conducted by the National Science Foundation (NSF). These survey results rely heavily on respondents'

judgement for such crucial items as the classification of R&D projects across industries, geography, and institutional settings. NSF surveys provide the best data of its kind and scope, but because they were not crafted specifically to help track activities in the invention-to-innovation divide, our interpolations of ESTD funding flows from this data depend on our analysis of these survey results and our best guesses—informed by the perspectives of both practitioners and the data-gatherers—as to how categorizations of ESTD activities into basic research, applied research, and development categories vary across institutional settings. These are described in Part II.

Time series data would be helpful in tracking trends in funding flows and identifying relationships with business cycles, but the scope of the present study provides only a point estimate for the given observation year. Some insights into trends over time that developed during the course of this project are presented later in this report. Regional and sectoral concentrations of resources are largely ignored in Table 1, though the importance of these patterns is well recognized.

4. PROJECT OUTPUTS

The project delivers the following products:

- the core report from the project team (this document);
- an independently researched and authored report from Booz Allen Hamilton; and
- a set of four case studies, separately published.

The core report contains an executive summary, this chapter on motivation and approach, and two additional chapters—the first (Part I) summarizing qualitative findings, drawing upon the insights offered at the practitioner workshops, and the second (Part II) presenting the methods behind our analysis of funding for ESTD from different institutional categories. The core report also includes several Annexes:

- Annex I is a summary of independent research on corporate support for ESTD performed by Booz Allen & Hamilton on behalf of the project's principal investigators;
- Annex II provides a set of detailed company narratives (distinct from the case studies mentioned above) expanding the discussions at the workshops;
- Annex III includes the agendas for the three workshops and participant biographies.

The case studies and the full report from Booz Allen Hamilton are available as publications of the Advanced Technology Program which can be found on the program's website: <<http://www.atp.nist.gov>>.

5. TEAM

A team of researchers at the Belfer Center for International Affairs, Kennedy School of Government, Harvard University carried out the project, which was funded by the Advanced Technology Program of the U.S. Department of Commerce. Professor Lewis Branscomb (Aetna Professor of Public Policy and Corporate Management, emeritus, Kennedy School of Government, Harvard University) and Dr. Philip Auerswald (Deputy Director of the Science, Technology and Public Policy Program and Adjunct Lecturer, Kennedy School of Government, Harvard University) led the project team. Brian Min contributed substantially to the research and writing of Part II of the report. Independent research on corporate support for ESTD was carried out in support of this project by a team at Booz Allen Hamilton (BAH) 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.). A memorandum summarizing the BAH finding is attached as Annex I. Dr. Mona Ashiya, Robert Kolasky, Thomas Livesey, and Jonathan Westrup authored supporting case studies of technology projects and institutional innovations; these are published separately from this report. Livesey additionally contributed research support.

Understanding Early-Stage Technology Development

There are thus two parts to the explanation of the role of technology in Western economic growth. First, Western basic science created explanations of nature that possessed unprecedented potentialities for practical application.... Second, the West bridged the traditional gap between science and the economic sphere and translated scientific explanations into economic growth.

— Nathan Rosenberg and L.E. Birdzell, Jr. (1985: 243)

1. THE ECONOMIC NATURE AND VALUE OF TECHNOLOGY-BASED INNOVATIONS

A. TOWARD A PROJECT-LEVEL DEFINITION OF TECHNOLOGY-BASED INNOVATION

A natural starting point for a study of early-stage technology-based innovation is to seek coherent, consistent definitions of the terms “innovation,” “early stage,” and “technology based.” Let us begin with *innovation*. “Technological innovation is the successful implementation (in commerce or management) of a technical idea new to the institution creating it.”²⁷

27. Branscomb (2001). Traditionally, management innovations were considered a different meaning of the word “innovation” from a new product in the market, but in recent years with the patenting of business models and the importance of dot-com businesses, in which a novel business model creates value, the distinction is beginning to fade. For this study, however, we focus on innovations based on novel scientific or engineering ideas.

A commercial innovation is the result of the application of technical, market, or business-model ingenuity to create a new or improved product, process, or service that is successfully introduced into the market.²⁸ An *invention* is distinguished from an innovation by its character as pure knowledge. The direct products of a technological invention are not goods or services *per se*, but the recipes used to create the goods and services. These new recipes may ultimately be embodied narrowly in patents, or more broadly in new firms or business units within existing firms; they may eventually (and in some cases, immediately) be associated with products (through a successful innovation). However, the essence of technology-based *innovation* (as distinct from both market-based innovation and routine technology-based product development) is the systematic and successful use of science to create new forms of economic activity. Technology-based innovation thus represents a subset of all innovation, but it is an important one, for it has the potential to create entire new industries.²⁹

The theoretical distinction between technology-based innovation and incremental product enhancement is based on the extent of novelty in the science or technology being used in the product, where technical risk is greater than market risk.³⁰ Of course the most radical technology-based innovations are often accompanied by unique capabilities that allow new markets to be created, thus introducing high levels of both market and technical risks.

Technology-based innovations are also common to certain business models. Thus a company that defines its business by specializing in a specific area of technology, which it then brings to many markets, will expect to introduce many technology-based innovations.³¹ A company that defines itself by its market or its products will be less able to specialize in an area of science or engineering and is less likely to produce radical, technology-based innovations on its own (as an example, consider Microsoft).

Firms whose business strategy is based on incremental extensions of their technologies are only marginally engaged in technology-based innovation. Participants at the project workshops in Palo Alto and Washington, D.C., offered illuminating descriptions of the manner in which their firms focus on radical technology development rather than incremental product development. Michael Knapp of Caliper Technologies

28. Alic J. et al. (1992), fn. 8, p. 43.

29. In his study of national systems of innovation, Richard Nelson suggests that the element of novelty required for an innovation should be assessed at the level of the firm: "The processes by which firms master and get into practice product designs and manufacturing processes that are new to them" comprise an innovation. The key point is that an invention is only a potential innovation, and to become one must be successfully introduced into the market.

30. Auerswald, Kauffman, Lobo, and Shell (2000) suggest an empirical measure of technological distance linked to technological complexity.

31. Branscomb and Kodama (1993).

commented: “The business model that we have used in the first generation [of products] is to work with a bigger company that does the commercialization process while we primarily focus on the technology.... As a technology company it’s a little bit awkward to just focus on technology when people only care about the applications. So in fact, we are also working on applications, in a first generation, anyway.”³²

John Shoch of Alloy Ventures noted, “It is a very common evolution to start out with a core technology, look for an array of applications and markets in which you can deploy it, and find the one where you get the traction.”

Of her own firm, Nancy Bacon of Energy Conversion Devices stated, “ECD is basically engaged in three core businesses.... It looks like we’re in many disparate areas, but in reality, so many of them have the same core base in terms of the materials.”

B. APPLIED RESEARCH? SEED INVESTMENT? DEFINING “EARLY STAGE”

Our unit of analysis in the study of technology-based innovation is not the firm, but rather the project, which does not exist unless it has a champion.³³ In cases of innovations created within established firms, an innovative project is generally of a small scale (for instance, in terms of personnel) relative to the firm. However, in other important cases, the project or team is the link that binds a set of firms sequentially created out of a single core idea.³⁴

Because we are interested in the project, not the firm, there are problems related to the manner in which data on technology-based innovation are gathered and organized. Data on venture capital that is of particular interest in this context are broken down primarily by stage of firm development and by industry and geographical location. To get around this problem, as a first approximation, we assume that most venture-backed firms that are technology-based are built around a single project-team, and consequently that the stage of firm development reflects the stage of project development.

Venture economics defines the stages of project development as follows:

- **Seed financing** usually involves a small amount of capital provided to an inventor or entrepreneur to prove a concept. It may support product development, but rarely is used for production or marketing.

32. See also the accompanying case study on Caliper Technologies, authored by Mona Ashiya.

33. See Low and MacMillan (1988), Audretsch (1995), and Davidsson and Wiklund (2000).

34. An example is the so-called Shockley Eight: eight engineers, including Gordon Moore, who left Shockley Semiconductor and founded first Fairchild Semiconductor, then Intel and numerous other path-breaking Silicon Valley firms.

- *Startup financing* provides funds to companies for use in product development and initial marketing. This type of financing usually is provided to companies that are just getting organized or to those that have been in business just a short time, but have not yet sold their products in the marketplace. Generally, such firms have already assembled key management, prepared a business plan, and made market studies.
- *First-stage financing* provides funds to companies that have exhausted their initial capital and need funds to initiate commercial manufacturing and sales.

However, as John Taylor of the National Venture Capital Association pointed out at the D.C. workshop, using stage of funding as a proxy for stage of technology development is severely complicated by the large flows of funds in recent years to early-stage companies that had little or no real technology under development. “If you’re looking specifically at the question of R&D, or how much seed money has gone into companies that have a pure or implied R&D background, it’s very difficult to get at, because these days, stage definitions are almost meaningless. We saw in early 1999 a lot of early and seed-stage rounds in Internet-related companies, \$25, \$30 million or more ... [much of which went to] branding, which meant buying ads during Super Bowls, the national media and that kind of thing.”³⁵ This situation, of course, may have been unique to the extraordinary valuations achieved by some information technology companies in 1999 and 2000. We can expect that this particular skewing of the data will ease under the market conditions in 2001 and thereafter.

A parallel set of definitions emphasizes the stage of development of a technology, abstracted from institutional development, although any division of the innovation process into temporal stages is bound to be arbitrary and imperfect. One distinction that has often been employed by practitioners is that between “proof of principle” and “reduction to practice.”

Proof of principle means that a project team has demonstrated its ability, within a research setting, to meet a well-defined technological challenge: to show in a laboratory setting that a model of a possible commercial product, process or service can demonstrate the function that, if produced in quantity at low enough cost and high enough reliability, could meet an identified market opportunity. It involves the

35. During the late 1990s a prestigious group including Benchmark Capital, Sequoia Capital, Goldman Sachs, and CBS invested nearly \$800 million in Webvan—a single online grocery venture. Another \$430 million went to HomeGrocer, which was acquired by Webvan. Of the total investment in both companies, \$561 million was raised from venture capital firms and \$646 million from the public markets. Of the \$1 billion reportedly spent by Webvan as of February 2001, just \$54 million, or 0.5 percent, was dedicated to technology development generously defined—in this case, novel computer systems to handle orders (*New York Times*, February 19, 2001: C1).

successful application of basic scientific and engineering principles to the solution of a specific problem.³⁶

Reduction to practice means that a working model of a product has been developed in the context of well-defined and unchanging specifications, using processes not unlike those that would be required for scaled-up production. Product design and production processes can be defined that have sufficient windows for variability to validate the expectation that a reliable product can be made through a high-yield, stable process. In simple English, the technical risk has been reduced enough so that the innovator-entrepreneur can say to his managers and investors, “Yes, I can do that, and do it at a cost and on a schedule and to a market in which we can all have confidence.”

Kenneth Nussbacher of Affymetrix offered the following analysis of possible criteria for defining successful innovation: “If you have a company that’s in the process of generating databases or creating software tools, and they’re far enough along that they could enter into meaningful, paid collaborations with pharmaceutical companies, then that biotech has a product. It’s not the ultimate product; it is not the drug that they ultimately hope to discover. And in Affymetrix’s case, it wasn’t the arrays that we sell today, but we had a relationship in 1994 with Genetics Institute where they were paying us to try to apply our technology to a particular problem. That wasn’t the business model that we are pursuing today, but it’s enough of a business that you might say that we had reached the stage of innovation. The other test of innovation (which may be unique to biotech companies) is measured by the other ‘customer’ of biotech companies, the investment community. When you can find knowledgeable people who are willing to invest real money, people who are third parties to the company, you might argue that the company has reached the stage of innovation, because there’s something there that’s tangible enough for people to write meaningful checks.”³⁷

We hypothesize that seed funding corresponds to ESTD—the tasks that take an idea from proof of principle to reduction to practice.

In addition to models from venture capital and from stages of technical development, one might also attempt to relate technology-based innovations to available data using the government categories for research that are used in government data collections on R&D: basic research, applied research, and development. Unfortunately, these distinctions are based more on the motivations of the investigator than on those of the investor, and as such are of little use in our effort to track flows of invention to

36. In the life sciences, proof of principle is achieved “when a compound has shown the desired activity *in vitro* that supports a hypothesis or concept for use of compounds” (definition from Karo Bio AB <www.karobio.se>, a drug discovery company).

37. Statement at Palo Alto workshop.

innovation.³⁸ These distinctions are based on the classical linear model of R&D: scientists do research; they get great ideas; they give them to somebody who does applied research and figures out how you might make that into a technology. That somehow gets to an engineer who does the product development in the private sector. The problem is that applied research includes both original research believed to have applications and the application of existing knowledge to the solution of practical problems. The former might well represent a contribution to a radical innovation, but the latter probably does not. There is no way to apportion the government's statistical data on R&D between these two interpretations of applied research.

In Part II we confront the choices to be made in how to quantify flows of ESTD funding. None of the choices are fully satisfactory. Because the federal R&D data are not broken down into categories that reflect the purpose of the work, only widely disparate upper and lower ranges can be defined. The alternatives involve extrapolations from small samples of information derived from case studies. While the data in the cases are specific to our definition of ESTD, the extrapolations entail large uncertainties.

2. FROM INVENTION TO INNOVATION

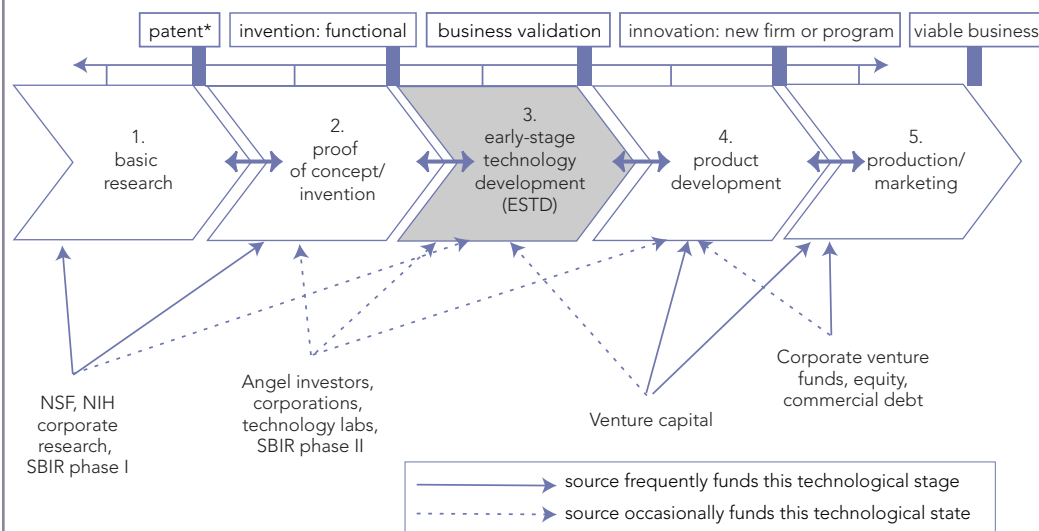
With a definitional framework in place, we can now focus our attention on the particular part of the process of greatest interest in our project: the stages between invention and innovation.

A. MODELING THE INTERVAL BETWEEN INVENTION AND INNOVATION

In this analysis, the model of the innovation process that allows us to define the early stage between invention and innovation is shown in Figure 2.³⁹ To show how the different models of the stages of technology-based innovation relate to one another, we segment the process in five stages. The first two lie within the world of basic research and prototype development, beginning with the research base on which innovative ideas rest, followed by the demonstration (proof of principle or concept) of a technical device or process believed to have unique commercial value. This is the point for which

38. By the same token, some scholars believe these distinctions are of limited value in allocating government resources for R&D. Branscomb and Keller (1998: 114).

39. The literature on technology management contains many variants on this diagram. A good example is that developed in Lane (1999).

FIGURE 2. Sequential model of development and funding**Note:**

The region corresponding to early-stage technology development is shaded in gray.

The boxes at top indicate milestones in the development of a science-based innovation.

The arrows across the top of, and in between, the five stages represented in this sequential model are intended to suggest the many complex ways in which the stages interrelate. Multiple exit options are available to technology entrepreneurs at different stages in this branching sequence of events.

*A more complete model would address the fact that patents occur throughout the process.

we are using the shorthand label “invention.” It is not always—perhaps not often—patent protected, but it does represent technical information whose value can be protected in some manner.

The beginning of the third stage is the invention that initiates the transition we are studying here. In the third stage, product specifications appropriate to an identified market are demonstrated, and production processes are reduced to practice and defined, allowing estimates of product cost. This is the point at which a business case can be validated and might begin to attract levels of capital sufficient to permit initial production and marketing—the activities at the start of stage 4. At the end of stage 4, the product has been introduced in the marketplace and an innovation has

taken place. In stage 5, investors can expect to see the beginning of returns on their investments.

Note that our phrase “Early-stage Technology Development” is intended to correspond to stage 3. We see the phase invention and innovation as corresponding to ESTD and thus to stage 3. But since the definition of an innovation requires successful entry to market, the phrase “invention to innovation” should embrace, strictly speaking, both stages 3 and 4 as they appear in Figure 2.⁴⁰ However, our concept of the critical gap between the established institutions of R&D and those of business and finance really concerns only stage 3. There is no generally agreed term for the point between stages 3 and 4 except “reduction to practice,” which refers only to the technical activities in stage 3, and “seed and startup finance,” which are concepts specific to venture capital, which is only one of the potential sources of funding for traversing stage 3. In our analysis of capital flows, we attempt to focus on only phase 3, the gap between invention and a validated business case.

Reporting on their interviews with corporate technology managers and venture capitalists, the team from Booz Allen Hamilton emphasized the importance of interpreting the framework presented in Figure 2 as a sequence of idealized stages potentially linked in complex ways: “Most interviewees generally agreed with the classification of R&D into the four steps in the innovation framework used in our discussions (Basic, Concept/Invention, ESTD, Product Development). However, there were many reactions to the linear simplicity of the framework, compared to the typical path from invention to commercial innovation that the participants have experienced. The four-step framework represents an idealized view of technology progression, while the actual pathway included multiple parallel streams, iterative loops through the stages, and linkages to developments outside the core of any single company.” At the Cambridge workshop, Mark Myers of Wharton and formerly of Xerox Corporation emphasized that the manner in which technology managers employ patent protection is significantly more nuanced than suggested by Figure 2: “Patents do not occur just at the front end of this process; they occur throughout.” Colin Blaydon of Dartmouth College further commented that the top line in Figure 2 does not capture the full range of exit options available to managers of technology projects in the early stage, the “different alternatives and branches of where projects go, and what happens to them.”

40. In the text, when we are not attempting to be precise in characterizing flows of funding, we use the phrase “invention to innovation” somewhat loosely, simply because there is no accepted name for stage 3, for which we are using the admittedly awkward acronym ESTD.

B. THREE ELEMENTS OF STAGE 3

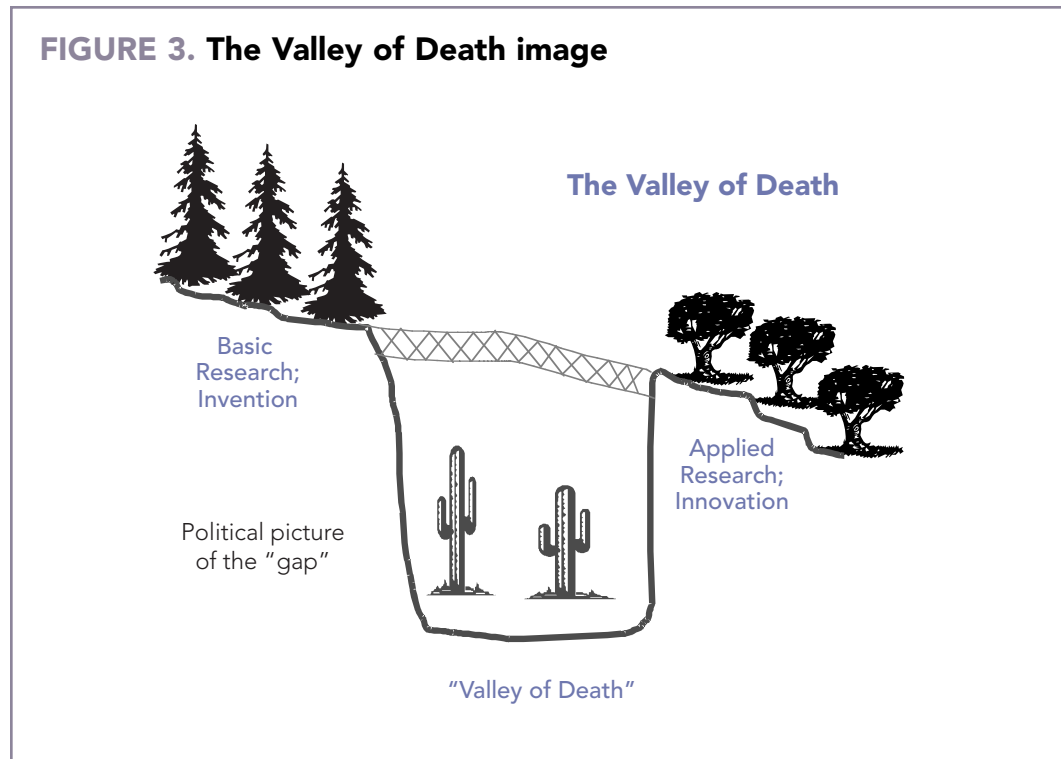
The specific region of the innovation space in which we are most interested is bounded at the earliest stage with the verification of a commercial concept through laboratory work, through the identification of what looks like an appropriate market, and perhaps the creation of protectable intellectual property. Congressman Vern Ehlers, among others, uses the term “Valley of Death” to dramatize the particular challenges facing entrepreneurs engaged in the transition from invention to innovation (see Figure 3.) This term suggests the capital gap affecting early-stage innovation: champions of early-stage projects must overcome a shortfall of resources. At the Palo Alto workshop, Gerald Adolph (Booz Allen Hamilton) provided an elaboration:

I would define [the] Valley of Death [as occurring] when the amount of money you’re starting to ask for—the bill—starts to add up to the point where management says, ‘What are you guys up to, what are you doing, and what am I going to get out of it?’ But yet it is sufficiently early in the process that you don’t feel you can answer that question. If you are fortunate enough that the questions come when you have an answer, you, in fact, have scooted over the Valley. If not, you are squarely in that Valley.

The imagery of the Valley of Death appears in the schematic drawn by Congressman Ehlers in Figure 3.⁴¹ Death Valley suggests a barren territory. In reality, however, between the stable shores of the science and technology enterprise and the business and finance enterprise is a sea of life and death of business and technical ideas, of big fish and little fish contending, with survival going to the creative, the agile, the persistent. Thus, instead of Valley of Death, we suggest that the appropriate image is that of the Darwinian Sea (Figure 4). In Branscomb and Auerswald (2001) and the “Managing Technical Risk” report to ATP (Branscomb and Morse 2000), we identified the three challenges of the Darwinian Sea” in the following terms:

Motivation for research: Initially an innovator demonstrates *to his or her own satisfaction* that a given scientific or technical breakthrough could form the basis for a commercial product (proof of principle). However, a substantial amount of difficult and potentially costly research (sometimes requiring many years) will be needed before the envisioned product is transformed into a commercial reality with sufficient

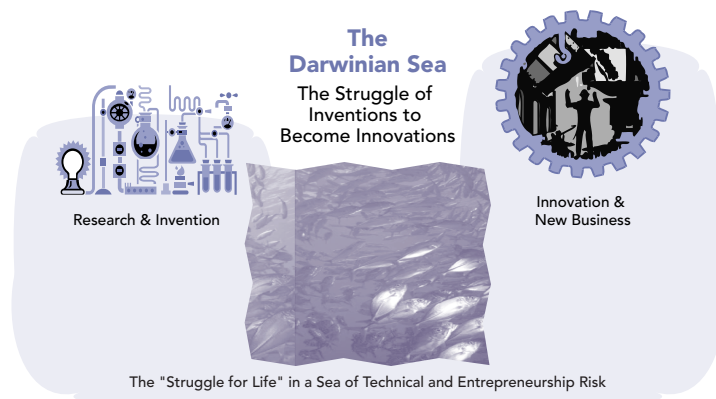
41. Ehlers (2000).

FIGURE 3. The Valley of Death image

function, low enough cost, high enough quality, and sufficient market appeal to survive competition in the marketplace. Few scientists engaged in academic research (or the agencies funding their work) have the necessary incentives or motivation to undertake this phase of the reduction-to-practice research.

Disjuncture between technologist and business manager: On each side of the Darwinian Sea stands a quite different archetypal character: the technologist on one side, and the investor/manager on the other. Each has different training, expectations, information sources, and modes of expression. The technologist knows what is scientifically interesting, what is technically feasible, and what is fundamentally novel in the proposed approach. In the event of failure, the technologist risks a loss of reputation, as well as foregone pecuniary returns. The technologist is deeply invested in a vision of what could be. The investor/manager knows about the process of bringing new products to market, but may have to trust the technologist when it comes to technical particulars of the project in question. What the investor/manager is generally putting at risk is other people's money. The investor is deeply invested in producing a profitable return on investment, independent of the technology or market through which it is realized. The less the technologist and investor/manager trust one another the less

FIGURE 4. An alternative metaphor for the invention-to-innovation transition: the Darwinian Sea



they can communicate effectively, the deeper is the Darwinian Sea between invention and innovation.⁴²

Sources of financing: Research funds are available (typically from corporate research, government agencies or, more rarely, personal assets) to support the creation of the idea and the initial demonstration that it works. Investment funds can be found to turn an idea into a market-ready prototype, supported by a validated business case, for the project. In between, however, there are typically few sources of funding available to aspiring innovators seeking to bridge this break in funding sources. They include angel investors (wealthy individuals, often personally experienced in creating new companies or developing new products); established firms making equity investments in high-tech startups to get a look at emergent technologies; venture capital firms specialized in early-stage or seed investments; military or other public

42. At the Washington, D.C. workshop, Arden Bement, who has since become Director of the National Institute of Standards and Technology, cautioned that the hypothesized disjuncture between technologists and management may underestimate the extent to which management is involved very early in the technology development process: "[T]he simple model that was posed where one end of the Valley of Death is more or less dominated by technologists and the other end is sort of dominated by management, is probably not accurate in all contexts. There's a much more disciplined process where management gets involved right up front and is part of the process all the way through, which may help projects across the Valley of Death." In Branscomb and Morse (2000), medium-sized firms were identified as institutions where there might be a higher likelihood of such an integration of technical and financial entrepreneurship, making those firms particularly interesting sources of technical innovations.

procurement; state or federal government programs specifically designed for the purpose; and university funding from public or private sources.

A consensus existed among Palo Alto and Washington, D.C. workshop participants that the severely constrained resources in the Darwinian Sea include not only cash but also—equally important—time, information, and people. Noteworthy shortages include information concerning the technological *and* market prospects of target projects, and people capable of evaluating and validating that information. Washington, D.C. workshop participant John Alic (a consultant on technology policy) suggested, “Our focus should be not on money, but on the technical resources—on individuals, small groups, technical professionals” involved in supporting early-stage ventures. Jeff Sohl of the University of New Hampshire emphasized the difficult matching problem faced by angel investors in high-quality projects: “Investors ... indicate that they have capital. What they lack is, and the adjective is very important, *quality* deal flow. They can find plenty of laundromats and dry cleaners, but they can’t find quality deal flow. So, this funding gap is not really a funding gap anymore. It is more of an information gap.”⁴³

We conclude that despite the large amounts of capital looking for lucrative private-equity investments, the ability to place the money is limited by the ability to match the needs of the technical entrepreneur and business investor. From the perspective of the would-be innovator, this situation will look like a funding gap.

C. INFRASTRUCTURE REQUIREMENTS AND COMPLEMENTARY ASSETS

Another critical obstacle facing champions of most radical innovations in the process of getting from invention to innovation is the absence of necessary infrastructure.⁴⁴ By infrastructure we mean not only the large scale infrastructure required for final products in the marketplace (such as gas stations for internal combustion automobiles, or software to run on a new operating system), but also all of the complementary assets that may be required for market acceptance—suppliers of new kinds of components or materials, new forms of distribution and service, training in the use of the new technology, auxiliary products and software to broaden market scope.⁴⁵ Another example of a

43. We emphasize, however, that both the Palo Alto and Washington, DC, workshops were held in early 2001, before levels of venture disbursements fell off sharply, which may have contributed to the feeling at the time that an information gap was particularly problematic.

44. Gerald Adolph of Booz Allen Hamilton commented, “The whole notion of how that infrastructure needed to develop and get worked out was, in fact, the majority of what we spent our time worrying about” [with clients seeking to bring radical innovations to market] (statement at Palo Alto workshop).

45. Teece (1987).

complementary asset is availability of critical equipment, either for research or pilot production.

Richard Carlson and Richard Spitzer noted the lack (or prohibitive cost) of the machinery with which to build the innovation as obstacles. At the Washington, D.C. workshop, Richard Carlson stated that BP Solar found it necessary to develop its own equipment, which increased the time and cost of development. At the Palo Alto workshop, Richard Spitzer of Integrated Magneto-electronics noted that he found that borrowing and sharing equipment is very time consuming and not adequate for functional prototypes:

In some cases the requirement for infrastructure [sets] a prohibitive market entry barrier. For example, an auto powered by fuel cells burning hydrogen gas would have to have a network of stations able to fuel the cars. In this special case the innovation may require government action in order to proceed on a timely basis.

D. VALUE CAPTURE

Even where a technology has demonstrated promise to create value for consumers, the question remains: how much of that value will the innovative firm be able to capture? As Gerald Adolph (see Text Box 1 below) and Arden Bement indicated at the practitioner workshops, motivating support for a technology-based innovation means not only demonstrating value creation, but also the potential for value capture.

Understanding the mechanism by which value will not only be created, but captured, is a necessary component of the business system that allows an invention to become a successful commercial innovation:

At the Palo Alto workshop, Gerald Adolph commented:

We argue that value isn't created until you get a business system [model] along with the invention. The business system is the mechanism by which value is delivered to someone and captured by someone ... focusing on the business system allows you to be more articulate to those who are asking for funding about the business implications, the success implications, the competitive implications, without requiring answers to the other questions that perhaps no one can answer at those early stages—as in, exactly how big will it be? How much will I charge for it? How much money will I make?

In order to execute the given strategy for value capture, the firm in question must have the internal capabilities and other resources necessary to leverage its first-mover

Text Box 1. The challenge of value capture

Gerald Adolph (Booz Allen Hamilton): "There's a certain uneasiness that comes with being in this 'valley [of death]' for a business person. The uneasiness goes beyond doubts of whether you can be successful technically, and it even goes beyond the question of whether or not you can create value.... [It relates to] whether or not you are going to *capture* any value.... Faster technology development cycles are making it even tougher to [capture value], but it actually is, in our view, an old problem. The sources of leakage of value capture [are] competitive offerings, or consumers or other users who are just unwilling or unable to pay. Any of you who have come up with brilliant innovations and then had to market it to the automotive companies certainly ran into that to the fore. Or, there are just structural reasons why it's hard to capture value. If I come up with an innovation in carpets and it prevents the carpet from staining and I call it Stain Master, I can collect value because there's only one step between me, the fiber maker, and the retail chain. It's a carpet company, and they tend not to have particularly strong brands. On the other hand, when I try to put that in apparel, when I look at the nature of the chain, there are three and four and five people in between me and the person who ultimately cares about that claim. So, simply by observation, I know that I'm going to have a more difficult value capture problem." (Statement at Palo Alto workshop)

advantage into longer—term market success. At the Washington, D.C. workshop, Arden Bement argued that there is a market control gap; the real concern is whether, having entered the marketplace, one has all the technologies or intellectual properties in place to have staying power.

At every stage, firms weigh opportunities for value creation and value capture against risks and anticipated costs. As Arden Bement observed:

Value is really a ratio of opportunity over risk. And the way you enhance the opportunity is either [to] increase the value through partnering or leveraging your core competency, as Nancy Bacon pointed out, or reduce the risk by going through the risk waterfall that Bruce [Griffing of GE] brought up. So, it's really paying attention to both opportunity and risk, but trying to enhance the ratio of opportunity.

As illustrated by the case of amorphous silicon at GE (one of the separately published case studies) a large corporation will develop a given technology platform first in markets where, all things being equal, mechanisms for value capture are better established and production costs are lower., Bruce Griffing described GE's view of consumer electronics at the Washington, D.C. workshop:

It was a commodity business. It would not be a high-margin business going forward, and that's one of the reasons we didn't pull amorphous silicon along that particular direction. But the aerospace business needed very high performance displays, relatively low volumes. The capital investment required to produce that kind of a factory was not as great.

Thus, in addition to all the disjunctures between inventor and investor, there is a daunting set of external obstacles to realizing a successful venture. These difficulties may be viewed differently by the various parties.

3. FUNDING INSTITUTIONS AND THEIR ROLES

A tremendous variety of institutions intersect and overlap to define the landscape traversed by a technology-based innovation project. In the report to ATP of the “Managing Technical Risk” project (Branscomb *et al.*, 2000), the co-investigators for this project reviewed in detail the interdependent institutions involved in bringing radical technology-based products to market. In this section we highlight some features of the institutional landscape that are particularly relevant to the interpretation of data. As our emphasis is on private, rather than public, support for ESTD, we focus on the roles of corporations, venture capital firms, and angel investors; only briefly do we discuss ESTD support from universities, states, and the federal government.⁴⁶

To systematically sort through the output of science for ideas that have the potential to be converted into products that either support the core business or (in rare but important cases) define new lines of business, we begin with corporations—the original centers for technology-based innovation. We then briefly describe and compare the roles of venture capitalists and angels involved in buying parts of new firms, using their expertise and contact networks to enhance the firms' values, and then seeking to sell their interest in the firms (in most cases either to another firm or the public markets). Referring to material covered in Branscomb and Auerswald (2001) and the report of the “Managing Technical Risk” project (Branscomb and Morse 2000), we then note some key features of the complex roles of universities in producing the talent on which both new technology enterprises and corporations depend. This generates many of the scientific and technical breakthroughs that are the basis for commercial innovations; and, increasingly, directly supporting new firm formation through technology licenses, university-affiliated incubators and direct investment. Finally, referring again to the

46. The university and government roles in the invention-to-innovation transition have been the subject of considerable prior research, which we do not attempt to summarize in this report. See, for example, Branscomb and Kodama (1998), Branscomb and Auerswald (2001: Chapter 5) and references therein for further discussion.

“Managing Technical Risk” report, we note the equally complex role of the federal and state governments. Both bodies are integrally involved in defining the environment for business through regulation and enforcement of intellectual property rights. Government also provides a significant share of the demand for high-technology goods through procurement. Additionally, government directly supports the innovation process through grants and contracts to both scientific and engineering research⁴⁷ as well as project-level support of early-stage commercial technology development.⁴⁸

A. CORPORATIONS

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.” The first corporate laboratories were engaged in “testing, measuring, analyzing and quantifying processes and products already in place.” 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.”⁴⁹

The golden age of corporate research laboratories occurred in the 1970s, a time when the Bell Telephone Laboratories set the standard. Bell Labs’ management goals were far-sighted; they focused on attracting the most able researchers and gave them a great deal of latitude.⁵⁰ The Laboratories’ scientific achievements, recognized by several Nobel prizes, brought the company great prestige. However Bell Labs was not often in a position to commercialize its out-of-core inventions. Other firms sought to imitate Bell with commitments to basic science, making a serious effort to incubate within the firm ideas that the product line divisions could commercialize. Few firms survived long in this mode. This 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.

47. Importantly, the National Institutes of Health (NIH), National Science Foundation (NSF), Department of Energy (DOE), and Department of Defense (DOD).

48. Importantly, the Advanced Technology Program (ATP) and Small Business Innovation Research (SBIR) program.

49. Addressing the earliest cases of the transition between invention and innovation, Rosenberg and Birdzell write: “After 1880, industry was moving toward a closer synchronism with pure science, if we may judge by the fact that the intervals were growing shorter between scientific discovery and commercial application. Faraday discovered electromagnetic inductance in 1831, but it was a half-century before transformers and motors became significant commercial products.... By comparison, Marconi developed an apparatus for using Hertz’s waves commercially nine years after Hertz discovered them. Roentgen’s X-rays were in medical use within even less time, partly because apparatus development from Roentgen to medical offices was more straightforward.” Rosenberg and Birdzell, p. 250, emphasis added.

50. To some extent this strategy was made possible by the fact that the costs of Bell Laboratories formed part of the investment base on which AT&T’s regulated monopoly telephone service prices were based. Few other firms had this luxury.

At the Washington, D.C. workshop, David Carlson of BP Solar described the “great environment”: “But boy, did they have trouble getting products out of that lab that were not core, in part of what they called a core business... Most of them never saw the light of day in terms of commercialization.”

In the 1980s a more mature and sophisticated form of technical management in industry focused on core business interests and expected the corporate laboratory to create commercializable technologies. As they became more sophisticated in the 1980s, 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.⁵¹

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. By the 1990s, firms began to out-source 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. By the late 1990s, some larger firms were creating their own venture investment funds to observe and selectively capture this innovative potential from outside the company.

Internal corporate innovations (inside vs. outside the core business)

Recent real increases in U.S. national R&D have all come from industry. During the 1990s, industrially funded R&D doubled, while federal R&D has been relatively flat in total. Industry investments (including those by venture capital backed companies, but dominated by large corporations) continue to be the source of most of the resources converting basic science breakthroughs into commercializable products. However, these have increasingly been focused on near-term product development.⁵² These 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 Intel has been so successful is that we have tried to eliminate unnecessary 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). Any region

51. See, for example, description of Xerox innovation system by Hartmann and Myers (2001).

52. Porter and vanOstals (2000: 39).

without larger companies at the technology frontier or research organizations of large companies will probably have fewer companies starting or spinning off.”⁵³

Within nearly all large technology-based corporations, formal processes exist for assessing the commercial prospects of early-stage technology projects.⁵⁴ Such processes are effective in boosting near-term profitability based largely on continual evolutionary improvements to core products. The downside of such processes is, however, that they tend to suppress projects involving high magnitudes of technical risks, departures from the core business, or both.

As Bruce Griffing of General Electric noted at the Washington, D.C. workshop of large firms’ central labs:

What we do is develop great evolutionary products that don’t have a lot of technical risk. Most of the development that goes on in a company like GE is of that character. Revolutionary products require taking substantial technical risks, and that’s basically the job of a lot of the people we have at the R&D center—to pursue those things that are difficult, frankly, to do in the environment that we’re in.... Even in big companies that have a lot of resources, there is this valley [of death] that you talk about. And it’s not always easy to overcome, and there are a lot of projects where this doesn’t happen.

Excubating innovations: outsourcing innovations through contracts and partnerships

Developing better relationships with suppliers in the corporate supply chain and with joint venture partners is increasingly important, as corporations seek to distribute risks and benefits from increasing returns to scale and scope in research efforts. As noted in McGroddy (2001), with the telling title “Raising Mice in the Elephant’s Cage,” looking outside the firm for partners to commercialize an innovation (“excubating”) is an increasingly common way of compensating for the limitations of technical scope in the firm and reducing the institutional constraints on creating new, out-of-core products.

At the Washington, D.C. workshop, Nancy Bacon of Energy Conversion Devices observed that partnerships can also address problems arising from limits on technical expertise and resources through joint ventures: “As a small organization there’s no way that we can go ahead and set up both the manufacturing and the marketing [for some big projects]. But when we deal with the larger batteries for electric and hybrid vehicles, we’re working mostly with regard to joint venture relationships.”

53. Moore and Davis (2000).

54. See Branscomb and Auerswald (2001: Chapter 3) and Chistensen (1997).

Text Box 2. The corporate bias toward incremental innovation within the core business

Raman Muralidharan (Booz Allen Hamilton): “What corporate R&D management processes do is actually further this bias of driving more investment towards products where the commercial case is stronger. People are trying to design products which can push more money earlier into the process. But the very nature of a corporation as a commercial entity limits that. So the key question which I would pose if I were trying to get a corporation to fund early-stage research requires developing a way to frame the problem at hand in commercial terms. What’s required for a corporation to fund early-stage research? It’s saying, have a top level view of how the technology can create commercial value. If a project has high technical risk, generally, people will invest in it only if the pay-off is large if successful. Is it relevant? Is it related to the core business of the corporation, or is it an investment, a selected area for growth? What are some of the options for value capture? Will value capture require different, significant changes in the chain? Who is going to champion the project? And who is going to take on the role of the executive sponsor, which is very equivalent to that of a VC? And then, some process discipline: What are the next milestones? You don’t have to spell out how you’ll progress through the entire product development process, but what milestones should be met for the next branch of funding, and what’s it going to take in terms of resources to get there?” (Statement at Washington D.C. workshop)

At the same workshop, Raman Muralidharan of Booz Allen Hamilton noted, “Corporations typically invest in [early-stage technology development] through external alliances. A lot of the funding which goes into such alliances is outside the corporation. I think there are a couple of fundamental reasons for doing this. One is ... more reach for less money. You can build awareness of new technical developments which will affect your business and offer you an opportunity to grow without needing to fund them entirely within the corporation.... The second benefit is that typically the trade-off of keeping something proprietary and in-house versus outsourcing or joint venturing is in favor of growing the state of knowledge.”

Corporate venture capital

A particular form of looking outside the firm for commercializing a new product idea is the creation of a new firm to exploit an idea that is generated inside the firm but which lies outside the core business. Some firms may cooperate with an inventor in the firm who desires to leave and start his or her own business. In other cases firms undertake to do this with corporate funds, perhaps engaging a venture capital firm like Amper-sand in Boston that specializes in creating spin-off businesses from large firms.

Text Box 3. Outsource R&D

Ron Conway (Panasonic Ventures): "What Panasonic is doing is what I call outsource R&D, and they're using a kind of three-pronged approach to do this, a corporate venture fund, an incubator, and what they call a global network—a way of developing strategic partnerships within Panasonic and Matsushita, the parent company... We try and introduce [our portfolio companies] to lead investors, we work on their business strategy, their revenue models. We work with them [by] introducing them to potential customers. We have an advisory board, a network of banks and attorneys and the Suns and HPs and other people of the world to provide them discounted services, and we just try and help them accelerate the growth of their company. We put no restrictions on them. We don't care who their customers are. If their first customer is Sony, that's fine with us. The only caveat is that we want to be able to do an investment in their company and we want them to be interested in developing the strategic partnership. By the time they go to the next round of financing, our hope is that we will bring to the table a strategic partnership with Panasonic or Matsushita that'll be meaningful and a win for us and for that company." (Statement at Palo Alto workshop)

The more aggressive firms may create a venture investment portfolio for the purpose of acquiring a position in a new technology they believe might be of strategic importance.⁵⁵ As John Taylor of the National Venture Capital Association noted at the Washington, D.C. workshop, "Corporate venture investment has become very significant. For 2000, it could be as much as 20 percent of the money that's involved, and yet, the corporate venture groups are in about 35 percent of the deals, well over a third of the deals, with a lot of these new corporate venture groups coming in some kind of co-investment role. The lone wolf days of the early 1990s really aren't the current model. A lot of these deals are being done in conjunction with venture firms."

At the Palo Alto workshop, Ron Conway of Angel Investors L.P. estimated that "perhaps a third of all funding today include a corporate partner, and we [Angel Investors L.P.] absolutely encourage that. We have 12 people on our staff. One of them does nothing but work with corporate partners and introduce them to all of our portfolio companies. It's a very, very effective means of getting your companies funded." This point is elaborated in Text Box 3 above.

Jim Robbins described the business proposition for Panasonic Ventures: "We screen these [new] companies and we identify companies when they're very young,

55. See Gompers and Lerner (2000: Chapter 5) for a thorough discussion of corporate venture capital, including an illuminating case history of Xerox Technology Ventures.

Text Box 4. Milestone financing

E. Rogers Novak, Jr., (Novak Biddle Venture Partners): “How we go about financing is we’ll milestone finance. We’ll put a little bit of money in [a seed investment]. We’ll look to see if the company’s getting traction. We’re really quick to change directions, face off of what we’re hearing back. We’re continually talking to the market. When we put money in, we take one of our IT entrepreneurs and have him co-invest with us, so that he is actively involved with the mentoring and expanding outwards. We use the government [sources of R&D finance] a lot. We look for contracts to bridge from the original idea and demonstrate that we’re going to have a real product, but we don’t want to take money that’s going to divert us from our mutual purpose. And after that, once we really look and see a proof of concept, we then go on to the next stage of venture funding. By the time we get a proof of concept, we’ve pretty much worked out what the business model needs to be, and then we generally would go out and start recruiting in a few key management people. Over the last three years there’s so much money out there that if you had a business model that worked, proof of concept, and management, we could get these enormous step-ups from one round to the next.” (Statement at Washington D.C. workshop)

before they have any venture investment, typically. Three or four founders are the norm. And we identify companies where we think that there’s a good potential for a larger strategic partnership with Panasonic or Matsushita.”

B. VENTURE CAPITAL

Venture capital firms provide, in an iterative manner, the demand for angel-funded companies and the supply of companies to the public markets. Seed investments by venture capital firms may take the form of a risk-limited small investment in a milestone finance program (see Text Box 4 for an elaboration) or as a device to establish a relationship with a technical entrepreneur who is working in an area of great promise but not yet ready for reduction to practice and the identification of the market that might be created.

A number of small venture firms specialize in supporting very early-stage opportunities. At the Washington, D.C. workshop, Taylor noted, “When you look at those venture funds that were out there in the marketplace raising money during 1999, and look at what they said their targeted size was for that fund, it’s not all the billion dollar funds.... It’s very easy to lose sight of the fact that there are a lot of smaller funds, many of which are very, very successful. In the year 2000, well over 90 percent of the money

was raised by existing venture funds, experienced venture funds, so the prospects for that segment is good. Venture capitalists have not abandoned seed.”

Nevertheless, broad anecdotal evidence suggests that as venture capital funds grow in size they tend to fund less risky, later-stage investments. At the Palo Alto workshop, Christine Cordaro of CMEA Ventures described her experience with developing transgenic technology. Comparing support by the venture community for high-risk technology-based projects with that prevalent 10 years ago, she observes, “we look at things in a very different way now. Today we would never invest in something like that. Not to say we wouldn’t invest in that kind of technology. We wouldn’t invest at that level of risk and lack of clarity.”

Almost all venture capital investments tend to be local, so that the venture capital firm can remain in very close touch with the firm in which it invests.

This is especially important for seed financing. At the Washington, D.C. workshop, E. Rogers Novak, Jr., of Novak Biddle Venture Partners observed, “If you look at early-stage investing, it’s got to be local if you’re really going to make it work, because we are backing one and two people. Our first ten companies had 27 people [when they received seed financing]... [collectively] these companies now employ over seventeen hundred people.”

Another limitation is the increasing size of venture capital funds and the associated rise in the average size of investments, noted by John Taylor at the Washington, D.C. workshop: “The average per company deal [in 2001 has been] about \$15 million.... But what gets overlooked is that the median, meaning the middle of the deal size range, has been half of the average amount for three or four years now. So, those of you who are into statistics know that it’s the very, very large deals that are skewing those numbers upward, that in fact, half of the deals that are being done are being done at less than the \$7 million size.” Jeff Sohl of the University of New Hampshire interpreted the data as suggesting a diminishing tendency for venture capitalists to invest at the seed stage: “The [average VC] deal size, and more importantly, the median deal, as John pointed out, is \$7 million [or less]. But the venture capital is pulling further to the right.... I’m not saying they’re abandoning seed, by any means, but they’re doing some bigger stage deals.”

We conclude that while venture capital is only a modest contributor to ESTD funding, venture capital firms are an essential instrument for transforming a nascent enterprise into a viable business with such strong prospects it can be sold in a private or public market, thus making the investor’s money liquid. This process may proceed in a number of steps in which the enterprise spins off businesses to venture investors as a

means of sustaining an investment stream to allow pursuit of the central technical vision of the firm.⁵⁶

C. ANGEL INVESTORS

The term “angel” investor comes from the theater, where wealthy individuals took very high risks in funding the production of Broadway shows. By analogy, angels in high-tech investing are traditionally individuals with a successful record of commercial innovation, who use their wealth and their experience to invest very early in new, high-tech businesses.⁵⁷ The discussion that follows describes how the concept has broadened to include individual private investors who neither have the personal ability (or inclination) to perform the due diligence required for responsible investing, nor are in a position to take board seats or help the firms with its most critical management problems.

The provision of risk capital by wealthy individuals for support of technology development goes back as far as seventeenth and eighteenth century systems of patronage. Organized venture capital, in contrast, is a recent phenomenon, dating back only as far as the immediate post-World War II era. Angel investing has, in past years, undergone a surge related to the dramatic growth of venture capital disbursements.

At the Palo Alto workshop, Ron Conway of Angel Investors L.P. commented on the variety of forms of angel investing, and the varying burdens of due diligence each places on the investor, “If you look at the types of angel investing, there are many, many types of angel investing, and I’ve probably done all of them myself, and I think all of them have different benefits. If you’re going to be an angel investor, you need to decide how much time you want to put to it. If it’s going to be a casual angel investor and do one or two investments a year, then it would be very useful for you to join a group like the Band of Angels and other groups like that that are now all over the country. Hans Severiens, who’s here, literally started that entire idea [see Text Box 5.] I’ll bet there are 500 angel groups across the country now. So, there’s the spectrum from the ad hoc angel investor who only wants to do one to two deals a year, and I would say angel investors, the fund that I started, is at the very opposite end of the spectrum, where we actually have general partners who are full-time, processing the

56. Michael Knapp of Caliper Technologies noted at the Palo Alto workshop that his company is “generating revenue from little, tiny spin-offs, buying time with my peers to go and do the rest of the work. And so, they look at me as a source of all the value. So, they’ll let me go and do the deeper research in some of the others as long as I keep spinning things off that have market potential and improve our profitability, and that’s the way that I’m trying to avoid hitting this valley where I’m stuck if I don’t get funded.”

57. Luis Villalobos, of Tech Coast Angels, noted at the Palo Alto workshop that some people call all individual investors angels: “I think it is useful to make a distinction between active investors who perform due diligence and participate on boards, from passive investors who only provide money. I call the active ones ‘angels’ and the passive ones ‘private investors.’”

Text Box 5. The Band of Angels

Hans Severiens (Band of Angels): "We started the Band of Angels really at the end of '94. It became clear to some of us that the big venture funds were getting bigger and bigger. What used to be a normal venture capital partnership, which maybe managed \$50 million, all of a sudden, they were managing ten times as much, and nowadays one hears of billion-dollar ones. And as a result of that, the average amount of money going in per deal had to go up. Of course, you're certainly not going to increase your staff by a large number. You don't need to, because you only need to make fifty, sixty, seventy investments to get adequate diversity to mitigate the risks. These things go to square root of the number. The bigger funds were not funding quite as much as they used to. There seemed to be an opportunity for some of us." (Statement at Palo Alto workshop)

deal flow from a venture fund that's structured just like a normal VC. But, the unique thing is that all the investors in that VC fund are angel investors, individually."

Jeff Sohl of the University of New Hampshire observed that angel investors invest close to home: they want to get there, see the company, and get back to their desk within a day. He estimates that 95 percent of an angel's deals are within half a day's travel time. At the Washington, D.C. workshop, Sohl commented:

As investors say, they're looking for an attachment and a return, so [the firm is] getting a little bit more than just money, but it is a financial deal. They have to be close to that deal, face to face. They want to be close to home both to enjoy that and to bring value to the company. These angels are value-added investors. They want to bring more to the party. Angel investors need to sit on the board. They call themselves 'mentors for money.' What they want to do is be involved with the excitement, but they don't want the sleepless nights sitting there on Thursday night wondering if you're going to meet cash flow on Friday for payroll. They want to help this company out, but it's not just for benevolent reasons, which is why some angels do not like the term 'angel.' It is for hard-nosed financial reasons. They feel like they can help this company, put it in a better position to both grow and to be ready for the next round of financing.

Severiens of the Band of Angels observed that while angels do invest early and take risks, they, like more conventional venture capital investors, are much more on the business side of the invention and innovation gap: "We are not a missionary institution. Our people invest their own money, and they really want to get money back. So, we

look at things very, very much from a venture capital point of view. Money goes in. What are the risks? We do early-stage things, of course, because that's where we have an effect. We add value, but we do expect to get a great return soon. So, I'm afraid I don't think we really can fill that gap [Valley of Death or Darwinian Sea]. We don't really play there very much."

He went on to observe that innovative combinations of early-stage investing structures are being developed, representing a combination of early- and later-stage approaches. He gave an example from his personal experience: "It became clear to me that it would be very nice if I had a pool of money that... we could shower on some of the better deals... So, I formed a venture partnership with another man, so there are the two of us managing it... Out of the deals coming through the Band of Angels, we can now add money... and make the deals somewhat bigger. We can lead deals more efficiently. We also have a little bit of a staff... The source of that [added] money has not been from angels. We purposely went to institutions, so we have a couple of endowments, pension funds, and corporate investors in... a \$50 million fund."

D. UNIVERSITIES

Research universities in the United States have a long history of research and consulting by faculty in support of American industry. That relationship has been profoundly changed by the extraordinary power of modern science to generate new commercial opportunities. Universities understand that while their primary role is education and advancing basic knowledge, most of them are also interested in protecting their intellectual property and exploiting it to produce income. While there are many concerns about the effect on the university's culture and purpose, the most rapidly rising source of support for university research is the university's own funds. This is to some extent a consequence and to some extent a cause of the licensing of faculty inventions.

At the Palo Alto workshop, John Shoch of Alloy Ventures identified four primary mechanisms by which universities become engaged in supporting technology development, using Stanford University as an example.

First, to maximize returns on their endowments, universities invest heavily in venture capital firms. In recent years, the high returns on these investments have helped university endowments. Second, in some cases Stanford will participate as an investor in a startup. In these cases, friends of the university who are members of the venture capital community assist the Stanford fund-raising effort by providing a gift to Stanford, which they invest on the university's behalf in selected deals. Third, Stanford has recently started taking equity in firms in return for exclusive licenses. Shoch reports

that, in the past, the university hesitated to take equity positions because it was thought to be “more pure to take the royalty payment rather than the equity payment.” This was “a source of tremendous consternation, because the equity is more valuable [to the university] than the royalty payment, as many firms, particularly in the biotech field, go public and gain commercial value long before they are able to generate a revenue stream.”

Finally, as documented by Lerner (1999), a number of universities have started their own venture capital funds, specifically designed to help push projects beyond the research stage to commercial viability. Josh Lerner identified some nineteen such university-financed venture capital funds up to 1998 (Branscomb, Kodama and Florida, 1999: 387). The total amount of money available for investment in this way is quite modest, but financial officers of the large private universities are well aware that by far the most successful part of their investment strategy for their multi-billion dollar endowments in 1999 and 2000 was in private equities. Thus, if they believe they will be successful in their investments in their own faculty inventions (about which Lerner is quite skeptical), they have substantial assets that could be brought into play.

The other significance of university-financed venture funds is that they permit the university to attempt to bridge the Darwinian Sea from both shores: from the business shore, by creating new startups, and from the R&D shore, by using the venture funds to pay for the reduction-to-practice research of the faculty, both in the university for the benefit of the venture. The fact that the major part of university research is paid for by federal agencies also suggests a public policy issue: should government agencies, eager to see the fruits of the research they sponsor commercialized for the economic benefit of the nation, extend their academic science support farther downstream—that is, closer to the definition of products and of processes that will be required?

E. STATE PROGRAMS

State governments are eager to promote commercial activities in order to maintain full employment and create wealth for their citizens. Those states with economies based on a declining industrial sector—the so-called rust belt states are particularly motivated to replace the lost employment with new, high-technology business opportunities. States are also inclined to emphasize science-based opportunities that utilize their very large investments in higher education, in collaboration with federal support for academic research and development. Finally, unlike the federal government, states are unabashed in their embrace of industrial policy as a means to accomplish economic restructuring.

Historically the primary mode of investment has been public financing, tax relief, and other forms of subsidies to attract new plants and keep existing ones from moving

out of state. States have experimented with a large variety of plans for nurturing science-based innovations, with the expectation of leveraging federal investments in research.⁵⁸ States hope to replace rust-belt economies with high-growth, high-tech firms, with the thought that high-tech industry can create employment with little adverse impact on environmental and energy resources.

More recently, states have begun to provide capital for commercialization through a variety of modes. California and New York have investment sums in the hundred of millions of dollars in new “Centers of Excellence” on leading-edge technologies. These investments are explicitly designed to spur the creation of technology-based entrepreneurial start-ups. California is providing matching funds to help its technology entrepreneurs meet the cost-sharing requirements of many federal R&D programs. NASA and the state of California are collaborating to develop an exciting new research park at NASA’s Ames Research Center, creating important new ties that will help sustain funding for this federal laboratory. New York and Minnesota are creating new technology transfer incentive programs that don’t just license technology, but invest in further development—as well as business plans—to move the technology forward into the market place, enhancing the likelihood of private investment, and capturing jobs for the local community.⁵⁹ At the Washington, D.C. workshop, Marianne Clark of the State Science & Technology Institute offered the example of Kentucky’s \$20 million commercialization fund.⁶⁰ This is a fund that can provide up to \$75,000 a year for three years to researchers at their universities who have a technology that they have gotten to a certain point [on the shores of the Darwinian Sea]. “It really isn’t to the point where they can interest a private business, so this is an area that they’re seeing... a gap, and some of the states are trying to provide some funding for that.”

F. FEDERAL FUNDING

Despite the historic reluctance of the Congress to authorize federal investments in commercial technology, a consensus developed in the 1980s that the U.S. high-tech economy was losing its competitive edge.⁶¹ The 1988 Trade and Competitiveness Act changed the name and mission of the National Bureau of Standards (within the U.S. Department of Commerce) and created the Advanced Technology Program (ATP).

58. See Coburn and Bergland (1995), State Science and Technology Institute (1998), and Schachtel and Feldman (2000) for comprehensive reviews.

59. MTC, “Maintaining the Innovation Edge,” <www.mtpc.org.pubs>.

60. The STTI is the National Governors’ Association’s institution for sharing information on state research and innovation activities. See <www.ssti.org>.

61. Exceptions to this history, documented in Hart (2001) are the defense industry (where government makes the market) and agriculture (where agricultural extension and its supporting federally sponsored research created a highly productive agricultural industry).

Managed by the National Institute for Standards and Technology, ATP was created to foster collaborative technology development of high-tech industrial products with the potential to foster significant future economic growth. An earlier statute, the Small Business Innovation Development Act of 1982, created the Small Business Innovation Research (SBIR) program. While the positive trade balance in high-tech goods had already begun to decline before 1982, the SBIR program was originally created in response to concerns that the Department of Defense and other agencies procuring R&D services were concentrating too much of this business in large firms. SBIR required that a fixed percentage (originally 1.25 percent, now increased by statutory amendment to 2.5 percent) of all R&D purchased by each agency must flow to small business. The agencies are increasingly sensitive to the economic goals of the small business applicants for SBIR grants, more or less independent of each agency's primary operational mission.⁶²

Federal programs such as ATP and SBIR are cost-shared R&D programs, not investments in private equity, but they are designed with the expectation of commercial exploitation of the R&D performed in the firm. Branscomb and Keller (1989), Branscomb and Morse (2001), and Branscomb and Auerswald (2001) discuss these and other ESTD-relevant federal programs at length.

Our workshops revealed a variety of experiences with attempts to use federal R&D resources to support high-tech innovation. For example, Nancy Bacon noted that Energy Conversion Devices would

first... do some internal funding.... Then we seek government-industry partnerships. And in many cases ... [the] U.S. Department of Energy, NIST/ATP and other government agencies have played a key role in helping us get to the point where we can prove feasibility and have prototypes so we can attract... strategic alliances and partnerships and joint ventures. Government support from NIST led to development of "roll-to-roll" manufacturing technology (described in Annex II), which led to a joint venture with GE. And NiMH, batteries developed through a \$30 million contract with the U.S. Advanced Battery Consortium (USABC), part of the government-industry Partnership for a New Generation of Vehicles (PNGV), led to a joint venture with GM.

62. Thus SBIR projects are ostensibly constrained to work falling within the existing statutory missions of the agencies, and thus were not free to respond to any area of commercial opportunity, independent of existing statutory missions. However, with the growing political popularity of SBIR, and the broad flexibility of most agency R&D missions, SBIR is increasingly seen as a tool for stimulating economic advance among new and small firms (Scott Wallsten, "Rethinking the Small Business Innovation Research Program," in Branscomb and Keller 1989).

Text Box 6. The validation role of federal funds

Hylan B. Lyon (Marlow Industries): “I think the biggest thing [federal contracts] did for me was to help me overcome fears in the senior management team and convince them that we were credible. We could think our ideas out and get a government bureaucrat who has been reviewing proposals in highly competitive environment to fund six or eight or 10 of these SBIRs. And by the way, they’re all on different topics, and I think they were all successful. They all were little pieces of that development plan. Then, they said, well, you’re real.” (Statement at Palo Alto workshop)

Bruce Griffing (GE): “I went with my boss, basically against the wishes of the guy who ran the medical systems business, to Jack Welch, who’s the guy that runs GE, and we pleaded with him to keep the project [using amorphous silicon for medical imaging] going. We told him it was going to be very important to the business—similar to making a pitch to investors, except within the firm. And the fact that we had these [federal] contracts made a big difference. I don’t think, honestly, we would have been successful if we didn’t. It made a difference to him that outsiders, like the NIH and DARPA, were interested enough to actually put up money to keep this thing going. Furthermore there is a money-leveraging effect because of the cost-sharing program.” (Statement at Washington D.C. workshop)

Kenneth Nussbacher (Affymetrix): “I do think that in the front end of the process, the idea that an academic individual could move into a company environment and bring grants with them or apply for new grants in that setting is a really important part of getting the very best scientists into environments where they aren’t just doing academic work, but doing commercial work. And it’s certainly been very valuable to Affymetrix to be able to bring people in who continue to keep their foot in their academic network through the granting process and have the freedom to pursue things that they’ve been dedicating their career to, while gradually migrating into a commercial environment where more tangible products can be generated.” (Statement at Palo Alto workshop)

A number of workshop participants reported that federal procurement contracts had provided both resources and validation to early-stage projects at critical junctures. Typically the product or service purchased by the government is an intermediate one with respect to project goals (for instance, appropriate for a specialized application, but not yet suitable for a broader market). Buyer-supplier co-development projects linking large corporations and their suppliers similarly provide support for small company ESTD efforts. While recognizing the importance of these channels of support, we focus in this report on direct funding mechanisms.

4. CONCLUSION

The challenges faced today by those involved in crafting and implementing science and technology policy at the federal level parallel those faced by the leading technology corporations in the United States in the 1960s, 1970s, and 1980s. These large companies generated many basic science breakthroughs in noted research facilities such as Bell Labs and the Xerox Palo Alto Research Center (PARC). Yet, in many well documented and widely discussed cases, these companies missed significant opportunities to turn inventions into profitable innovations. What is worse—in many cases the companies lost not only the inventions, but the inventors, as a result of inadequate support for the invention to innovation transition. The founder of Intel, Gordon Moore (noted also as the originator of Moore's Law) observed last year at a conference at Stanford University: "In a pattern that clearly carries over to other technological ventures, we found at Fairchild that any company active on the forefront of semiconductor technology uncovers far more opportunities than it is in a position to pursue. And when people are enthusiastic about a particular opportunity but are not allowed to pursue it, they become potential entrepreneurs. As we have seen over the past few years, when these potential entrepreneurs are backed by a plentiful source of venture capital there is a burst of new enterprise."⁶³

How much innovation is the right amount in a large corporation? A region? A nation? In every case, some spillovers or leakage occur of ideas, people, and projects. Moore continues: "One of the reasons Intel has been so successful is that we have tried to eliminate unnecessary 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). Any region without larger companies at the technology frontier or research organizations of large companies will probably have fewer companies starting or spinning off."

A similar tension faces regions and nations as they struggle to encourage the horizontal connections between researchers to spur invention, at the same that they encourage vertical connections between technologists and business executives in achieving the invention to innovation transition. In his Industrial Research Institute Medalist's Address—provocatively titled "The Customer for R&D is Always Wrong!"—Robert Frosch (former head of research at General Motors and Administrator of NASA, among other distinctions), offered the following observation:

63. Moore and Davis (2000), paper prepared for the Stanford CREEG Conference "Silicon Valley and Its Imitators," July 28, 2000.

There is a kind of Heisenberg uncertainty principle about the coordination connections that are necessary in R&D. One needs all of these deep connections among kinds of knowledge, and the ability to think about the future, that works best in an institution that puts all those people together. One also needs connection with the day-to-day, market thinking, and the future thinking of the operating side of the business, which suggests to many that the R&D people should be sitting on the operating side of the business.

This is an insoluble problem; there is no organizational system that will capture perfectly both sets of coordination... There is no perfect organization that will solve this problem—the struggle is inevitable.

Neither the United States, nor its venture capital firms, nor its large corporations, have arrived at the perfect organizational structure to manage innovation. To our knowledge, no such perfect organization exists elsewhere. If Frosch is correct (and we think he is), even in theory, fundamental contradictions inherent in the planning of innovation suggest that it is misguided to aspire toward elegance, symmetry, and efficiency in this context. In the Darwinian Sea, the struggle is inevitable—not just the struggle between aspiring technologies and their champions, but also the struggle between institutional forms and approaches to the management of innovation.

The chaotic character of the Darwinian Sea is probably necessary to provide a wide range of alternative ways to address issues of technical risk, to identify markets that do not yet exist, to match up people and money from disparate sources. But on one bank of the Sea—the S&T enterprise—technology push policies may encourage agencies to fund research closer to the reduction to practice required for a solid business case. And on the other bank—the world of business and finance—technology pull policies will continue to enhance the incentives for risk taking (for example through moderated capital gains tax rates). Programs which have elements of both push and pull will continue for some time to be viewed as experimental, but will become more securely anchored on the research shore of the Sea if they are to maintain effectiveness at the same time that they secure lasting public and political support.

Estimating the Distribution of Funding for Early-Stage Technology Development⁶⁴

1. OVERVIEW

Early-stage technology development (ESTD) is the engine that drives long-term economic growth.⁶⁵ Yet funding flows supporting such work is difficult to track and the magnitudes are largely unknown.

This part of the report describes the methods used to model the share of R&D funding in the United States actually devoted to this important region of the innovation landscape. Specifically, we propose an approach towards interpreting publicly available data to arrive at more realistic estimates of funding flows into ESTD.

Identifying the portion of reported R&D investments and expenditures that are directed toward early-stage technology development is a challenging task. Existing data⁶⁶ are not gathered in a way that allow direct comparison of flows of funding from different public and private institutional sources in support of ESTD projects. Blurred distinctions between the traditional categories of basic research, applied research, and

⁶⁴. This section of the report was co-authored by Brian Min, Research Associate to the Between Invention and Innovation Project. Thomas Livesey, also a Research Associate, provided supporting research.

⁶⁵. The definition of ESTD, early-stage technology development, is given at the front of the executive summary and is elaborated in Part I.

⁶⁶. Important sources are the NSF surveys on research and development funding and expenditures, data on the venture capital industry from Venture Economics, and the limited data on angel investing reported by Sohl (1999) and van Osnabrugge and Robinson (2000).

development further complicate accurate analysis of existing data.⁶⁷ Such distinctions are often based more on the motivations of the investigator than of the investor, and as such are of little use in our effort to track funding supporting early-stage commercialization efforts. Ambiguous common usage of terms like applied research leaves the door open for variation in interpretation by survey respondents, especially across different firms and industries. Moreover, research deemed to be applied may include both original research believed to have applications and research that applies existing knowledge to the solution of practical problems. There is no straightforward way to use government R&D data to identify what portion of the aggregated funding is directed toward ESTD activities.

Attempts at a top-down interpretation of existing data require the subtraction from a large, aggregate number (such as total industry R&D) of a speculative estimate of the portion not directed toward ESTD, leaving a small and uncertain residual. Attempts at a bottom-up approach involve either dramatic extrapolation from anecdotal testimony, or the sort of large-scale data gathering effort that has not been done and is outside the scope of the current project. Relevant existing data are gathered inconsistently, with the unit of analysis being firms in some contexts and projects in others.

The methodology outlined here does not overcome these fundamental constraints. Rather, it represents an attempt at benchmarking the existing data in a manner that takes the limitations of the data as given. Because of these challenges, our method of arriving at an reliable estimate was to create two models based on different interpretations of ESTD definition—one very restrictive (that is, biased toward a low estimate) and the other quite inclusive (that is, biased toward a high estimate). We have not attempted a best-informed estimate lying between our upper and lower estimates. Instead we have focused on estimating the fraction of ESTD funding flowing through each of the channels discussed, since this fraction seems relatively invariant to the model selected and is the figure most relevant for informing public policy (see Figure 1 on page 23).

We wish to determine what fraction of U.S. national R&D expenditures, or of the investments involved in creating the half-million new firms founded in the United States each year, is directed toward ESTD. Since the unique feature of the transition from invention to innovation is the intimate interdependence of technical research and market sensitivity with product specifications, we suggest that the intent of the investor to develop a new high-tech product or service should be the central criterion

67. See, for example, Council on Competitiveness (1996): “The old distinctions between basic and applied research have proven politically unproductive and no longer reflect the realities of the innovation process.”

used to identify ESTD investments. Such a definition suggests, for example, that the federal SBIR and ATP programs, which expressly have this intent, are clear examples of federal programs upon which our attention should focus and represent a lower bound to the ESTD estimate for federal contributions. Similarly, angel investments and some venture capital funds that focus on the seed and early stages of a business enterprise can be assumed to share such an intent. So too do efforts by companies and universities to spin out new ventures in areas outside the core business, based on their in-house inventions.

2. RESULTS

Based on the approach described in this part of the report, we estimate that of the \$266 billion (see Table 1) that was spent on national R&D and invested by angels and venture capitalists in the U.S. in 1998, investments and expenditures flowing into ESTD activities accounted for a range between 2 and 14 percent, or between \$5 and \$37 billion. Despite this great difference produced by the assumptions of the two models, we are able to state with some confidence that the majority of ESTD funding is, first, dominated by industry, angel investor, and federal government sources, and second represents a modest fraction of total national investments in R&D and venture private-equity investment. These results are summarized in Table 1. The assumptions that underlie the two models are discussed in the remainder of this chapter.

Table 1 allows us to bracket the range of ESTD investments from each of six institutional sources. Figure 1 (above, page 23) presents the data of Table 1 in the form of pie charts, making visible the similarity of the percentage distributions in the two models. One caveat that limits the significance of this apparent independence of the model we use is the fact that a more accurate model might represent different choices from one or another permutation of the high and low model assumptions that generated Table 1. Our qualitative judgments are based largely on the views of participants in the workshops, discussed in Part I.

The left side of Table 1 presents highly aggregated data on inputs into technology development and the maturing of new product and new business innovations. The table is based on data categories frequently used as independent variables in empirical work on determinants of technological innovation.⁶⁸ These totals suggest that some \$266 billion of financing from a variety of sources was available to support scientific

68. We do not suggest that these statistics in their raw form are somehow invalid as predictors of innovation in general. We only mean to suggest that these numbers overstate the inputs into early-stage technology development activities.

TABLE 1. Estimates of funding flows to early-stage technology development (ESTD) from data on financial support for scientific and technological innovation (1998 data)

Funding Source	Total Financial Support for Innovation		Estimates of Funding Flows to Early-Stage Technology Development (ESTD)			
			Low Estimate		High Estimate	
	\$B	Derivation	\$B	Derivation	\$B	Derivation
Industry	149.7	Total industry-funded R&D, National Science Board (2000) table 2–5	1.7	Early-stage innovation research in central research laboratories	16.8	Half of all basic research and a third of all applied research funded by industry
VCs	16.8	Total VC disbursements, National Science Board (2000) table 7–14, based on data from Venture Economics.	0.4	Seed-stage disbursements to product-based technology firms	0.8	Fractional components of all VC disbursement to product-based technology firms.
Angels	20.0	Total angel disbursements, as reported by Sohl (1999)	1.5	Angel disbursements based on extrapolations from Silicon Valley data	10.0	Angel disbursements to new technology startups based on Reynolds and Sohl
Universities	5.0	Total university-funded R&D, National Science Board (2000) table 2–5.	0.2	University support for faculty spin-offs	1.8	All universities funding for applied research and development
Federal Government	72.1	Total federal obligations for R&D, National Science Board (2000) table 2–25.	1.4	Total funding for ATP, SBIR, and STTR programs	7.3	Portions of federal obligations for non-defense R&D
State Government	2.3	Total state-funded R&D in 1995, State Science and Technology Institute (1998) table 13	0.2	Fractional portion of state-funded applied research in 1995	0.8	All state funding for applied research in 1995
Totals	\$265.9	Total support	\$5.4	Lower estimate	\$37.5	Upper estimate
			2.0%	of total support	14.1%	of total support

and technological innovation. However, the surveys and studies upon which these data are based capture a much broader portion of the R&D and new business development spectrum than we are focused on here. Our analysis yields new baseline translations of the data to derive better estimates of funding flows into ESTD. These estimates are summarized in the right-hand side of Table 1 with upper and lower ranges that suggest the broad range of uncertainty we attach to our estimates.

We preserve this broad range to remind the reader that these are primarily meant to provide a plausible notion of the relative importance of these different sources of ESTD funding. The particular value for the policy interests of this paper is the comparison of the levels of federal investment, especially for ATP and SBIR, with all the others: corporate, VC, angels, states, and universities. Further descriptions of each estimate and funding source follow in the subsections below.

Our examination of the data suggests the following significant findings:

- Federal funds are among the largest sources of financing for ESTD, with an estimated range between \$1.4 and \$7.3 billion depending on assumptions made. Even the low model assumptions of federal ESTD funds, counting only ATP and SBIR, which are targeted specifically on the invention-to-innovation transition, make up an important portion of such federal funds and of the total flows of ESTD investments.
- Although the science-based innovation expenditures of larger high-tech companies are only on the order of 10–15 percent of total corporate R&D expenditures, they nonetheless represent a major source of ESTD funding. Increasingly important modes of corporate support include outlays from corporate venture funds, and partnerships between large and small firms enabling small firms' access to emergent technologies and to providing an outlet for excubating inventions the large firm does not wish to commercialize internally because they fall outside the firm's core activities.
- Venture capital investment in ESTD varies dramatically by stage of funding and industry. The low estimates depend on treating seed venture capital as a lower boundary to ESTD from venture firms; the higher estimates depend on how much of subsequent stages of venture funding represent R&D aimed at preparing new products for market entry. In either case it is clearly a less significant source of funding than that provided by angel investors, or by corporate and federal sources.

3. DETAILED ASSUMPTIONS UNDERLYING THE TWO MODELS IN TABLE 1

A. CORPORATIONS

In 1998, corporations reported to NSF investments in R&D totaling \$149.7 billion. They indicated (perhaps somewhat arbitrarily) allocation of \$11.3 billion to basic research, \$33.6 billion to applied research, and \$104.7 billion to development.⁶⁹ These massive investments are highly concentrated; the top 500 firms accounted for nearly 90 percent of all corporate R&D expenditures.⁷⁰ Most firms in the highly competitive technology sector invest heavily in R&D to compete, and while they frequently achieve important breakthroughs, the overwhelming majority of corporate research investments pertain to the core business. While some of these core business innovations may represent radical advances in the sense that they are based upon fundamentally new technologies, most 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, which is the intent of government programs like ATP.⁷¹ Consequently, our analysis sought to focus on corporate investment in early-stage technology development *outside of a corporation's core business*.

(i) Lower estimate: Early-stage innovation research funding in central research laboratories

Central corporate research laboratories are a primary locus for pre-commercial ESTD research at many large corporations. In contrast, business-segment laboratories tend to focus almost exclusively on extensions of existing products in their core business. Researchers in central corporate labs are relatively free from intense pressures by business managers to maximize profits and the imposition of cultural norms that promote loyalty to existing product lines that exist in business-segment laboratories. Thus, researchers in central corporate labs have more latitude to engage in new areas of research and push the development of innovations that might not survive in business-segment laboratories. Such motivations were driving factors in the establishment and success of famous central laboratories such as AT&T Bell Laboratories, Xerox PARC, and IBM's T.J. Watson Research Center.

69. National Science Board (2000), tables 2–5, 2–9, 2–13, and 2–17.

70. National Science Foundation and U.S. Department of Commerce (1999). Note that firms with less 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.

71. Christensen (1997) offers a detailed elaboration of the concept of disruptive technologies.

TABLE 2. Fraction of corporate R&D in central research laboratories, selected companies, 1998

Company	<i>Company funded R&D as a % of sales</i>		
	Total	Central lab	Ratio
Nokia*	12.2	1.2	10.0
Rockwell	5.0	0.5	10.0
General Electric	3.2	0.4	13.0
Hughes	2.0	0.3	14.0
United Technologies	5.1	0.3	6.5
Raytheon	3.0	0.1	2.8

Source: Tassey (2001: 25) from HRL Laboratories and company data.
 *Not a U.S. firm.

NIST economist Gregory Tassey reports that for a small sample of corporations with large R&D program budgets, approximately 9.4 percent of reported R&D is carried out in central research labs (see Table 2).⁷² Since only the largest and most R&D-intensive firms have the resources to maintain prominent central research labs, we presume that such labs are found primarily in those firms with R&D programs larger than \$100 million. These would include the approximately 200 top R&D-performing firms, which spent \$112.7 billion on R&D in 1998, about two-thirds of total industry expenditures.⁷³ Using Tassey's reported average, we estimate that, in the top 200 R&D-performing firms, total central research lab expenditures are approximately \$11 billion (~9.4 percent of \$112.7 billion).

Based on his experience at IBM and other observations, Lewis Branscomb, the co-author of this report, conjectures that within the large central labs, ESTD work comprises perhaps 15 percent of the research. This figure is not inconsistent with estimates produced by the Industrial Research Institute that 6 percent of R&D funds in central labs are directed toward basic research and 36 percent toward applied research, since ESTD work is likely to be categorized by corporations as both basic and applied research.⁷⁴ Therefore, we assume that 15 percent of R&D in central research labs, or \$1.7 billion (15 percent of the \$11 billion figure derived in the paragraph above), is spent on ESTD research, and without including any other in-house

72. Tassey (2001).

73. National Science Foundation (2000c), tables A-5 and A-6.

74. Bean, Russo, and Whiteley (2000), table 6.

corporate R&D expenditures, use this as a lower-range estimate for industry funding of ESTD work.

(ii) **Upper estimate: Portions of industry funded basic and applied research**

Investments by industry into basic research are often more targeted and constrained than in the academic laboratories where the majority of the nation's basic research takes place.⁷⁵ Within the corporate context, a deliberately composed research staff (with specifically chosen skills and interests) and constant market pressures tend to drive basic research to focus on areas of practical relevance to the firm. As a first approximation, some significant portion of these corporate basic research flows may provide an estimate of research into non-core businesses, since most research in the core would generally be characterized as applied research. In 1998, industry expenditures on basic research totaled \$11.3 billion.⁷⁶ Reported basic research expenditures probably include both the science research that results in new laboratory ideas and builds links to university research, as well as the funds to transform the concept into the kind of viable commercial proposal required for a product division to accept the project into its business plan. We arbitrarily allocate one-half of these basic research funds, or \$5.6 billion, to ESTD investments.

Some corporate applied research funds may also flow to ESTD projects. The majority of these applied research investments focus on core business areas, working to extend existing product and service lines rather than to encourage new breakthrough innovations of the sort we focus on here. Moreover, survey-based estimates of applied research expenditures typically include new research in areas with potential applications as well as the application of existing knowledge to the solution of practical problems. We attribute a third of these applied research funds, or \$11.2 billion, to ESTD work, while acknowledging that this assumption probably overstates the true funding levels by a significant margin. Combining these totals, our model for an upper-range estimate for corporate funding of ESTD research is \$16.8 billion.

One source of information that suggests that the upper-range estimate may be closer to reality comes from a study commissioned by this project by BAH (see Annex I). Interviews were conducted with corporate executives from companies selected at random, representing the software, telecommunications, electronic component

75. As defined by the NSF's Industrial Research & Development Information System (IRIS), "Basic research analyzes properties, structures, and relationships toward formulating and testing hypotheses, theories, or laws. As used in this survey, industrial basic research is the pursuit of new scientific knowledge or understanding that does not have specific immediate commercial objectives, although it may be in fields of present or potential commercial interest."

76. National Science Board (2000), table 2-9.

manufacturing, automotive manufacturing, and biotechnology industries to assess spending trends and research activities in ESTD. The BAH study concluded that:

- industries focused on quickly developing technologies such as biotechnology and computer hardware spent a higher proportion of their R&D on ESTD than did industries based on more established technologies;
- product-based technology companies tended to spend more of their resources on ESTD work early in the company's life cycle than they did later;
- mature product-based companies tended to focus more of their investments on product development rather than on new ESTD projects.

The BAH report estimates corporate ESTD (out of core business lines) at approximately \$13 billion, roughly 9 percent of total corporate R&D investment as reported by NSF for 2000.

B. VENTURE CAPITAL

Venture capital disbursements cover a broad swath of industries and stages of company development. Venture Economics reports that in 1998 a total of \$16.8 billion was disbursed mostly to small, innovative firms.⁷⁷

As a rule, venture capital firms specialize in acquiring promising technology firms, not in building such firms from scratch. While venture capital firms support nascent ventures through mechanisms other than investments categorized as seed stage (such as bridge loans),⁷⁸ only a fraction of venture capital funding at all stages of company advancement directly supports the development of new technology (as distinct from other activities of new firms such as management, production, and marketing).

To be able to distinguish what portion of venture capital disbursements fund ESTD work, venture capital disbursement data have to be broken down by activity, something not readily feasible with current broad-based surveys of venture capital firms. A simple model of the percentage of venture capital that is directed toward ESTD can be calculated by making assumptions based on the stage of funding being pursued by the company. Essentially, the earlier in development a company is, the more venture funding will go towards R&D activities. Seed-stage financing occurs very

77. National Science Board (2000), table 7–14, based on data from Venture Economics.

78. Bridge loans represent a particularly important source. These (usually small) loans are provided to early stage ventures prior to an initial round of funding. If a funding round takes place, the loans are converted to equity. We thank Josh Lerner for emphasizing this point.

early in the life cycle of a new venture and usually involves a small amount of capital provided to an inventor or entrepreneur working in an area of great promise to reduce the technical idea to practice and identify the market that might be created.

We further focus our analysis by counting only efforts in product-based technology industries, where technical breakthroughs can lead to discontinuous innovations in a manner that only seldom occurs in service-based industries. Startup efforts that hinge upon technical extensions of current technologies or new business models built around pre-existing products and services are therefore excluded.

(i) Lower estimate: Seed-stage venture capital disbursements

In 1998, seed-stage deals made up \$0.72 billion, or only 4.3 percent of total venture capital disbursements. Approximately 60 percent of seed-stage disbursements, or \$0.44 billion, were directed toward firms in product-based technology industries in 1998. All such disbursements are estimated to be directed toward ESTD work.

(ii) Upper estimate: Components of all venture capital disbursements for product-based technology firms

About half of the \$16.8 billion in venture capital funding awarded in 1998 went to firms in product-based technology industries, where ESTD work is most likely to occur. At the seed stage, about 60 percent of venture capital funds went to entrepreneurs in product-based technology industries. All \$0.44 billion of seed-stage funds are estimated to fund ESTD activities. At the startup financing phase, about one-half of the \$0.97 billion invested are for firms in product-based technology industries. These funds are normally provided for use in product development and initial marketing. We assume that one-half of startup financing is for ESTD research, with the remainder focused on other business development activities, providing an estimate for ESTD of one-quarter of startup-stage funding, or \$0.24 billion at the startup stage.

First-stage and other subsequent early-stage disbursements are provided to support commercial manufacturing and sales, and made up about \$3 billion in investments in 1998. Only a small portion of companies will be investing funds acquired at this stage into significant new technology-based research. We estimate that half of first-stage funds are invested in product-based technology firms and that just 10 percent of these disbursements, or \$0.15 billion, fund ESTD work.

Based upon these speculations, we project that as much as \$0.83 billion of venture capital might have directed toward support of ESTD in 1998.

C. ANGEL INVESTORS

The level of investment provided by private individuals is very difficult to track. Most angel deals are private, individually small in size, and do not readily show up in major statistical reports. Jeff Sohl of the University of New Hampshire says that, in this country, “conservative estimates suggest that about 250,000 angels invest approximately \$10–20 billion every year in over 30,000 ventures,” for an average deal size of about \$330,000 to \$660,000 per venture (Washington, D.C. workshop). Most angel deals occur very early in the life cycle of a startup and typically provide funding for a single project team—sometimes a single individual—focused on a single project.

(i) Lower estimate: Angel disbursements based on Silicon Valley data

Luis Villalobos of Tech Coast Angels estimates that its investments break down as “60 percent high-tech, 30 percent dot-com, and 10 percent services.” Band of Angels founder Hans Severiens states that from 1995 through the end of 2000, the Band of Angels invested collectively a total of \$83 million in 132 companies, for an average deal size of about \$625,000. Severiens further estimates that angel activities in the Silicon Valley area are likely to be around \$200 to \$300 million yearly.

While these data are instructive, angel deals in Silicon Valley are likely to be larger and more heavily skewed towards technology-based startups than in the rest of the country. Assuming that the distribution and characteristics of angel deals in Silicon Valley relative to the United States are roughly similar to observed trends in venture capital financing deals, we assume that angel deals in Silicon Valley represent on the order of 30 percent of total U.S. angel activities, that the average national angel deal size is \$500,000, and that two-thirds of these investments are made in product-based technology ventures.⁷⁹ This gives us a range estimate of total U.S. technology-oriented angel investments of around \$1.5 billion.

(ii) Upper estimate: Angel disbursements to new technology startups, based on Reynolds and Sohl

New data from the National Panel Study of Business Start-ups reported by Paul Reynolds at the Cambridge workshop suggests that there are about 200,000 technology-based startups in existence; of these, about a third have employees and can

79. According to the PriceWaterhouseCoopers MoneyTree survey, VC investments in Silicon Valley in 1998 were \$4.6 billion, or 30 percent of the national total of \$15.3 billion.

be categorized as small businesses.⁸⁰ Reynolds' estimate is of startups in existence and not the number of startups founded each year. The numbers from Reynolds are roughly consistent with the estimates by Jeff Sohl, based on surveys conducted by a team based at the University of New Hampshire. Jeff Sohl's team found that in 1998 roughly 20,000 firms received funding from angel investors. We scale Reynolds' number downwards, estimating that only about one in ten of the 200,000 startups reported to be in existence by Reynolds—about 20,000 business entities—seeks angel financing each year.

If each of these 20,000 technology startups received \$500,000 in angel financing (an average consistent with the UNH surveys), then total angel financing for ESTD innovation would be roughly \$10 billion. Given the tendency for businesses to use "technology" in a much looser sense than would technical people, we suggest that this is a generous, upper-range estimate.⁸¹

D. UNIVERSITIES AND COLLEGES

Academic institutions play a significant role in the national R&D enterprise. While the federal government provides most of the funds for academic R&D, universities and colleges have funded a steadily increasing portion of their own research budgets since the 1960s.⁸² Universities and colleges provided \$5.0 billion in funding for R&D in 1998; of this, \$3.2 billion was devoted to basic research, \$1.5 billion to applied research, and \$0.3 billion to development.⁸³

Universities are the nation's largest performers of basic research, conducting nearly half of all basic research. Most university basic research, however, is truly just that—basic. Very little, if any, of reported basic research expenditures is likely to fund ESTD work. Applied research activities are more likely to be pertinent to an analysis of ESTD in the academic setting. Some development funds could also be directed toward ESTD. Most surveys do not include a category that specifically tracks support for the commercialization of university intellectual property, complicating any effort to accurately tabulate such investments.

80. Based on the "National Panel Study of U.S. Business Startups," Reynolds estimates that there are fifteen million entrepreneurs in the United States, that 3 percent (approximately 450,000) of entrepreneurs are technology entrepreneurs involved in a startup, and that the average startup has a team size of two. This guess leads to an estimated of 200,000 startups in existence (not startups created each year). Reynolds (2000) and personal communication with Reynolds.

81. From discussions with practitioners and reading of the popular press, we suspect that the very broad use of the word "technology" to include any activity involving information technology or software development may carry over to survey results.

82. Surveys typically ask universities for their R&D expenditures by source, identifying states, federal, industry, and independent laboratories as specific sources and lumping all other sources of income to the university, including gifts from individuals and philanthropy from industry (in contrast to contracts) as "university own funds."

83. National Science Board (2000), tables 2-9, 2-13, and 2-17.

(i) Lower estimate: University support for faculty spin-offs

Universities have become an increasingly fertile ground for the development of new commercial innovations. Respondents to an Association of University Technology Managers (AUTM) survey have reported that revenues from academic licenses nearly quadrupled between 1991 and 1998. The same survey reports that since 1980, more than 2,600 new startups have been formed based on a license from an academic institution, with at least 364 such startups being formed in 1998.⁸⁴ For every successful startup, there are likely many uncounted unsuccessful ventures that never succeed in crossing the divide from laboratory discovery to commercializable innovation. Calculating the portion of university funds that finance such ventures is difficult. Anecdotal evidence suggests that direct financial investments into faculty or student startups by universities is rare, though a number of universities have long-established venture capital funds designed to invest in such initiatives.⁸⁵ More significantly, universities offer support in the form of faculty and staff time, resources of the university technology transfer office, office space, and the like. Survey results reported by the National Science Foundation (NSF) show that universities funded \$327 million in development activities, the “D” in R&D, which may capture post-ESTD efforts of faculty and students in converting academic research into commercially viable innovations.⁸⁶ A similar result would be obtained if 1,500 university-based ventures, one quarter of which were successfully licensed, received \$200,000 each in university support. Thus, we use \$327 million (the NSF number for university development expenditures) as the lower estimate for academic funding of ESTD.

(ii) Upper estimate: University funded applied research

Most ESTD activities within academic institutions are likely to be categorized as applied research in academic R&D surveys. Universities and colleges provided \$1.5 billion for applied research in 1998. Some academic R&D (about 12 percent), however, occurs in fields of science and engineering that have limited prospects for technical breakthroughs of the kind leading to pre-innovation ESTD work. The remaining 88 percent of academic R&D occurs in fields where ESTD activity is more likely: the life sciences, physical sciences, environmental sciences, and engineering.⁸⁷ If we assume that a similar proportion of applied research funds is directed toward these fields, this means that about \$1.4 billion in academic applied research funds are potentially available to fund ESTD research. A significant portion of applied research activities within

84. Association of University Technology Managers (2000).

85. Lerner (1999).

86. National Science Board (2000), tables 2–17.

87. National Science Foundation (2000a), table B–3.

academic laboratories may not have a focus on eventual commercialization of innovations. Nevertheless, we use \$1.4 billion as our upper estimate. This exaggerates the portion of university R&D budgets aimed at promoting commercialization of laboratory inventions, but it sets a practical upper ceiling on estimates of potential university funding of ESTD research.

E. STATE GOVERNMENTS

States play an increasingly crucial role in encouraging regional economic growth through investments in science and technology development. A state government emphasis on applied research with commercial intent is also consistent with the widely accepted premise that state governments are strongly motivated to promote technological innovation and commercialization. They engage in these activities in order to maximize economic prosperity in their states; and, therefore, a considerable share of states' applied R&D funds will potentially be directed toward ESTD activities.

In 1995, the latest year for which comprehensive data is available, state government funding for research and development totaled \$2.4 billion, of which 56 percent was for basic research, 32 percent for applied research, and 12 percent for development and commercialization activities.⁸⁸

(i) Lower estimate: Portions of state-funded applied research

State governments provided \$778 million in applied research funding in 1995. Based on overall state R&D financing patterns, \$523 million of the total is projected to have been spent in fields of science and engineering where ESTD work potentially takes place. Looking at where state-funded applied research is performed can provide a clue to the character of work thus funded. In 1995, an estimated 80 percent of state-funded applied research took place within academic institutions (state colleges, universities, and hospitals), where the motive to commercialize on technical discoveries is presumably less compelling than in industry, the site of only about 4 percent of such research. We arbitrarily allocate only one-half of state-funded applied research performed in universities and colleges, or \$209 million, to ESTD activities, since it is unlikely that all state-funded academic applied research is aimed at commercializing lab-bench discoveries. We include 75 percent of state-funded applied research performed by industry, \$16 million, on the basis that most of it is funded in state-supported innovation programs, in incubators, and other innovation promoting programs.

88. State Science and Technology Institute (1998), table 1 (most recent available data).

An additional 10 percent of state R&D funds were spent intramurally by state government agencies, significantly lower than the portion of federal R&D dollars that remained in house. We allocate half of such research, or \$26 million (half of 10 percent of \$523 million) as potentially funding ESTD activities. Combining these figures provides a lower estimate of \$251 million of state funds flowing to ESTD research.

(ii) Upper estimate: All state-funded applied research funding

Among the state programs that are narrowly targeted at funding pre-commercialization research are cooperative technology programs; public-private initiatives that sponsor the development and use of technology and improved practices by specific companies. Such programs exist in all fifty states, and include notable successes such as the Kansas Technology Enterprise Corporation and Maryland's Enterprise Investment Fund. A State Science and Technology Institute study reported \$405 million in combined state funding for cooperative technology programs across the country in 1995 (the latest year for which data is available), an increase of 32 percent since 1992.⁸⁹

We use a larger number, all state funding for applied research as reported by the State Science and Technology Institute—\$778 million—as our upper estimate for state support of ESTD innovation. While this estimate significantly overstates the proportion of early-stage, pre-commercial research funding in state R&D budgets, it sets an operational upper limit for this assessment.

F. FEDERAL GOVERNMENT

In 1998, federal obligations for research and development equaled \$72.1 billion including \$15.9 for basic research, \$15.6 for applied research, and \$40.6 billion for development.⁹⁰ Nearly half of this total is defense-related. While these funds play a significant role in the development of important military technologies, defense R&D is primarily motivated by national security considerations and largely falls outside of the sphere of market-driven commercial innovation activity that we are focused on here.⁹¹ We therefore exclude defense-related funds, other than SBIR (to which defense is the largest contributor), from our analysis of ESTD research. Of non-defense related funds, only a small proportion is intended explicitly to provide incentives for commercialization of new technical inventions. In addition to programs like the Advanced Technology

89. State Science and Technology Institute (1996).

90. According to the NSF, Federal obligations represent the amounts for orders placed, contracts awarded, services received, and similar transactions during a given period, regardless of when funds were appropriated or payment required. Obligations data allows for detailed analysis of where Federal dollars are ultimately spent. Budget authority data cannot provide such insight since many agency R&D programs do not receive explicit line items in the Federal budget. National Science Board (2000), tables 2-25, 2-27, 2-29, and 2-31.

91. Alic, Branscomb et al, (1992).

Program and the Small Business Innovation Research program that focus on funding ESTD research, a massive variety of research initiatives exist within all federal cabinet agencies and dozens of smaller agencies, including the National Institutes of Health, the National Science Foundation, the Department of Energy, the Food and Drug Administration, and the U.S. Agency for International Development. Within these programs are an unknown—and unknowable—number of R&D projects that might have the potential to lead to new firms or new products of an innovative nature.

(i) Lower estimate: ATP, SBIR, and STTR funding

The Advanced Technology Program (ATP) funds, on a cost-sharing basis, high-risk, early-stage, technology-based projects in both small and large firms. In 1998 (our reference year, chosen for reasons of data availability as well as correspondence with current funding levels), ATP made 79 awards at a total level of \$460 million (public plus private funds). Of this total, ATP provided \$235 million, with the remaining share financed by industry matching funds.⁹²

In the same year (1998) the Small Business Innovation Research (SBIR) program funded 2,975 exploratory-stage (phase I) awards and 1,283 seed-stage (phase II) awards at a total level of \$1.05 billion. In addition, the Small Business Technology Transfer Program, which provides grants to small business and non-profit research institution partnerships to help bring laboratory results into the marketplace, awarded 208 exploratory-stage awards and 108 seed-stage awards at a total level of \$67 million.

All funding by these programs is considered to be directed toward ESTD, since the statutory authority on which they rest call specifically for public-private research partnerships for enabling technologies to encourage high-tech innovations. As noted above, while ATP is explicitly directed toward encouraging innovations of broad value to the economy, SBIR is historically and by law focused on the mission of the agency. However, the flexibility of most agency's R&D portfolio and the political popularity of SBIR has given rise to a substantial emphasis on the economic value attributed to SBIR, even if legally this value is a secondary consequence of the agency's legislative mandate. The combined federal funding for these programs in 1998 was \$1.4 billion and provides a lower estimate for federal ESTD funding flows.

92. The Advanced Technology Program <www.atp.nist.gov> summarizes its mission as follows: "The Advanced Technology Program (ATP) bridges the gap between the research lab and the market place, stimulating prosperity through innovation. Through partnerships with the private sector, ATP's early stage investment is accelerating the development of innovative technologies that promise significant commercial payoffs and widespread benefits for the nation." Significantly, two-thirds of ATP funds were awarded to joint venture projects; these are the kinds of projects one might presume carry the highest technical and financial risks, precipitating the formation of such partnerships. National Science Board (2000), table 2-61.

(ii) Upper estimate: Portions of federal obligations for non-defense research and development

Total federal obligations for non-defense basic research are \$14.8 billion, with most of these funds under the jurisdiction of the National Institutes of Health (NIH), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), and the National Science Foundation (NSF). Over two-thirds of the 1998 total went to academic research institutions where the majority of the nation's most fundamental basic research takes place. Strictly speaking, the scope of basic research work, particularly in academic institutions, would not include ESTD activities, but for purposes of building an upper range estimate on federal ESTD funding, we consider that as much as 10 percent, or \$1.5 billion, of non-defense basic research might be allocated to ESTD work.

For applied research, federal non-defense obligations totaled \$12.7 billion, with \$10.6 billion in fields of science and engineering where ESTD work most likely takes place.⁹³ If half of all these applied research funds, including funds for intramural work at regulatory and non-research-based government agencies, are available and potentially used for ESTD research, we can set an upper range estimate of \$5.3 billion for applied research funds to ESTD activities.

It might also be argued that some portion of federal funds for development flow into ESTD activities. Over 90 percent of the \$9.7 billion in federal non-defense development funding is earmarked for NASA, the Department of Energy, and the National Institutes of Health, and it is unlikely that administrators at these research-focused agencies would report a significant portion of ESTD work as development activities rather than in the generally more appropriate basic or applied research categories. We designate only 5 percent, or \$0.5 billion, of federal non-defense development obligations as potentially flowing to ESTD projects.

Adding these fractional estimates for basic research, applied research, and development provides an upper estimate of \$7.3 billion in federal funding for ESTD research.

93. National Science Board (2000), Table 2-38.

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Annex I.

Summary of Report by Booz Allen Hamilton⁹⁴

INTRODUCTION

In the context of the Between Invention and Innovation project, the Booz Allen Hamilton team completed thirty-nine interviews with respondents from randomly⁹⁵ selected firms: thirty-one with corporations across eight industry sectors and eight with venture capital firms. This memo outlines our findings, including key trends that are influencing the research and development (R&D) environment, resultant pressures these trends have created, and emerging structural solutions. The role and approach to managing ESTD in this changing environment is addressed throughout.

TRENDS

The interviews revealed three key trends that are shaping the environment for corporate R&D, including its approach to ESTD investments. These include the increasing complexity of technology development, increased pressure to demonstrate financial value from R&D investments, and differences in industry and company life cycles.

94. This summary was authored by a team at Booz Allen Hamilton 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). The full report is available on the Advanced Technology Program's website, <<http://www.atp.nist.gov>>.

95. By use of the term "random," we mean to say that the criteria by which firms were selected were not correlated in a direct or obvious way with any questions or issues or interest in this study. Among the key biases in the firm selection process was a strong tendency on the part of the project team to select for interviews respondents from firms with which Booz Allen Hamilton has an existing or past business relationship.

R&D PROCESS EVOLUTION: INCREASING COMPLEXITY AND WEB-LIKE PROCESS

Most interviewees generally agreed with the classification of R&D into the four steps in the innovation framework used in our discussions (Basic, Concept/Invention, ESTD, Product Development). However, there were many reactions to the linear simplicity of the framework, compared to the typical path from invention to commercial innovation that the participants have experienced. The four-step framework represents an idealized view of technology progression, while the actual pathway includes multiple parallel streams, iterative loops through the stages, and linkages to developments outside the core of any single company.

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 invention to commercial innovation pathway 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 has rapidly diminished. There are simply too many potential ideas and too few resources to go it alone.

PRESSURE FOR MEASURABLE RESULTS: FINANCIAL RETURN

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, and makes it difficult to justify many activities that do not support existing lines of business. Projects that did not have demonstrable financial benefits were not funded, and the R&D portfolio shifted dramatically toward product development. This trend transcended all of the industries that we covered.

INDUSTRY AND COMPANY LIFE-CYCLE 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 life-cycle positions. Overall, ESTD spending was estimated at \$13.2 billion annually, 9 percent of total corporate R&D spending. However, the level of spending on ESTD differs widely by industry, and by company within specific industries. For example, the estimated ESTD spending in the computer software industry is essentially zero, while the bio-pharmaceutical industry spends about 13 percent of its R&D funds on ESTD. Within the bio-pharmaceutical industry, spending on ESTD ranged from 0 percent to 30 percent at the companies interviewed.

We believe that the key driver of these differences is the life-cycle position of the industry and the individual company. More mature industries such as automotive tend to invest a smaller percentage of R&D into earlier stages such as ESTD than do industries at an earlier stage of development such as biotech. 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 and earlier stages after recognizing that they were not positioned for growth. In some cases they have managed complete transformations out of a historical line of business and into high-tech sectors in which they did not participate a decade ago.

IMPLICATIONS

The observed trends in R&D have resulted in two critical problems that are forcing organizations to re-evaluate their approaches to funding and managing the innovative process. Technology complexity has altered the scale and scope tradeoff of R&D while financial and life-cycle pressures have created a bias toward supporting product development for established firms.

SCALE AND SCOPE CHANGES FOR R&D

ESTD projects can generate tremendous value due to their potential broad applicability as new enabling technologies. However, most large corporations are interested in ESTD for a few specific applications related to their core businesses, and are often not interested in fully exploiting ESTD in other markets.

There is nothing new about this scope dilemma that stems from R&D; it is widely recognized and is called by many names, including spillover effect and options value. However, there is a strong sense among the companies interviewed that the scale of opportunity required to justify ESTD investments has increased with technology complexity, while the ability of corporations to exploit the full range of such potential opportunities is the same or less. Further, the cost of bringing an ESTD to market is significant. Consequently, constructing a compelling business case for allocating funding to ESTD becomes extremely important.

TABLE 3. R&D spending profile by industry

	2000 R&D Spend Allocation				R&D Spending (\$ million)			
	Basic	Concept/ Invention	ESTD	Product Dev't	Surveyed Companies	Industry	ESTD	ESTD Range
Surveyed Industries								
Electronics	0%	5%	11%	84%	1,039	30,408	3,463	0%–40%
Chemicals	3%	28%	33%	38%	2,000	8,548	2,778	25%–40%
Biopharmaceutical	0%	0%	13%	86%	509	17,722	2,373	0%–30%
Basic Industries & Materials	0%	5%	7%	87%	1,078	21,215	1,547	0%–15%
Telecommunications	0%	0%	10%	90%	157	13,085	1,305	0%–35%
Machinery & Electrical Equipment	0%	0%	10%	90%	540	10,642	1,064	10%
Automotive	1%	3%	3%	93%	6,800	20,389	612	3%
Computer Software	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	–	
Services						10,545	–	
Aircraft, missiles, space						4,175	–	
Subtotal						39,649	–	
Total						180,419	13,213	7.3%

Source: BAH Analysis; Interviews with Corporations; National Science Foundation and the United States Department of Commerce, "U.S. Corporate R&D: Volume 1. Top 500 firms in R&D by Industry Category," NSF 00–301.

BIAS TOWARD PRODUCT DEVELOPMENT AND KNOWN MARKETS

The combination of financial pressure and industry and company life-cycle issues has also created a bias toward product development and support. Table 3 clearly shows that the bulk of R&D spending is concentrated in these later stages.

In addition, most corporations interviewed expressed a bias toward focusing their R&D on their existing businesses rather than creating new technology that might enable entry into new markets. Thus, as shown in Figure 5, most R&D funds flow into the left-hand side, with the bulk serving existing markets and existing technologies. Very little spending flows to drive breakout developments that represent new technology for new markets.

Interviews with venture capitalists also revealed a strong preference for investments targeted to exploiting a technology in a specific market application. Seed funding often goes to help develop a commercial prototype, but the largest rounds of funding are concentrated on taking the product commercial.

FIGURE 5. Typical corporate R&D spending profile

Market	New	5–10%	<5%
	Existing	80–100%	5–10%
		New	Existing
		Technology	

EMERGENT RESPONSES

Formalized approaches to managing R&D portfolios and an increased reliance on alliances, acquisitions, and joint-venturing to obtain access to ESTD and earlier stage technologies were cited as the most common reactions to the changing R&D environment and resultant pressures. In most cases a key stated objective was to maintain access to critical new ideas, while maximizing the leverage that could be obtained from any such investment.

PORTFOLIO MANAGEMENT MODELS

Most of the companies interviewed described a formalized R&D portfolio management process that they used to select investments. Many have revisited the issue of how the portfolio should look over time, especially as they hit discontinuities in their core businesses. Several described how they consciously made an effort to restructure the process to increase funding allocated to earlier stage work like ESTD, after discovering that they had allowed their technology portfolio to swing too far toward the product development end of the spectrum. Others felt that the portfolio process at their company helped maintain a bias toward the near term.

While no two companies appeared to be using the same approach to managing their R&D portfolio, several common elements were apparent. These include defining a set of technical core competencies to guide investment decisions, a split of funding control between business units and a central corporate organization, and some discretionary funding mechanism that can be used to foster new ideas (for instance, granting senior scientists slush funds, or creating central investment funds dedicated to long-term investments). Many also had established dollar or percentage spending targets for specific types of investment and used a classification system similar to the four-steps model or new and existing model as illustrated in Figure 5. 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.

ALLIANCES AND ACQUISITIONS AND VENTURE FUNDS

Alliances, acquisitions, and other external ventures were cited as an increasingly common way of maintaining access to a steady flow of new technologies and ideas, including ESTD. The companies interviewed also indicated that they have become increasingly targeted in selecting partners and technology rights. Adopting a market-like approach to acquiring early-stage technologies as opposed to developing it internally helps limit the scale of R&D required to sustain their organization and to pay for only the portion of the ESTD scope that they intend to use.

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

Most interviewees also indicated that they had partnerships with universities and sometimes government labs. These interactions can be somewhat broader than an outright alliance, but are generally targeted to provide 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 a relationship with a specific professor or scientist rather than an academic department or entire school.

Establishing a relationship with venture funds as another form of alliance was frequently described. 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 and obtained rights to more actively participate in offerings that become commercially interesting to them.

SPIN-OUT OF R&D FUNCTION: ESTD ENGINES FOR HIRE

An alternative solution to the ESTD funding barrier faced by corporate R&D was demonstrated by one of the companies interviewed. This company had been the corporate R&D arm of a Fortune 500 firm, but was spun out as a private entity that is now in the business of contract R&D. Compared to the portfolio of firms with captive R&D, this company works disproportionately on ESTD research; nearly 80 percent of its R&D spending is allocated to ESTD type research. Essentially, this spin-out company has become an ESTD engine for its client companies. Because its business plan is not captive to a single business or focused in a specific industrial sector, it is better able to exploit the scope potential of ESTD by structuring its contacts to maintain rights in fields of use that are not of interest to its clients. It then either licenses or commercializes products in the untapped areas.

Annex II.

Company Narratives

This section presents brief profiles of early-stage technology development in four of the companies whose representatives participated in Between Invention and Innovation workshops: Affymetrix (Ken Nussbacher), Energy Conversion Devices (Nancy Bacon), Marlow Industries (Hylan Lyon), and PolyStor Corporation (James Kaschmitter).

Four case studies, separately published, examine in detail the experiences of selected project participants in managing the process of transition from invention to innovation, providing specific examples with successful projects. The subjects (and authors) of those case studies are: Band of Angels (Jonathan Westrup); Caliper (Mona Ashiya); GE/Amorphous Silicon (Bob Kolasky); PPL Technologies (Thomas F. Livesey). Each of those full case studies provides an overview of the history of the firm or project group, a discussion of the evolution of the technology that forms the basis of the effort, a description of the enablers and constraints that the effort faced as it moved from invention to innovation, and a discussion of how this fits into the current thinking on public support of such work. The case studies are available on the Advanced Technology Program's website, <<http://www.atp.nist.gov>>.

1. AFFYMETRIX

Affymetrix, located in Santa Clara, California, is a leader in the field of DNA chip technology. Affymetrix has developed its GeneChip system and related microarray technologies as a platform for acquiring, analyzing, and managing genetic information. Affymetrix sells its products directly to pharmaceutical and biotechnology companies, academic research groups, private foundations, and clinical laboratories in the United States and Europe. Affymetrix has more than 750 employees.

Affymetrix is a spin-off from Affymax. The latter was founded in 1988 by Dr. Alejandro Zaffaroni—who also launched Syntex Laboratories, Alza Corp. and Dnax Research Institute—to accelerate the drug discovery process. The traditional approach in drug discovery has been to synthesize or discover new candidate drugs and then test their activities one at a time. This is a tedious and cumbersome approach, so speeding up or automating this process is of substantial interest to pharmaceutical companies. To launch Affymax, Zaffaroni assembled a list of star scientists, including Carl Djerassi, Joshua Lederberg, and Peter Schulz. The firm's board of scientific directors included four Nobel laureates. The combinatorial chemistry and high-throughput screening technology developed by Affymax combined synthetic chemistry and photolithography to enable synthesis and screening of compounds on chips.

A variant of this technology was developed by Steve Fodor and his colleagues at Affymax, using solid-phase chemistry and photolithography to achieve spatially addressable parallel chemical synthesis to yield a well-defined microarray of peptides or oligonucleotides. This formed the basis of Affymetrix's technology. The team's initial focus of using chips to synthesize peptides useful in the drug discovery process did not work very well, and Fodor shifted his attention to DNA probes, with extremely successful results. The work was published in *Science* in early 1991 in what is now considered a landmark paper. The original team that developed the idea—Fodor and his colleagues Pirrung, Read, and Stryer—won the Intellectual Property Owners Association's Distinguished Inventor award in 1993. Affymax spun off Affymetrix the same year. The new firm raised \$21 million in its Series A private placement, then another \$39 million in its Series B placement. It went public in 1996 with a valuation of \$300 million.

At the time of the spinoff, Affymetrix had no specific product—in fact, its principals did not even think of it as a product company. Through further development of this technology over the next five years, however, Affymetrix developed the initial versions of its first commercial product, the GeneChip system. Affymetrix's R&D expenditures rose over this period from \$1.57 million in 1991 to \$6.57 million in 1993 and \$12.42 million in 1995 (funded internally as well as through research contact and grants). The GeneChip system consisted of disposable DNA probe arrays containing gene sequences on a chip, instruments to process the probe arrays, and software to analyze and manage genetic information. The company commenced commercial sales of the GeneChip system and an HIV probe array for research use in 1996. As of March of that year, Affymetrix had been able to sell nine GeneChip systems, all intended solely for research use. Still, Affymetrix's stated goal in its IPO prospectus was to establish the GeneChip system that it had developed as the platform of choice for acquiring, analyzing, and managing complex genetic information in order to improve

the diagnosis, monitoring, and treatment of disease. By September 2001, the majority of the top pharmaceutical companies, over a dozen biotech firms, and more than 1000 academic institutions were customers for the firm's GeneChip and other technologies. At the time of its public offering, all of Affymetrix's revenues had been derived from payments from collaborative research and development agreements and government research grants (\$4.63 million in 1995). By 2000, Affymetrix's R&D expenses were \$57.4 million and its product sales for that year were \$173 million.

With the aim of broadening its product offerings, Affymetrix acquired firms such as Genetic Microsystems, to help it access the spotted array market, and Neomorphic, to advance its bioinformatics software and enhance chip design. Affymetrix also formed and financed Perlegen Sciences at a cost of about \$10 million to leverage its technology to perform whole-genome scanning and assess genetic variance. Beyond its internal R&D efforts, Affymetrix entered into a variety of collaborative agreements and alliances with other firms to help develop and improve its products, even during its earlier stages. In late 1994, the company entered into a collaborative agreement with Hewlett-Packard to develop an advanced scanner for use with the GeneChip probe arrays. The firm had two agreements with the Genetics Institute in 1994 and 1995 relating to use of GeneChip technology to measure gene expression in order for the Genetics Institute to develop new therapeutic proteins. In 1996, Affymetrix entered into an agreement with Incyte Pharmaceuticals, Inc., to explore potential uses of DNA probe arrays in the area of gene expression. In the same year, Affymetrix entered into an agreement with Glaxo (now Glaxo-Wellcome) to design, test, and supply probe arrays to demonstrate use of the arrays in detecting polymorphisms in specific genes.

Affymetrix illustrates one stage of the innovation process, whereby a startup firm that is engaged in generating databases or creating software tools, even if these are not its ultimate product, enters into meaningful collaboration with larger firms that are in essence outsourcing part of their R&D to these startups. In Affymetrix's case, this is not the business model that it is pursuing today, but it was a useful stream of revenue for it that time.

Building an intellectual property base is an important component of Affymetrix's strategy. The company believes that its success depends in part on its ability to obtain patent protection for its products and processes, to preserve its copyrights and trade secrets, and to acquire licenses related to enabling technology or products used with the company's GeneChip technology. At the end of the year 2000, Affymetrix had 105 patents. License fees and royalties also contributed about 10 percent of the firm's income in that year.

Affymetrix also relied on numerous government grants for funding various components of its research program and technology development efforts. For example, the firm received over \$500,000 in 1992 and 1993 under a Small Business Innovation Research grant from the Department of Energy (one of the many SBIR grants that it has received). The first phase of the grant helped demonstrate proof of the concept of using large arrays of DNA probes in genetic analysis. The Phase II grant was intended to assist Affymetrix in moving the technology towards commercialization. Scientists at Affymetrix also received several grants from the National Institutes of Health. For example, Fodor was a principal investigator on a three-year \$5.5 million NIH grant. One component of this grant addressed the development of chip-based sequencing, resequencing, and sequence checking and physical, genetic, and functional mapping. A technology development component addressed the production of chips and the development of instrumentation and software specific to the chip applications. Affymetrix's biggest government grant came from the Advanced Technology Program (ATP) of the National Institute of Standards and Technology (NIST). A consortium established by Affymetrix was awarded a \$31.5 million, five-year grant in 1994 to develop miniaturized DNA diagnostic systems. Under this grant, Affymetrix directly received \$21.5 million, some of which was used to fund activities at a number of collaborating institutions as subcontractors to the project. As part of this grant, Affymetrix and its partner Molecular Dynamics collaborated with researchers at the California Institute of Technology, Lawrence Livermore National Laboratory, Stanford University, the University of California at Berkeley, and the University of Washington to develop the next generation of diagnostic devices to capitalize on the advances of the Human Genome Project.

These kinds of collaborative research efforts are a deliberate strategy of Affymetrix, carried over from Affymax, to maintain simultaneously within the firm an entrepreneurial environment as well as an academic environment. The firm had a goal to attract preeminent researchers and convince them that the company was a place that was carrying out cutting-edge technology. Steve Fodor, for example, was persuaded to leave his postdoctoral research position at the University of California, Berkeley—despite his initial lack of interest in leaving academia—by the possibility of continuing to work with some of the field's brightest academics as well as having in-house funds with which to do research. The freedom to seek outside grants to pursue research peripheral to the company's core strategies was also considered a very important tool in attracting very high-quality people to the project. It has been very valuable to Affymetrix to be able to attract staff who continue to keep their academic contacts through participation in preparing grant proposals, and who have the freedom to pursue ideas to which they have dedicated their career, while gradually migrating into a

commercial environment where more tangible products can be generated. The exercise of building a consortium of other companies to work together under the ATP project, for example, fed a very collegial environment where researchers worked hard with the best people in their field around the world, pushing these technologies to a stage at which they could be commercialized successfully.

2. ENERGY CONVERSION DEVICES

Energy Conversion Devices, Inc. (ECD), is a technology and manufacturing company located in Troy, Michigan, and founded in 1960 by Stanford and Iris Ovshinsky. The firm is engaged in the invention, engineering, development, and commercialization of new materials, products and production technology with a focus on atomically engineered amorphous materials. ECD's business strategy is technology-driven and focused on the development and commercialization of enabling technologies for use in new global markets and industries, such as alternative energy and information technology. ECD has just over 500 employees.

ECD has three core product areas:

- **energy storage**—nickel metal hydride (NiMH) batteries and hydrogen storage systems;
- **energy generation**—regenerative fuel cells and thin-film, flexible, low-cost (solar) photovoltaic (PV) products; and
- **information and data storage & retrieval**—phase-change optical and electrical memory technology.

All of these core products are based on ECD's proprietary materials and technologies in the area of disordered and amorphous materials.

ECD's early-stage technology development often starts with some internal funding but is generally dependent, for carrying the R&D forward, on government/industry partnerships (involving, for example, the Department of Energy, the National Institute of Standards and Technology's Advanced Technology Program, or other government agencies). ECD also routinely establishes joint ventures, licensing arrangements, and other strategic alliances with major companies around the world to bring its products to market and generate funds for R&D efforts. ECD's direct R&D expenditures in the year ending June 2001 were \$34.7 million, of which licensees, government agencies, and

industrial partners accounted for \$26.9 million and internal funds accounted for the rest. In the area of photovoltaics, for example, ECD formed a strategic alliance and joint venture in April 2000 with N.V. Bekaert S.A. from the Netherlands to manufacture and sell solar cells. United Solar, an ECD joint venture that will manufacture these PV-based products, is building a plant with an annual capacity of twenty-five MW. These products—for remote power applications, telecommunications, PV-powered lighting systems, and building-integrated PV systems—are based on a sophisticated multi-layer amorphous silicon thin-film solar cell developed originally by ECD. The spectrum-splitting technology of this cell allows it to convert the different visible and near-infrared wavelengths of sunlight efficiently. The United Solar spectrum-splitting multi-junction design now holds all the world's records for amorphous silicon solar-cell efficiency. These solar cells are manufactured in a unique continuous “roll-to-roll” solar-cell deposition process, also developed by ECD, in which the thin-film semiconductor layers that comprise the cell are sequentially deposited in separate, dynamically isolated, plasma-enhanced chemical vapor deposition (PECVD) chambers as the stainless steel substrate progresses through the machine.

ECD began developing this thin-film PV technology as well as the roll-to-roll manufacturing process during the 1970s. The firm initially started its PV work with internal funding. ECD also had an agreement—essentially a license focused on R&D—in 1979 with Arco. At this time, ECD had small, laboratory-sized prototypes. Arco ended up withdrawing in 1982 from the relationship because the limited size of the PV market was unattractive. ECD then formed a joint venture with Standard Oil (SOHIO) in 1981 that built a pilot plant to test the roll-to-roll technology—the first time this was done on a pilot-plant basis. This joint venture was terminated after British Petroleum took over Standard Oil. Soon after this, ECD was approached by Canon, which was using amorphous silicon technology in its copiers. The usefulness of ECD's amorphous silicon technology for copier drums, as well as Canon's increasing interest in PV, resulted in the signing of a license agreement between the two firms that was basically a \$15 million paid-up license providing ECD with funds for further research and development. In 1990, Canon and ECD upgraded their relationship to a joint venture, named United Solar, that was focused on market development. Eventually, Bekaert provided the funds by which ECD bought out Canon's share of the joint venture.

The United Solar joint venture built a five-MW plant that was based on roll-to-roll technology that had been refined enough to set up a production line. The triple-junction solar cells produced by this plant were the result of R&D efforts on solar-cell design over the past decade. The relationship with Bekaert is the latest step, then, in what has been a long road to the development and commercialization of ECD's advanced photovoltaic technologies. Bekaert's total investment commitment relating to this strategic

alliance is \$84 million, which includes \$24 million provided to ECD as partial payment to purchase Canon's stock in United Solar and an investment of \$60 million in United Solar and in Bekaert ECD Solar Systems, another joint venture that assembles and sells the solar panels and systems manufactured by United Solar. ECD has also benefited from technology development contracts with the U.S. Department of Energy (through, for example, the PV:BONUS, the Thin Film partnership, and the PVMAT program) and the Department of Defense.

Based on R&D that ECD conducted in the 1980s, ECD and United Solar have developed, and United Solar and Bekaert ECD Solar Systems are manufacturing and selling, products for the building industry. These include photovoltaic PV shingles, metal roofing products, and PV laminate products that emulate conventional roofing materials. United Solar received the Popular Science 1996 Best of What's New Grand Award and the Discover Magazine 1997 Technology Innovation Award for its flexible solar shingles.

Protecting its leadership position in the science and technology of new materials, products, and production systems is an important component of ECD's strategy. As of early 2001, it had 354 valid and current United States patents and 832 foreign patents. Its proprietary PV technology is protected by 165 U.S. and 622 foreign patents. In 1982, it had thirty-five U.S. patents in this area; by 1986 it had 52 patents; by 1988 it had 107 patents; and by 1990, 122 patents. Thus its patent portfolio has grown along with its technical and business development of amorphous silicon PV technology.

U.S. government agencies have played many other key roles in ECD's early-stage technology development by helping the company get to a point where it can prove feasibility of its technologies and develop prototypes so that it can attract strategic alliances, partnerships and joint ventures. For example, ECD received a grant from ATP to demonstrate a new optical disk manufacturing technology that allowed it to apply its expertise in roll-to-roll vacuum manufacturing and phase-change materials to develop a process technology that both formats and coats DVD disks as part of a continuous, low-cost manufacturing system. The technology developed with the help of this project eventually led to a joint venture with General Electric. The evolution of work done under another ATP grant between 1997 and 2001 to develop advanced materials technology for future low-cost, high-energy-density improved NiMH batteries using magnesium-based hydrogen storage materials eventually led ECD to build a relationship with Texaco on hydrogen storage technology. ECD was also part of the U.S. Advanced Batteries Consortium through which it received about \$30 million for its work on NiMH batteries that resulted, in part, in a joint venture with General Motors.

3. MARLOW INDUSTRIES

Marlow Industries is the global leader in thermoelectric cooling technology. Established in 1973 in Dallas, Texas, as a spin-off from Texas Instruments, Marlow Industries has developed and manufactured thermoelectric coolers (TECs) and subsystems for the military, aerospace, medical, high-speed integrated circuits, and telecommunications markets. It is a technology leader; its materials are the most efficient, about 15 percent above the average of all other firms' offerings, including those in Russia, Japan, and the United States. Marlow has over 700 employees.

The basic idea underlying thermoelectric devices is fairly old. Thermoelectric coolers are solid-state heat pumps that operate on the Peltier effect, first observed in 1834. Major advances in thermoelectrics, however, did not come until the 1950s; advances in thermoelectric materials became possible following burgeoning research into semiconductors, since these materials share many of the same characteristics. Lack of significant advances in efficiency of thermoelectric devices led to a cutback in basic research in thermoelectrics in the mid-1960s and a stagnation until the early 1990s, when new research jump-started the field.

About the same time, the curiosity of Raymond Marlow, the founder of Marlow Industries, was piqued by customers asking why the efficiency of thermoelectric materials seemed to have reached a limit. He and his researchers wanted to improve their theoretical understanding of the problem and renew the search for materials that might break this barrier.

This led Marlow to hire Hylan Lyon, a chemist by training, to set up a research program to tackle these issues. Before Lyon was hired in 1993, Marlow Industries had no research on thermoelectrics to speak of. It was a specialty manufacturer of thermoelectric devices and its strengths were engineering and manufacturing; it was then, as it is now, the leading supplier of thermoelectric devices in the world.

Lyon started the research program with a focus on developing new materials with a higher "figure of merit" (a measure of the efficiency of the device that can be built using this material). There were a number of directions the research program could have gone at that point, and Lyon's choice was to explore a number of options simultaneously. The firm now has a unique proprietary position in a number of areas. New materials developed by Marlow are generating earnings and the firm is in the position to increase its revenues significantly. Lyon also started looking at new manufacturing processes and eventually the focus of his research and development including production.

The firm started the research program with its own funding to begin with. Marlow is in the fortunate position of being a specialty manufacturer with higher margins than most commodity manufacturers. It is privately held and has little debt and thus could start the research with its own funds. It had a contract with NASA to develop and improve refrigerators it was using in the space station and other applications. While this did not force much of a shift in the firm's technology, the revenue stream from this contract allowed the company to hire some researchers. Marlow applied successfully for a number of SBIR grants at a number of agencies such as NASA and DARPA. Overall, it obtained about eight Phase I grants in the range of \$75,000–100,000 each. These grants were mostly of different but inter-related topics, all little pieces of the overall development plan.

While it received very good reviews and were recommended for Phase II on essentially all of these grants, due to other factors (such as programmatic constraints in the funding agencies or bureaucratic reasons) the company received only three Phase II grants. Still, this amounted to a substantial level of research funds. Marlow has also received funds from the DOE in the form of research grants as well as a Cooperative Research and Development Agreement (CRADA) through the Oak Ridge National Laboratory. Marlow also applied for two ATP grants, although these applications were unsuccessful. The first time, says Lyon, it was told that its proposal was too risky and the second time that it was not risky enough.

An important benefit of raising money from competitive government programs was to increase the credibility of the R&D team with the company's senior management. The fact that funding was obtained from government agencies in multiple cases in a very competitive environment improved the team's standing. The share of the R&D that is funded internally has been steadily increasing. In fact, Lyon is in the process of doubling its R&D budget, the number of people, and the equipment budget.

Marlow also tried to raise money by approaching as strategic partners those who would have the most to gain if the firm succeeded, such as refrigerator manufacturers and chip coolers. While these partners expressed interest, ultimately they were unable to provide funding to Marlow. Conversations with venture capitalists and family funds were also unsuccessful, in large part because it was difficult for these entities to assess the risks associated with this unusual technology.

One of the problems faced by Marlow in the funds that it raised from agencies was the lead times involved. One of the NASA programs had a 22-month gap from the time Marlow bid to the time it got its first cash. In another case, an NSF Phase II process went on for a year and half before a final decision was made. In such cases, it

would have been impossible to hold the team together without internal resources. In many other SBIRs, though, there is only a small lag between finding out that one has been awarded a grant and being able to obtain funds from the agency.

An important strategy for Marlow has been to fund external researchers on retainer. For example, some researchers at the Jet Propulsion Laboratories (JPL) were about to be laid off because of a short-term cash problem, so Marlow covered their salaries for three months through a technology-associated agreement to keep them there and assure the continued growth of the department. This has resulted in a very fruitful partnership.

4. POLYSTOR CORPORATION

PolyStor, a privately held company based in Livermore, California, designs, develops, and manufactures rechargeable lithium-ion and lithium-ion polymer batteries for mobile devices and portable electronic products. The firm was founded in 1993 to bring to the market technology that was developed by its founders in the 1980s when they were at the Lawrence Livermore National Labs (LLNL) and engaged in the development of lithium-ion (Li-ion) technology for the Strategic Defense Initiative (“Star Wars”) defense program. After suffering a sharp decline for its products in 2001, tied to a global decline in demand for cell phones, PolyStor ceased operations in winter 2002.

PolyStor was the first Li-ion battery producer in the United States and the first to use a nickel cobalt oxide cathode that delivers the highest capacity and energy density in the industry. Based on an exclusive license for technology developed by Motorola, the firm also produced the world’s first commercially available curved Li-ion polymer battery. In winter 2001 the firm employed roughly 150 people, with a staff of 35 in research and development.

The founders of PolyStor were interested in spinning out the technology in the early 1990s at the end of the Cold War when government funding for military projects such as the one they were engaged in was starting to go down. At the same time, they had been able to develop some very successful cells and had also applied for patents to protect this technology. Concerns about conflicts of interest between inventors and commercial users were avoided by spinning out PolyStor through a Defense Advanced Research Projects Agency (DARPA) Technology Reinvestment Project (TRP) grant in which LLNL was also a participant. Commercial companies such as Rockwell were also partners in this project.

This DARPA contract was for development of an ultracapacitor. The Aerogel capacitor, which also utilized technology developed by another group at LLNL, was one of the firm's early products. The research on this capacitor was related, through the underlying chemistry, to the basic technology of the company's proprietary cells. For the first year, the company was funded by the DARPA contract as well as by the founders' own money. This was followed by seed funding from a Korean firm that allowed the firm to build its program further based on a successful demonstration of the company's battery. The development of the firm's lithium-ion cell took about two or three years after this point, and it took another year once the cell had reached production to ensure that the product was safe and would pass UL testing. It ultimately did and has been tested by Motorola and other major manufacturers. By 1996, the firm was producing these lithium-ion cells. At that time, though, PolyStor did not have its own manufacturing capabilities—it made the components in the United States and then shipped them to Korea for assembly.

Soon after, Polystor received an SBIR grant from the Ballistic Missile Defense Organization. This grant allowed the firm to carry out further research on a cell with a nickel-cobalt (Ni-Co) chemistry. Developing the Ni-Co chemistry was important for PolyStor's ability to access the market because it differentiated the company from Japanese companies that were manufacturing cells with cobalt chemistries. The Ni-Co cells also offered the advantages of higher energy density and lower costs, although getting them to work right in production presented significant technical hurdles.

About the same time PolyStor received the SBIR grant from the BMDO, it also obtained funding from a British company that allowed it to build its own plant in Livermore for which it ordered high-volume, automated production lines from Sony of Japan. The firm still needed to work out some issues relating to the production of its cells for which it needed more resources; it experienced a brief lapse in funding here. In 1998, the firm signed a contract with the U.S. Army CECOM group for Li-ion batteries. The firm began mass production in 1999 with its 8-millimeter-thick Li-ion prismatic cells.

The same year, it also won a major \$9.5 million grant from the United States Advanced Battery Consortium (USABC), part of the government-industry Partnership for a New Generation of Vehicles (PNGV). The technology that had been developed by PolyStor worked very well for pure-electric or hybrid vehicles that are driven by battery-powered motors. The larger cell developed by PolyStor for these applications can deliver a high current (150 amperes) and using a stack of cells (to get the right voltage) in a car will allow for improved acceleration. PolyStor also won a grant in late 2000 from the National Institute of Standards and Technology's (NIST) Advanced

Technology Program (ATP) to help it to develop a safe, ultrahigh-capacity rechargeable battery based on Li-ion polymer gel technology. The objective of this grant was to allow PolyStor to develop the next generation of safe, ultra-light batteries for the handheld rechargeable battery market.

Overall, government funding played a central role in PolyStor's formation and technology development efforts. The firm might not have been started but for the DARPA funding. The SBIR from the BMDO underpinned the research on the Ni-Co chemistry. The firm would not have had the resources to develop the advanced car batteries without PNGV funding—the development of these larger cells at PolyStor was completely subsidized by the government funding. Most of its venture funding was focused on meeting near-term financial goals, ramping up production, and marketing. The government funds were also helpful because these funds gave the company better leverage in negotiating over other funding. Government contracts also were useful to PolyStor because they allowed the firm to develop partnerships. Subcontractors involved in PolyStor's ATP grant included groups at Argonne National Laboratory, Entek International, and the Illinois Institute of Technology.

Annex III.

Agendas for Workshops and Participant Biographies

Two practitioner workshops were held: at the Carnegie Endowment for International Peace in Washington, D.C., on January 25, 2001, and at the Xerox Palo Alto Research Center (PARC) in Palo Alto, California, on February 2, 2001. An analytic workshop was held at the Kennedy School of Government (Cambridge, Massachusetts) on May 2, 2001. The workshops brought together representatives from the following groups:

- venture capitalists and angel investors;
- corporate technology managers;
- university technology licensing officers;
- technologists;
- entrepreneurs;
- representatives from the Advanced Technology Program (ATP) of the National Institute for Standards and Technology and the Small Business Innovation Research programs (SBIR);
- representatives from both federal agencies and private firms engaged in gathering and organizing data on private-sector R&D investments, including the National Science Foundation (NSF), the Census Bureau, and the National Venture Capital Association (NVCA); and
- academics specializing in the study of technological innovation and entrepreneurship.

WASHINGTON, D.C.

(Carnegie Endowment for International Peace):

January 25, 2001

PANEL 1. EARLY-STAGE, TECHNOLOGY-BASED INNOVATION: OVERVIEW OF DATA AND DEFINITIONS

Can we sensibly define a stage in the innovation process beginning with invention (proof of concept for a high-tech innovation) and ending with innovation (readiness for market entry with first product)? What is known about the sources of finance for the R&D required for this transition? What is further known about the distribution of those sources according to specific stage of technology development, technology area, geographical region? How do public and private institutions and funding sources interact to support technology development in this stage? How might existing public data be interpreted to provide us with a more realistic picture of the intensity of effort over time in this stage of technology development?

Is there enough information about supply and demand for seed, angel, and bootstrap resources to justify the conclusion there exists a financial gap in the support of early-stage, technology-based innovations (that is, market failure) to match the R&D gap derived from institutional failures? (See Branscomb and Auerswald 2001.) How do firms, investors, and agencies view the problem of finding resources for the invention-to-innovation transition? What type of further research (such as data gathering and/or analysis) would help to inform this question? What is the public policy motivation for exploring these questions? In particular, to what extent are government programs like ATP—perhaps SBIR and others as well-motivated by perceptions that there exists a financial gap as described above and are consequently aimed at the stage of innovation we characterize as being between invention and innovation. What other motivations (other than government procurement) exist for federal programs that provide support to early-stage, technology-based innovation?

Lewis Branscomb, *Kennedy School of Government, Harvard University*

Philip Auerswald, *Kennedy School of Government, Harvard University*

PANEL 2. TECHNOLOGY FOCUS: AMORPHOUS SILICON

We first hope that the panelists will reconstruct for us, in summary form, the history of commercial amorphous silicon (Si) devices. When and where were the key inventions made? Was there a point when proof of concept for a commercial product was in hand, but before product specs, production processes, costs and markets were defined and

business revenue could be committed? Can these two points be recognized in the history or were there multiple, overlapping, premature entries to market before the technology was ready for successful commercialization? Does the history of this case match the “invention to innovation” model proposed for this project?

For which firms were amorphous Si devices a mainstream product for the business the firm considered “core” and for which were they an attractive, but off-core opportunity? How did that influence decisions and sources of funding for the R&D to exploit the opportunity?

Further questions to each panelist

- How was the early (seed) stage of the work funded in the panelists’ respective firms and elsewhere, and how were the decisions made to invest? Was funding from internal corporate resources? Venture capital? Federal grants or contracts? Potential customers or business partners?
- Do you know if your firm’s R&D is reflected in the National Science Foundation (NSF) industrial survey that generates the data for the biennial Science & Engineering Indicators reports, and, if so, how the research on amorphous Si work was reported (that is, as basic, applied, or development)?

Mark Myers, *Xerox Corp. (ret.) and Wharton School* (moderator)

David Carlson, *Thin Film Division, BP Solarex*

Nancy Bacon, *Energy Conversion Devices*

PANEL 3. MAPPING CORPORATE INVESTMENTS

What are the best sources of data on corporate funded R&D? Can the fraction devoted to technology-based, high-tech innovations be teased out of the data? Specifically, what does the NSF industrial survey tell us about this? Even more specifically, is there anyway to distinguish corporate R&D that is invested in innovations for markets outside the corporate core business and those within it? Or is the former simply too small to measure?

Even for the corporate R&D within the core business, can the decisions on investment be matched to the model proposed in this project—that is, research to generate inventions and proof of concept for commercial applications, versus research to convert that knowledge into the information (product specs, production process, estimate costs, and initial market) required to put the product in the corporate revenue plan? Do individual firms manage innovations in such a way that they even know what the

R&D gap costs are? How close does this second decision point compare to the point at which venture capitalists invest the first stage venture funding in high-tech start-ups?

Is there any way to estimate what fraction of the NSF aggregate data on industrial R&D is—first, outside core business priorities, and second, as it corresponds to funding to bridge the disjuncture between invention and innovation?

Arden Bement, *Purdue University* (moderator)

Bruce Griffing, *Corporate Research Center, General Electric*

Raman Muralidharan, *Booz Allen Hamilton*

John Jankowski, *National Science Foundation*

PANEL 4. MAPPING VENTURE CAPITAL AND ANGEL INVESTMENTS

How can we quantify the three major sources of private finance for early-stage conversion of inventions to innovations—venture capital seed investment, angel investments, bootstrap financing? Can we get any useful breakdown by technology/industry and by geographical region? Is there any way to know or estimate how much of this funding is spent on technical work, such as R&D, rather than other business costs associated with building a new enterprise? Is this money captured in the NSF survey?

How well do our working definitions of the stage in technology development from invention to innovation correspond to the definitions of stage of development of a new firm or venture (such as seed or early stage)? How are the definitions operationally different for different industries/technologies?

What is your interpretation of the significant shifts in the pattern of early-stage resources in recent years? Are such patterns likely to be cyclical or long range?

Should venture capital investments be seen as national, regional, or local in scope and coverage? In other words, is the concentration of venture capital investment in the coasts, Texas, and a few other areas a reflection of where the venture capital firms and wealthy angels are located, or is it a realistic reflection of the differences in socio-economic capital, regionally?

John Taylor, *National Venture Capital Association* (moderator)

E. Rogers Novak, Jr., *Novak Biddle Venture Partners*

Colin Blaydon, *Amos Tuck School of Business Administration, Dartmouth College*

Jeffrey Sohl, *Whittemore School of Business, University of New Hampshire*

PANEL 5. REGIONAL DISTRIBUTION OF INVESTMENTS AND STATE PROGRAMS

What is the role of the states in funding early-stage, high-tech invention-to-innovation transition? How large is the total investment, and regionally, how does it compare to private and or federal investment? To what extent are these programs tied to or at least intended to leverage private or federal money?

Does achieving a more broadly distributed pattern of high-tech innovation in the U.S. depend on local and regional efforts to enhance all the elements of infrastructure (social capital) that are required for efficient innovation, and, if so, have any states demonstrated their ability to make a significant difference?

Maryann Feldmann, *Johns Hopkins University* (moderator)

Marianne Clarke, *State Science and Technology Institute*

Robert Heard, *National Association of Seed and Venture Funds*

PANEL 6. TECHNOLOGY FOCUS: LIFE SCIENCES

How is the search for invention-to-innovation funding influenced by the subsidy of the pre-invention research in a government-supported, not-for-profit organization (for instance, university, hospital, or government laboratory)? Do public funds, especially in biomedical fields, allow the work to go beyond proof of concept and thus become part of the picture of resources for invention-to-innovation conversion? Do the patterns of funding for biomedical innovations differ significantly from other kinds of high-tech innovations?

Christopher Coburn, *Cleveland Clinic Foundation Innovations*

Jeff Schloss, *National Institutes of Health*

PANEL 7. MAPPING FEDERAL GOVERNMENT INVESTMENTS

What are the federal programs of R&D support that most nearly correspond to the invention-to-innovation transition? In each case how well do the starting and ending points correspond to our model, and how variable are they from case to case, program to program? Consider ATP, SBIR, public-private partnerships, and any others that come to mind. What can we know about the distribution by technology/industry and by geographical region of this funding?

How well do any of these programs correspond to the model proposed here?

Can these federal programs be judged the same way corporate executives or venture capitalists would judge their high-tech innovation investments? What levels of risk are acceptable in each case?

Charles Wessner, *National Academy of Sciences* (moderator)

Donna Fossum, *RAND*

Kelly Carnes, *U.S. Commerce Department*

Rosalie Ruegg, *Advanced Technology Program (ret.)*

Ken Simonson, *Office of Advocacy, Small Business Administration*

PARTICIPANT BIOGRAPHIES

Nancy Bacon, *Senior Vice President, Energy Conversion Devices, Inc.*

Nancy M. Bacon is senior vice president of Energy Conversion Devices, Inc. (ECD). Her responsibilities include finance, public and private financings, development of business plans; presentations to major international corporations for the commercialization of ECD's technologies; negotiations for establishment of joint ventures and the licensing of company technologies and the preparation/administration of government proposals/contracts.

Ms. Bacon is a member of the boards of directors of Energy Conversion Devices, Inc., United Solar Systems Corp., and Bekaert-ECD Solar Systems (ECD's U.S. photovoltaic [solar] joint ventures with Bekaert N.V.), Sovlux, Ltd. (ECD's solar and battery joint venture with KVANT and the Russian Ministry of Atomic Energy), Environmental and Energy Study Institute (EESI), and the Michigan Science and Mathematics Alliance (MISMA). In 1997, Ms. Bacon was recognized by *Crain's Detroit Business* as one of Detroit's most influential women. Ms. Bacon, a CPA, has a B.S. in Accounting, and prior to joining ECD was a manager with Deloitte and Touche.

Arden L. Bement, *Basil S. Turner Distinguished Professor of Materials Engineering, Purdue University (now Director of the National Institute of Standards and Technology)*

Arden L. Bement, Jr., was sworn in as the twelfth director of the National Institute of Standards and Technology (NIST) on December 7, 2001. Prior to his appointment as NIST director, Bement served as the David A. Ross Distinguished Professor of Nuclear Engineering and head of the School of Nuclear Engineering at Purdue University. He has held appointments at Purdue University in the schools of Nuclear Engineering, Materials Engineering, and Electrical and Computer Engineering, as well as a courtesy appointment in the Krannert School of Management. He was director of the Midwest

Superconductivity Consortium and the Consortium for the Intelligent Management of the Electrical Power Grid.

Bement previously served as head of the Visiting Committee on Advanced Technology, the agency's primary private-sector policy adviser; as head of the advisory committee for NIST's Advanced Technology Program; and on the board of overseers for the Malcolm Baldrige National Quality Award.

Bement joined the Purdue faculty in 1992 after a 39-year career in industry, government, and academia. These positions included: vice president of technical resources and of science and technology for TRW Inc. (1980–1992); deputy under secretary of defense for research and engineering (1979–1980); director, Office of Materials Science, DARPA (1976–1979); professor of nuclear materials, MIT (1970–1976); manager, Fuels and Materials Department and the Metallurgy Research Department, Battelle Northwest Laboratories (1965–1970); and senior research associate, General Electric Co. (1954–1965).

Bement holds an engineer of metallurgy degree from the Colorado School of Mines, a master's degree in metallurgical engineering from the University of Idaho, a doctorate degree in metallurgical engineering from the University of Michigan, and an honorary doctorate degree in engineering from Cleveland State University. He is a member of the U.S. National Academy of Engineering.

Colin C. Blaydon, *William and Josephine Buchanan Professor of Management; Director, John H. Foster Center for Private Equity, Amos Tuck School of Business Administration, Dartmouth College*

Colin C. Blaydon is the founding director of the John H. Foster Center for Private Equity at the Tuck School of Business, Dartmouth College. He is also the William and Josephine Buchanan Professor of Management and Dean Emeritus at the Tuck School. He served as dean of the school from 1983–90, and again in 1994–95. Professor Blaydon has also been on the faculties of both Harvard and Duke Universities and served as vice provost of Academic Policy and Planning at Duke. He received his B.E.E. from the University of Virginia, his A.M. and Ph.D. in applied mathematics from Harvard University.

In addition to his academic career, Professor Blaydon has served twice in government, in the Department of Defense and the Office of Management and Budget. In the private sector he has served as a principal and managing director of two professional consulting firms, as executive chairman of a systems integration and software firm, as a

member of an international industrial investment group, and as a member of the board of a number of corporations and not-for-profit institutions. He also serves on the advisory boards of a venture capital fund and a fund of funds.

David E. Carlson, *Chief Scientist and Director, Advanced Material & Device Research, BP Solar*

David E. Carlson received his B.S. degree in physics from Rensselaer Polytechnic Institute in 1963 and a Ph.D. in physics from Rutgers University in 1968. After serving in the U.S. Army for two years, Dr. Carlson joined RCA Laboratories in 1970 as a member of the technical staff, where he invented the amorphous silicon solar cell in 1974. He was appointed group head, Photovoltaic Device Research, at RCA Laboratories in 1977. In 1983, he joined Solarex Corporation (merged into BP Solar in 1999) as the director of research of the Solarex Thin Film Division and became the general manager in 1987. He was promoted to vice president in 1988, and he became the chief scientist of BP Solar in 1999. Dr. Carlson received the top technical award of the American Ceramic Society (the Ross Coffin Purdy Award) in 1975 and was a co-recipient of the 1984 Morris N. Liebmann Award (IEEE). He was awarded the Walton Clark Medal by the Franklin Institute in 1986 and received the William R. Cherry Award (IEEE) in 1988. He received the Karl W. Boer Medal from the International Solar Energy Society and the University of Delaware in 1995. Dr. Carlson is a fellow of the IEEE and a member of the American Physical Society, the American Vacuum Society, the Materials Research Society, and Sigma Xi. He has published more than 120 technical papers and has been issued twenty-five U.S. patents.

Kelly Carnes, *former Assistant Secretary of Commerce for Technology, U.S. Department of Commerce*

Kelly H. Carnes, of Washington, D.C., served until January 2001 as the Deputy Assistant Secretary for Technology Policy in the Technology Administration at the Department of Commerce. In this role, she served as an advocate for American innovation and ensures that the industry's voice is represented in the nation's technology policy. Prior to joining the Department of Commerce, Ms. Carnes was a member of the technology and corporate practice groups of the Washington, D.C.-based law firm Shaw, Pittman, Potts, and Trowbridge. She specialized in representing technology companies in a wide variety of transactions, including joint ventures, strategic alliances, technology development and licensing arrangements, acquisitions, and venture capital transactions. During 1991 and 1992, Ms. Carnes served on the steering and international committees of the Northern Virginia Technology Council, where she helped develop programs to encourage Virginia-based technology companies to export their products

and services. Ms. Carnes holds a bachelor of arts degree from the University of North Carolina at Chapel Hill and graduated magna cum laude from Georgetown University Law Center.

Marianne Clarke, *Research Director, State Science & Technology Institute*

Marianne Clarke serves as the research director of the State Science and Technology Institute (SSTI), a non-profit organization dedicated to enhancing initiatives that apply science and technology for economic growth, particularly at the state level. Ms. Clarke also directs the Washington office of Battelle Memorial Institute's Technology Partnership Practice where she assists state and regional organizations in developing, implementing and evaluating technology-based economic development programs. Prior to her current positions, Ms. Clarke was the principal science and technology staff person for the National Governors' Association (NGA).

Christopher M. Coburn, *Executive Director, CCF Innovations, Cleveland Clinic Foundation*

Christopher Coburn is executive director of CCF Innovations (CCFI) and chief operating officer of NovaMedics, Inc. He is a recognized authority on technology commercialization and has consulted and spoken on the subject throughout North America and in eighteen countries. He is responsible for moving the inventions of the Cleveland Clinic into the private marketplace via established companies and the creation of new ones. Mr. Coburn also serves as a member of the Foundation's Conflict of Interest Committee.

Prior to joining the Cleveland Clinic, Mr. Coburn was vice president and general manager of the Battelle Memorial Institute, the world's largest independent non-profit R&D organization. Mr. Coburn was a member of Battelle's senior management team and directed one of Battelle's primary business units. He also directed a regional technology commercialization center. He is the editor and co-author of *Partnerships: A Compendium of State and Federal Cooperative Technology Programs*, the first comprehensive catalogue of technology commercialization initiatives of the federal government and the states.

Mr. Coburn served as staff director of the States Task Force of the Carnegie Commission on Science, Technology and Government. He was executive director of Ohio's Thomas Edison Program, Ohio's first Science and Technology Advisor (1984–1991), and deputy director of the Ohio Department of Development. He founded and directed the Science and Technology Council of the States and the State Science and Technology Institute. He served as assistant director of the Ohio Washington Office and has held

positions at the National Aeronautics and Space Administration and the National Institutes of Health. He also was an appropriations aide in the U.S. House of Representatives. He received his master's degree from George Washington University, and holds a B.A. from John Carroll University.

Maryann Feldman, *Research Scientist, The Jeffrey Skoll Professor of Innovation and Entrepreneurship, Rotman School of Management, University of Toronto*

Maryann Feldman's current work focuses on innovation and technological change, especially the diffusion and commercialization of university research as a source of economically valuable knowledge. Dr. Feldman holds a Ph.D. in economics and management and a n M.S. in policy analysis and management from Carnegie Mellon University. She received a B.A. in economics and geography from Ohio State University. Dr. Feldman has served as a consultant to local, state, and Federal government as well as private industry.

Donna Fossum, *RAND*

Donna Fossum (J.D. and Ph.D., Sociology) is a senior researcher in RAND's Washington office. Dr. Fossum's activities focus on the development, management, and deployment of RaDiUS, the first comprehensive database that tracks, in virtually real time and in substantive detail, the research and development activities and resources of the federal government. This work recently resulted in the report, *Discovery and Innovation: Federal Research and Development in the Fifty States, District of Columbia, and Puerto Rico* (RAND 2000), that for the first time describes in detail the R&D activities of the federal government by where they actually occur. Much of her time is also devoted to advising the Office of Science and Technology Policy in the Executive Office of the President on the overall structure of the federal R&D portfolio and the allocation of resources among federal R&D activities.

Prior to joining RAND, Dr. Fossum served as legal counsel and technology advisor to the Committee on Government Operations (now Government Reform and Oversight) in the U.S. House of Representatives. In that capacity, she was responsible for coordinating a wide variety of legislative and oversight activities regarding the budget, information collections and systems, technology and property management, and procurement systems of the federal government.

Bruce Griffing, *Manager, Industrial Electronics, Corporate Research Center, GE*

In 1979, Bruce Griffing joined the GE Research and Development Center in Schenectady, New York. From 1983 to 1985, Dr. Griffing served as the CRD Electronics Laboratory's

liaison fellow to Cornell University. In this capacity, he participated with Cornell faculty and students in research in the area of advanced integrated circuit technology.

In January 1988, he was named manager of the Large Area Electronic Systems Laboratory. The laboratory is now called the Industrial Electronics Laboratory. The most recent major development of the Lab is GE's amorphous silicon x-ray imaging technology. It is being applied to mammography, chest imaging and cardiac applications.

Bruce Griffing has published twenty-five papers and holds fourteen U.S. patents. He is a member of Sigma Xi, the American Physical Society and the Institute of Electrical and Electronics Engineers. He has served on and chaired program committees for the International Electron Devices Meeting (IEDM) and was general chairman for the 1988 IEDM. He has also organized tutorial courses in silicon processing for the IEDM. In 1982, he received an IR-100 award for his work on a water exposure system and received a Dushman award in 1985 for his work on contrast enhanced lithography. In 1995 he was awarded Purdue's School of Science Most Distinguished Alumnus Award.

Raman Muralidharan, *Vice-President, Booz Allen Hamilton, Inc.*

Raman Muralidharan is a strategist focused on technology intensive industries. He is based in the Cleveland office of Booz Allen Hamilton, and joined the firm in 1993. Mr. Muralidharan has significant expertise in biotechnology and pharmaceutical markets, and in the automotive industry. Prior to joining the firm Mr. Muralidharan was the senior geotechnical engineer at Engineers International Inc. He received his M.B.A. degree from the University of Chicago's Graduate School of Business, a n M.S. degree in structural engineering from the University of Minnesota, and a B.E. degree from the Delhi College of Engineering, University of Delhi.

Mark B. Myers, *Xerox Corporation (ret.) and Wharton School*

Mark Myers recently retired as senior vice president for corporate research and technology at Xerox Corporation in Stamford, Connecticut, where he directed the company's worldwide research, advanced technology including the corporate research centers, advanced development and development of emerging markets. He had oversight of the corporation's corporate research centers in Palo Alto, California, Webster, New York, and in Canada and Europe and was a member of the senior management committee responsible for the general management of the company.

Myers is a member of the National Research Council's Board on Engineering Education and the Task Force on Engineering Education in the U.S. and Japan. He serves on the board of directors of Xerox Canada, Inc., and SDL, Inc. and on university

advisory boards at Cornell, Illinois, Delaware, and Stanford. He is vice-chairman of the board of trustees of Earlham College and has held visiting faculty positions at the University of Rochester and at Stanford University. He holds a bachelor's degree from Earlham College and a doctorate from Pennsylvania State University.

E. Rogers Novak, Jr., *Founding Partner, Novak Biddle Venture Partners*

E. Rogers Novak, Jr. has over twenty years of experience as a venture capitalist, angel investor, and operating principal. Prior to co-founding NBVP, Roger was a private investor. In 1984, he was a co-founder and three fund general partner of Grotech Partners, where he was principally focused on information technology, with two of his investments, Verity and Secure Computing, among the top ten performing IPOs of 1995. Earlier in his career, Roger led the investment banking effort at Baker Watts & Co.

Roger currently serves on the boards of Blackboard, Inc., Engenia Software, Inc., Entevo Corporation, Para-Protect Services, Inc., and Simplexity.com, Inc. Roger was named to the State of Virginia's Joint Commission on Technology and Science, where he will serve on an advisory committee to examine the digital divide, including telecommunications, work-force shortage, and education. He also serves on the board of MMG Ventures, an SSBIC; the Maryland Chapter of the Nature Conservancy; and the Gilman School where he is a member of the investment and education committees.

Rosalie Ruegg, *NIST-Advanced Technology Program (ret.)*

Rosalie Ruegg, former Director of Economic Assessment Office and Chief Economist (now president and director of economic studies, TIA Consulting), directed economic evaluation activities for the Advanced Technology Program (ATP) from 1990 until her retirement in May 2000. She led the economic evaluation of ATP-funded projects and programs, advised on economic and business issues, and oversaw the economic and business peer review process performed by outside experts.

Ms. Ruegg has more than 50 publications, among them a book, *Building Economics: Theory and Practice*, co authored by Ruegg and Marshall (Chapman and Hall, 1990); a number of book chapters, including "Risk Assessment," *The Engineering Handbook* (CRC Press 1996), and "Economic Methods," *Energy Efficiency* (CRC Press, 1997); and many papers and reports, such as *The Advanced Technology Program's Evaluation Plan and Progress* (presented at the International Forum on Technology Management and published in the Proceedings); *Guidelines for the Economic Evaluation of the Advanced Technology Program* (NISTIR-5896); *An Economic Impact Analysis of Fire-Safe Cigarettes* (NBSTN 1242); and *Efficient Allocation of Research Funds:*

Economic Evaluation Methods with Case Studies (NBSSP 558). She has also served as editor for several journals and reference works.

Ms. Ruegg received her B.A. degree in economics with honors from the University of North Carolina, where she was elected to Phi Beta Kappa; an M.A. degree in economics from the University of Maryland, where she was a Woodrow Wilson Fellow; an M.B.A. degree with a specialty in finance from the American University; and professional certification from Georgetown University in instructional techniques. She received the Department of Commerce's Silver Medal Award, as well as numerous other performance awards; has served on national and international committees; and is a member of the federal Senior Executive Service. Speciality areas include program evaluation, including techniques of benefit-cost analysis, financial analysis, and risk assessment; strategic management and planning; business planning; and the economics of technological change.

Jeffery A. Schloss, *Program Director, Technology Development Coordination, National Human Genome Research Institute*

Jeffery A. Schloss is currently program director for technology development coordination at the National Human Genome Research Institute (NHGRI) where he manages a grants program in technology development for DNA sequencing and SNP scoring, and serves the NHGRI Division of Extramural Research and Office of the Director as a resource on genome technology development issues. He recently initiated a program to validate new sequencing technologies for use in high-throughput laboratories. He has also served the NHGRI as program director for large-scale genetic mapping, physical mapping, and DNA sequencing projects. Dr. Schloss represents the NIH on the NSTC's Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN), planning for the National Nanotechnology Initiative. He has worked with local high-school students with regard to DNA sequencing and the Human Genome Project. Before coming to NIH in 1992, Dr. Schloss served on the biology faculty at the University of Kentucky. He earned a B.S. degree with honors from Case Western Reserve University, the Ph.D. from Carnegie-Mellon University, and did postdoctoral training at Yale University. Dr. Schloss's research in cell and molecular biology included the study of non-muscle cell motility and regulation of mRNA expression.

Kenneth D. Simonson, *Senior Economic Advisor, Office of Advocacy, U.S. Small Business Administration*

Ken Simonson has served since August 1998 as senior economic advisor in the Office of Advocacy, U.S. Small Business Administration. He works with the chief counsel for

advocacy, Jere W. Glover, and his staff of attorneys, economists, regional advocates, communications people, and entrepreneur-in-residence to advocate and produce research on small business issues. In addition, the office has a key role in evaluating the impact on small business of proposed legislation and regulations.

Ken has over twenty-five years of public policy experience, including thirteen as vice president and chief economist for the American Trucking Associations (1985–98). There he was in charge of all federal tax policy and a wide range of other economic and regulatory issues. He also worked with the President's Commission on Industrial Competitiveness (1983–85), the U.S. Chamber of Commerce (1978–83), the Federal Home Loan Bank Board (1977–78), and an economic consulting firm (1972–77).

Ken is president of the National Economists Club and since 1982 has co-chaired the Tax Economists Forum, a professional meeting group he co-founded for leading researchers and policy makers among tax economists.

Jeffrey E. Sohl, *Director, Center for Venture Research, UNH, Whittemore School of Business and Economics*

Jeffrey Sohl is director of the Center for Venture Research and a professor in the Department of Decision Sciences at the Whittemore School of Business and Economics at the University of New Hampshire. He received his bachelor's degree in electrical engineering from Villanova University and his MBA and Ph.D. in management science from the University of Maryland. Prior to joining the Whittemore School, he was a consultant to the Department of Energy in the area of public policy analysis. His current research interests are in early-stage financing for high-growth ventures. He currently serves on the New Hampshire Governor's Advisory Committee on Capital Formation. He has presented his research in academic and practitioner forums in the United States, Europe, and Asia, and in briefings for several government agencies and scholars from the United States, Europe, Scandinavia, Australia, Asia, and Africa. He has appeared on CNBC, MSNBC, and National Public Radio, and has been quoted in *Inc.*, *Forbes*, *Fortune*, *Wired*, the *Wall Street Journal*, *Red Herring*, *Business Week*, *Worth Magazine*, and the *Nikkei Daily*. He has written several articles which have been published in academic and business journals, including *Venture Capital: An International Journal of Entrepreneurial Finance*, the *Social Science Journal*, the *Journal of Business Forecasting*, *Frontiers of Entrepreneurship Research*, the *Journal of Forecasting*, *Entrepreneurship and Regional Development*, the *Journal of Business Venturing*, the *Journal of Entrepreneurial Finance*, *Entrepreneurship 2000*, and *Entrepreneurship: Theory and Practice*.

John S. Taylor, *Vice President of Research, National Venture Capital Association*

John Taylor is vice-president of research at the National Venture Capital Association (NVCA) which is based in the Washington, D.C. area. He is responsible for developing and overseeing association data and research efforts. He joined the NVCA in 1996.

Mr. Taylor was a senior consultant with Andersen Consulting in Washington, D.C., and has since held senior product manager and IT positions in both large and small organizations. He has served as a board member of both for-profit businesses and non-profit organizations.

He received an M.B.A. degree from the Amos Tuck School at Dartmouth College, and a B.S. degree in chemistry from Dickinson College.

Charles W. Wessner, *Program Director, Board on Science, Technology and Economic Policy, National Research Council*

Chuck Wessner is the director of the Program on Technology and Competitiveness for the National Research Council's Board on Science, Technology, and Economic Policy. Dr. Wessner began his federal career with the U.S. Treasury, served overseas as an international civil servant with the OECD and as a senior officer with the U.S. diplomatic corps, and directed the Office of International Technology Policy in the Technology Administration of the Department of Commerce. Since joining the National Research Council, he has led several major studies working closely with the senior levels of the U.S. government, leading industrialists, and prominent academics. Recent work includes a White House-initiated study, "The Impact of Offsets on the U.S. Aerospace Industry," and a major international study, "Competition and Cooperation in National Competition for High Technology Industry" in cooperation with the HWWA in Hamburg and the IFW in Kiel, Germany.

Currently, he is directing a portfolio of activities centered around government-industry partnerships for the development of new technologies, and initiating work on measuring and sustaining the new economy. The Partnerships program constitutes one of the first program-based efforts to assess U.S. policy on government-industry partnerships. Recent publications include *Conflict and Cooperation in National Competition for High Technology Industry*, *Policy Issues in Aerospace Offsets*, *International Friction and Cooperation in High-Technology Development and Trade*, *Trends and Challenges in Aerospace Offsets*, *New Vistas in Transatlantic Science and Technology Cooperation*, *Industry-Laboratory Partnerships: A Review of the Sandia Science and Technology Park Initiative*, *The Advanced Technology Program: Challenges and Opportunities*, and *The*

Small Business Innovation Research Program: Challenges and Opportunities. Dr. Wessner holds degrees in international affairs from Lafayette College (Phi Beta Kappa) and the Fletcher School of Law and Diplomacy, where he obtained an M.A., an M.A.L.D. and a Ph.D. as a Shell Fellow.

PALO ALTO, CA

(Xerox Palo Alto Research Center):
February 2, 2001

PANEL 1. EARLY-STAGE, TECHNOLOGY-BASED INNOVATION: OVERVIEW OF DATA AND DEFINITIONS

Lewis Branscomb, *Kennedy School of Government*
Philip Auerwald, *Kennedy School of Government*

[Same as Washington, D.C. workshop.]

PANEL 2. TECHNOLOGY CASES (I)

We first hope that the panelists will reconstruct for us, in summary form, the history of technology conception, invention, and development in a specific example of a high-tech innovation. When and where were the key inventions/ideas made? Was there a point when proof of concept for a commercial product was in hand, but before product specs, production processes, costs and markets were defined and business revenue could be committed? Can these two points be recognized in the history or were there multiple, overlapping, premature entries to market before the technology was ready for successful commercialization? Does the history of these experiences match the “invention to innovation” model proposed for this project? If not, what is a better model of the transition from “invention” to “innovation”? How was the early (seed) stage of the work funded in the panelists’ respective firms and elsewhere and how were the decisions made to invest? Was funding from internal corporate resources? Venture capital? Federal grants or contracts? Potential customers or business partners?

John Shoch, *Alloy Ventures* (moderator)
James Kaschmitter, *PolyStor Corporation*
Hylan B. Lyon, *Marlow Industries Inc.*
Richard Spitzer, *Integrated Magneto-electronics*

PANEL 3. MAPPING VENTURE CAPITAL AND ANGEL INVESTMENTS

How can we quantify the three major sources of private finance for early-stage conversion of inventions to innovation-venture capital seed investment, angel investments, and bootstrap financing? Can we get any useful breakdown by technology/industry and by geographical region? Is there any way to know or estimate how much of this funding is spent on technical work, such as R&D, rather than other business costs associated with building a new enterprise? Is this money captured in the NSF survey? How well do our working definitions of the stage in technology development from invention to innovation correspond to the definitions of stage of development of a new firm or venture (i.e., seed, early stage)? How are the definitions operationally different for different industries/technologies? What is your interpretation of the significant shifts in the pattern of early-stage resources in recent years? Are such patterns likely to be cyclical or long range? Should venture capital investments be seen as national, regional, or local in scope and coverage? In other words, is the concentration of venture capital investment in the coasts, Texas, and a few other areas a reflection of where the venture capital firms and wealthy angels are located, or is it a realistic reflection of the differences in socio-economic capital, regionally?

Thomas Hellmann, *Stanford University* (moderator)

J.C. (Hans) Severiens, *Band of Angels*

Mark Horn, *Silicon Valley Bank*

Bob Evans, *Technology Strategies Alliances*

PANEL 4. INSTITUTIONAL INNOVATIONS: NETWORKS AND INCUBATORS

As a broader community of would-be private-equity investors look for ways to participate in the returns generated in 1999–2000, investors look for more efficient ways of covering their due diligence, and entrepreneurs look for more effective ways to access sources of capital, what new forms of networks and other institutional arrangements are appearing? Are these new mechanisms achieving their goals? Do they provide a more effective mechanism for covering the early-stage and seed-funding needs of high-tech innovators? We learned last week that a new and substantial source of private equity is from corporate venture funds. Are these a major factor in your experience? Are they likely to grow? What more novel forms of finance are arising and what is their likely future (angel mutual funds, venture capital-bank collaborations with debt capital attached to equity investments, Internet packagers of angel deals?)?

Manju Puri, *Stanford University* (moderator)

Ron Conway, *Angel Investors L.P.*

Jim Robbins, *Panasonic Ventures Fund and Panasonic Internet Incubator*

Luis Villalobos, *Tech Coast Angels*

PANEL 5. TECHNOLOGY CASES (II)

The questions here are similar to those for Panel 2 (above). But because these innovations are largely in the life/medical science area, some additional issues are of special interest:

To what extent was the early (seed) stage of the work funded by government (for instance, NIH), and if so did the terms of the support encourage or discourage the work required to make the business case for the innovation? Was the initial innovator in a not-for-profit institution when the commercial effort was launched?

Was seed funding from an established medical or drug company, and if so, did it fund the work in a non-profit organization or was the support for a new startup firm?

Lynne Zucker, *UCLA* (moderator)

Michael Knapp, *Caliper Technologies Corp.*

Christine Cordaro, *CMEA Ventures*

Kenneth Nussbacher, *Affymetrix, Inc.*

Gerald Adolph, *Booz Allen Hamilton*

PANEL 6. UNIVERSITY-INDUSTRY COOPERATION AND REGIONAL INNOVATION

How is the search for invention-to-innovation funding influenced by the subsidy of the pre-invention research in a government supported, not for profit organization (university, hospital, government laboratory...)?

Do public funds, especially in biomedical fields, allow the work to go beyond proof of concept and thus become part of the picture of resources for invention-to-innovation conversion? Do the patterns of funding for biomedical innovations differ significantly from other kinds of high-tech innovations?

Nathan Rosenberg, *Stanford University* (moderator)

Michael Wynblatt, *Siemens Technology-to-Business Center*

Michael Darby, *UCLA*

PARTICIPANT BIOGRAPHIES

Ron Conway, *Founding General Partner, Angel Investors L.P.*

Prior to founding Angel Investors, Ron Conway worked in business development for CBT Systems, a developer and distributor of interactive computer-based training. Mr. Conway was employed by National Semiconductor Corp., in the 1970s, and now serves on the boards and/or advisory boards of Red Herring Magazine, Gradient Technology, Blue Pumpkin Software, AtWeb (sold to Netscape), and OneMediaPlace (formerly AdAuction).

Christine Cordaro, *Partner, CMEA Ventures*

Christine Cordaro joined CMEA Life Sciences as a general partner with the Fund's formation in 1998. She is also the founder and a general partner of Viridian Capital. Ms. Cordaro has over 17 years experience in the life-science industry. Prior to CMEA/Viridian, she was a director of life science investments with Technology Funding Ventures, where she focused on venture capital investments in the biopharmaceutical, medical device, diagnostic, medical equipment, and healthcare service sectors. Prior to Technology Funding, Ms. Cordaro held senior management positions in R&D, product planning, and business development. Ms. Cordaro holds a B.S. and M.S. in bacteriology from the University of Wisconsin-Madison, and an MBA from St. Mary's College in California.

Michael R. Darby, *Warren C. Cordner Professor, John E. Anderson Graduate School of Management*

Michael Darby is the Warren C. Cordner Professor of Money and Financial Markets in the Anderson Graduate School of Management and in the departments of economics and policy studies at UCLA, and Director of the John M. Olin Center for Policy in the Anderson School. Concurrently he holds appointments as Chairman of The Dumbarton Group, research associate with the National Bureau of Economic Research, adjunct scholar with the American Enterprise Institute, and president of the Western Economic Association.

Darby served in several senior U.S. government positions, including assistant secretary of the Treasury for economic policy (1986–89), member of the National Commission on Superconductivity (1988–89), under secretary of Commerce for Economic Affairs (1989–92), and administrator of the Economics and Statistics Administration (1990–92).

Darby is the author of nine books and monographs and numerous other professional publications. From 1980 through 1986 he was Editor of the *Journal of International Money and Finance*, and he continues to serve on that Journal's Editorial Board. He also serves or served as a member of the editorial boards of the *American Economic Review*, *Contemporary Economic Policy*, *Contemporary Policy Issues*, and *International Reports*. Darby has received many honors, including the Alexander Hamilton Award, the Treasury's highest honor, in 1989.

Thomas F. Hellmann, *Assistant Professor of Strategic Management, Graduate School of Business, Stanford University*

Thomas Hellmann is an assistant professor of strategic management at the Graduate School of Business, Stanford University, where he teaches a popular MBA elective, "Strategy in Entrepreneurial Ventures." His research on the process of entrepreneurship and the role of venture capital has been published in top economics and finance journals. He has also collaborated with his former dissertation adviser, Joseph Stiglitz, working on issues of financial systems development. He holds a Ph.D. in Economics from Stanford University and a B.Sc. from the London School of Economics.

Michael R. Knapp, *Founder and Vice President of Science & Technology, Caliper Technologies Corp.*

Prior to co-founding Caliper, Michael Knapp was president, scientific director, a director and a scientific advisory board member at Molecular Tool, Inc., a company he co-founded in 1988. Under his direction, the company developed a proprietary DNA typing system with the demonstrated capability of performing up to 2.5 million genotype determinations per year. This system is rapidly becoming a standard for parentage determination in both veterinary and human applications. Additionally, Dr. Knapp authored a proposal in 1994 that was one of only eleven nationwide to receive a \$2 million technology development grant from the Department of Commerce's Advanced Technology Program in their first Tools for DNA Diagnostics focused competition. From 1981 to 1986, he was scientific director of Genetica, S.A. in Joinville-le-Pont, France, a genetic engineering affiliate of French chemical giant Rhône Poulenc. Dr. Knapp was a senior scientist on the staff of Columbia University's Center for Neurobiology and Behavior from 1986 to 1988, using the tools of molecular genetics to study the complex processes of learning and behavior in model biological systems. Dr. Knapp received his B.S. from Trinity College (Hartford) in biology in 1973. He received his Ph.D. in Medical Microbiology from Stanford University, specializing in recombinant DNA technology in 1981.

Hylan B. Lyon, *Vice President Materials Research, Development and Production, Marlow Industries, Inc.*

Hylan Lyon Jr. joined Marlow Industries Inc., in 1992 immediately after the company received the Malcolm Baldrige National Quality Award. His goal was to introduce a discovery-based material science program into a thermoelectric device company that had been growing for twenty years at a steady 15 percent rate. This last year Marlow Industries grew to six times its 1992 size with expectations of doubling its revenue in the year to come.

Dr. Lyon has thirty years of international, national, regional, and local policy, technological, and business experience. He serves as a member of the Technology Steering Group for the DOE Center of Excellence in the Synthesis and Processing of Advanced Materials, a director of the Baylor Research Institute, a past director of the International Thermoelectric Society, and a member of Institute for Defense Analysis Advisory Group on Critical Technologies. His Ph.D. from Berkeley in 1967 contained the discovery of surface recrystallization utilizing low-energy electron diffraction.

Kenneth J. Nussbacher, *Executive Vice President, Affymetrix, Inc.*

Kenneth Nussbacher has been executive vice president of Affymetrix since 1995, serving as chief financial officer from 1995 to 1997. Prior to joining Affymetrix, Mr. Nussbacher was executive vice president for business and legal affairs of Affymax. In his roles at Affymax and Affymetrix, Mr. Nussbacher played a central role in the development and implementation of business strategies for creating value in technology-based companies. His experience includes development, negotiation and implementation of commercial and scientific collaborations; licensing of intellectual property; and public and private financings. He holds a J.D. from Duke University and a B.S. in Physics from Cooper Union. Mr. Nussbacher is also a director of Symyx Technologies.

Manju Puri, *Associate Professor of Finance, Graduate School of Business, Stanford University*

Manju Puri holds a BA (Hons.), Delhi University, 1980; PGDM (MBA), Indian Institute of Management, Ahmedabad, 1982; MPhil, New York University, 1992, PhD, 1995. Fama-DFA Award for Best Paper, *Journal of Financial Economics*, 1999; NASDAQ Award for Best Paper (Western Finance Association), 1999; Trefftz Award for Best Paper (Western Finance Association), 1994; FMA Competitive Paper Awards for Best Paper(s) in Financial Institutions, 1994 and 1995; outstanding doctoral thesis awards: Irwin Award, 1993; NYU Salomon Center Award, 1994 and 1995; Herman Kroos Award, 1995. She has

served as account manager, The Hong Kong and Shanghai Banking Corporation, 1983–89; visiting assistant professor of finance at Yale University, 1997–98; Fletcher Jones Faculty Fellow for 1999–2000, and has been at Stanford since 1995.

James Robbins, *Executive Director, The Software Business Cluster*

Jim Robbins has twenty years' experience in the fields of new business formation, organizational design, technology development and management, business operations, and law. In addition to starting his own business to assist in the development of technology or focused incubators, he has worked for Digital Equipment Corporation and the U.S. Supreme Court and was a trial attorney. Jim is executive director of the San Jose Software Business Cluster, the San Jose Environmental Business Cluster, and the Panasonic Internet Incubator. He is a principal in Panasonic Ventures and vice-chair of the Pacific Incubation Network.

Nathan Rosenberg, *Department of Economics, Stanford University*

Nathan Rosenberg is the Fairleigh S. Dickinson, Jr., Professor of Public Policy in the Department of Economics at Stanford University. He was educated at Rutgers University, the University of Wisconsin, and Oxford University. He has taught at the University of Pennsylvania, Purdue University, Harvard University, the University of Wisconsin, The London School of Economics, and Cambridge University.

Professor Rosenberg's primary research activities have been in the economics of technological change. His publications have addressed the determinants and the consequences of technological change. His research has examined the diversity of the forces generating technological change across industrial boundary lines, as well as the mutual influences between scientific research and technological innovation. Professor Rosenberg's books include *The American System of Manufactures*, *Perspectives on Technology*, *Inside the Black Box*, *Technology and the Pursuit of Economic Growth* (with David Mowery), *How the West Grew Rich* (with L.E. Birdzell, Jr.), *Exploring the Black Box*, *The Emergence of Economic Ideas and Paths of Innovation* (with David Mowery), and most recently *Schumpeter and the Endogeneity of Technology*. He was awarded the Leonardo da Vinci Prize for his contributions to the history of technology.

Hans Severiens, *Coordinator, Band of Angels*

Hans Severiens holds a Ph.D. in nuclear physics from Johns Hopkins University and a B.S. in physics from Harvard College. He is the coordinator of the Band of Angels, a Silicon Valley private investment group of about 120 members, which he co-founded. The Band is composed mainly of active high-technology executives who seek out invest-

ment opportunities in start-up and early-stage technology companies, present them to the Band as potential investments, and invest in them for their own accounts. Dr. Severiens has been making and managing investments in closely-held technology companies since 1980. He was a partner/officer in two venture capital funds: Bay Ventures, a seed-stage investor, and MIP Equity Fund, a later-stage investment firm funded by the Dutch government. Early in his career he was at Perkin-Elmer (assistant chief scientist), Columbia University (research professor), the Atomic Energy Commission (staff scientist), and the Niels Bohr Institute in Copenhagen (Ford Foundation post-doctoral fellow). Thereafter he moved to Wall Street where he worked in security analysis and investment banking at Morgan Stanley Dean Witter, Merrill Lynch, and Paine Webber (Mitchell Hutchins). He was voted an All Star Institutional Analyst each year from 1973 through 1976. Dr. Severiens is a member of the board of directors of several private corporations, a member of the board of advisors of The Enterprise Network in Silicon Valley, a trustee of Golden Gate University in San Francisco, and a member of the Advisory Board of Los Alamos National Laboratory for Technology Commercialization. He has presented and published numerous scientific papers and articles in addition to being a frequent guest speaker on technology and business subjects.

John F. Shoch, *General Partner, Alloy Ventures*

John F. Shoch, Ph.D., joined Craig Taylor as a venture capitalist in 1985. Prior to this, he was president of the Xerox Office Systems Division. John received a B.A. (1971) in Political Science and an M.S. (1977) and a Ph.D. (1979) in Computer Science, all from Stanford. He joined Xerox in 1971 and worked at its Palo Alto Research Center (PARC) where he helped develop the Ethernet, a local area network system. In 1980, he became the assistant to the CEO of Xerox. In 1982, John became president of the Office Systems Division, developing networked office systems derived from Xerox PARC research. He is a director, and founding investor, of Conductus (Chairman) and Remedy, both public companies. He is also a director of several private companies, including AllAdvantage, Boldfish, Intersurvey, Kasenna, MontaVista Software, Network Elements, PostX, UpShot, and Zing Networks.

Luis Villalobos, *Tech Coast Angels*

Luis Villalobos is the founder of the Tech Coast Angels, and has a proven track record of investing in and coaching early-stage companies. He was founder and CEO of two ventures that were sold to large companies. He is an early investor in thirty-six startups, including Gadzoox Networks and Digi International. He has a technology background, including twelve patents as lead inventor. Luis earned an M.B.A. from Harvard Business School and an Sc.B. in mathematics from MIT.

Michael Wynblatt, *Siemens Technology to Business Center*

As director of Venture Technology at Siemens Technology-to-Business Center (TTB) in Berkeley, Michael Wynblatt has responsibility for identification of nascent-stage opportunities, and for coaching innovation teams in both the earliest phases of business development and the later stages of technology R&D. His background in next-generation information systems provides a perspective from which to evaluate and position new technologies to form new ventures. Dr. Wynblatt was a member of the founding team of TTB with particular responsibility for recruiting the TTB innovation team and defining the key innovation spaces in which TTB would operate. As a member of the TTB core team, he helps to set the strategic direction for the center. Prior to joining TTB, Dr. Wynblatt was a member of the technical staff at Siemens Corporate Research in Princeton, New Jersey. He holds a Ph.D. in computer science from the State University of New York at Stony Brook, and a B.S.E. in Computer Engineering from the University of Michigan.

Lynne Zucker, *Department of Sociology, UCLA*

Lynne Zucker received her Ph.D. in sociology from Stanford University. Her academic interests include formal organization theory, institutional structure and process, comparative international institutions, scientific productivity, and industrial organization. She is currently the director of the Center for International Science, Technology, and Cultural Policy for the School of Public Policy and Social Research at UCLA.

CAMBRIDGE, MASSACHUSETTS

(Kennedy School of Government, Harvard University):

May 1 and 2, 2001

KEYNOTE SPEAKER (MAY 1)

Mr. Alexander V. D'Arbeloff, *Massachusetts Institute of Technology*

PANEL 1. EARLY-STAGE, TECHNOLOGY-BASED INNOVATION:

INTRODUCTION AND PRESENTATION OF INITIAL RESULTS

The co-investigators will discuss initial findings as reported in the two-part project working paper. Part I of the working paper will summarize behavioral and institutional issues pertinent to early-stage, technology-based innovation, with emphasis on views

of practitioners articulated at workshops held earlier this year in Washington, D.C., and Palo Alto, California.

Lewis Branscomb, *Kennedy School of Government, Harvard University*

Philip Auerwald, *Kennedy School of Government, Harvard University*

PANEL 2. BEHAVIORAL AND INSTITUTIONAL ISSUES

Against the background of Part I of the project working paper (summarizing practitioner views on early-stage innovation), a group of leading behavioral economists, organizational theorists, and a prominent angel investor discuss how risk, trust, objectives, information, and institutions interact to define the particular obstacles and opportunities facing technology entrepreneurs. Among the issues of interest:

How do we explain the proliferation of institutional forms supporting technology development in the space between invention and innovation? How does the presence of behavioral and institutional disjunctures complicate the task of assessing the supply and demand for early-stage funding?

How do insights from behavioral finance—for instance, loss aversion, status quo bias, “barn-door closing”⁹⁶ and herding—help us understand technological innovation, particularly in the context of early-stage projects? Might such insights help us understand the tendency of private-sector investments to concentrate at any point in time on a limited subset of technological sectors (such as in the three years prior to March 2000, Internet, and biotech), as well as the strong variations over time in these preferred sectors?

To what extent is the disjuncture between invention and innovation, as described by practitioners, a transient phenomenon that we expect will be eliminated by institutional adaptation, or, instead, a more fundamental phenomenon reflecting underlying discontinuities (for instance, that between the definition of scientific success and that of commercial success)?

Richard Zeckhauser, *Kennedy School of Government* (moderator)

Michael Horvath, *Tuck School of Business, Dartmouth*

Nick Demos, *Booz Allen Hamilton*

Hans Severiens, *Band of Angels*

96. Concept developed in Jayendu Patel, Richard Zeckhauser and Darryll Hendricks, “The Rationality Struggle: Illustrations from Financial Markets,” 81(2), May 1991: pp. 232–236.

PANEL 3. MAPPING THE FUNDING FOR EARLY-STAGE INNOVATION: THE NUMBERS AND WHAT THEY MIGHT MEAN

With the initial results from the project team (Part II of the working paper) as a point of reference, core contributors to the empirical literature on R&D and an experienced technology manager discuss strategies for arriving at a comprehensive accounting of project-level investments in early-stage technology development. Among the issues of interest:

What definition (or set of definitions) of early-stage, technology-based invention-to-innovation transition can be applied across the full range of potentially relevant institutional settings (such as universities, existing corporations, startups)?

What published sources (such as raw data, surveys, empirical analyses) exist that can be used to justify a first-approximation estimate of the relative magnitudes of funding from key sources (private and public) that are used for project level R&D support for early-stage technologies?

Aside from funding, what other measures of inputs might be used to construct a comprehensive picture of the distribution support for early-stage technology creation?

Wesley Cohen, *Carnegie Mellon University* (moderator)

Scott Stern, *Sloan School of Management, MIT*

Andrew Toole, *Stanford University*

Mark Myers, *Xerox Corporation (ret.) and Wharton School, University of Pennsylvania*

PANEL 4. TURNING IDEAS INTO PRODUCTS: NEW PERSPECTIVES ON GROWTH THROUGH INNOVATION

In a recent article, Weitzman (1998) presents a model of recombinant growth in which new ideas arise from old ideas being reconfigured in new ways.⁹⁷ Weitzman's model suggests that "the ultimate limits to growth may lie not as much in our ability to generate new ideas, so much as in our ability to process an abundance of potentially new seed ideas into usable forms." In this session, leading economists of innovation and growth and a veteran technologist/CTO discuss the process of early-stage innovation as it relates to long-term growth. Among the core issues:

From a theoretical standpoint, how should we think about the contribution to economic growth made by the process of early-stage, technology-based innovation?

97. Martin L. Weitzman. "Recombinant Growth," *Quarterly Journal of Economics* 113(2), May 1998: pp. 331–360.

What can growth theorists learn from the insights of behavioral economists and organizational theorists (for instance, as presented in panel 2)? Vice versa?

If there does, indeed, exist a significant institutional and behavioral disjuncture between invention and innovation, then what are the implications for growth, if any?

Dale Jorgenson, *Kennedy School of Government, Harvard University* (moderator)

Martin Weitzman, *Department of Economics, Harvard University*

Karl Shell, *Department of Economics, Cornell University*

PANEL 5. NETWORKS, SOCIAL CAPITAL, AND CONCENTRATION BY REGIONS AND SECTORS

A dominant issue in discussions regarding the funding for early-stage, technology-based innovation is the extent to which both funding and projects are concentrated by region and sector. In this session, authors of some of the best recent work on the geographical and sectoral concentration of innovative effort discuss the importance of localized knowledge spillovers and social capital in concert with more standard economic factors affecting incentives such as time, travel, and crowding.

Purely from the standpoint of efficiency, and not distribution, under what conditions is the fact of geographical concentration consistent with social optimality? Are there public policies that might sufficiently enhance the networks and social capital in neglected regions in a manner that would increase not only local, but aggregate innovative efficiency?

How do we understand the causes of the observed large fluctuations from year to year in flows of capital to different high-tech sectors? If these fluctuations reflect the difficulty of assessing technical risks, is there a role for government in R&D investment outside these sectors in vogue, such as IT and biotech?

Adam Jaffe, *Department of Economics, Brandeis University* (moderator)

Paul Reynolds, *Babson College and London Business School*

David Hsu, *Sloan School of Management, MIT*

Maryann Feldman, *Rotman School of Management, University of Toronto*

PANEL 6. PUBLIC AND PRIVATE COMPLEMENTARITIES

In this session a distinguished group of policy makers and academics discusses the role of the federal government in financing R&D activities in the invention-to-innovation transition.

How does the magnitude of federal funding of early-stage projects compare with private funding, taking geographic and sectoral skew into account?

To what extent (if any) should we be concerned about federal investments in early-stage technology development crowding out industry investments? In what contexts is such federal investment a complement for private investment, rather than a substitute?

What is the appropriate role of the federal government (if any) in the support of early-stage, technology-based innovation? Is there enough evidence of a shortfall in early-stage funding to justify federal investment, or is the federal role to help innovators overcome institutional and behavioral barriers (such as shortcomings in social capital), perhaps by validation of the most promising projects?

Lewis Branscomb, *Kennedy School of Government, Harvard University* (moderator)

Josh Lerner, *Harvard Business School*

Marian Chertow, *Yale University*

William Bonvillian, *Office of Senator Lieberman*

PARTICIPANT BIOGRAPHIES

William B. Bonvillian, *Office of Senator Joseph Lieberman*

William Bonvillian is legislative director and chief counsel to Senator Joseph Lieberman (D-Conn.), and has served in that position since the senator was elected in 1989. Prior to that time he held several positions, including as a partner in the law firm of Jenner and Block in Washington, D.C., and as a deputy assistant secretary at the U.S. Department of Transportation. He has a B.A. from Columbia University, an M.A.R. from Yale University, and law degree from Columbia University School of Law.

Marian R. Chertow, *Director, Industrial Environmental Management Program, Yale School of Forestry and Environmental Studies*

Marian Chertow has been director of the Industrial Environmental Management Program at the Yale School of Forestry and Environmental Studies since 1991, following ten years in state and local government and environmental business. Her teaching and research focus on waste management, industrial ecology, environmental technology innovation, and business/environment issues. Since 1995 Marian has also been serving as director of the Environmental Reform: The Next Generation Project at the Yale Center for Environmental Law and Policy, leading a three-year effort to shape the future of environmental policy. In this capacity she is editor of *Thinking Ecologically: the Next Generation of Environmental Policy* with Daniel C. Esty (Yale University Press, 1997).

Wesley Cohen, *Department of Social and Decision Sciences, Carnegie Mellon University*

Wes Cohen is an applied economist working in the area of technological change and industrial R&D. His research addresses the links between firm size, market structure and innovation, the impacts of R&D on firms' abilities to evaluate and exploit outside knowledge, the sources of variation in innovative activity both across industries and across firms within industries, and firms' use of patents and other mechanisms to protect the competitive advantage due to innovation. He has also explored the links between university research and industrial R&D. Most recently, he has administered a major national survey to explore the nature and determinants of industrial R&D in the U.S. manufacturing sector, and has coordinated this project with similar efforts in Japan and Europe. On the basis of this project and in collaboration with overseas scholars, he is conducting cross-national comparisons of the sources of knowledge affecting industrial R&D, the strategies employed by firms to protect their innovations, and related questions. He has published in numerous journals, including the *American Economic Review*, the *Economic Journal*, the *Review of Economics and Statistics*, the *Administrative Science Quarterly* and *Management Science*. He is also a Main Editor for *Research Policy*.

Alexander V. D'Arbeloff, *Chairman of the Corporation, Massachusetts Institute of Technology*

Alex d'Arbeloff, a member of the MIT Corporation since 1989, was named chairman of the MIT Corporation on July 1, 1997. He has served on MIT's Corporation Development Committee and on visiting committees for the departments of economics, electrical engineering and computer science, and mechanical engineering. In addition, Mr. d'Arbeloff has taught classes at the Sloan School of Management, and developed and teaches a course on management and entrepreneurship for graduate students in mechanical engineering. He received his S.B. in management from the Massachusetts Institute of Technology in 1949.

Mr. d'Arbeloff is chairman of Teradyne, Inc., a leading manufacturer of automatic test equipment and interconnection systems for the electronics and telecommunications industries. He cofounded Teradyne in 1960 and has served as vice president (1960–1971), president and chief executive officer (1971–1997), and chairman (1977–present). Teradyne is now the world's largest producer of automatic test equipment.

Mr. d'Arbeloff also serves as a director of several private companies. He is a director and past chairman of the Massachusetts High Technology Council, and a trustee of the Massachusetts General Hospital and the New England Conservatory.

John Nicholas Demos, *Vice President, Booz Allen Hamilton*

John Demos is a vice president with Booz Allen Hamilton's Strategy Practice based in New York. Mr. Demos is a strategist whose work generally begins with conceptualization and continues through to implementation. His areas of expertise include industry restructuring, partnerships and alliances, pricing, business development and technology marketing. His clients have included life-sciences companies, agricultural companies, engineering companies, energy services companies, electric utilities, major oil and gas companies, consumer products companies, and other related industries. His most recent work has been in the area of biotechnology, specifically looking at partnership models that optimize the value creation and value capture of biotechnology innovation. Prior to joining Booz Allen, Mr. Demos was employed as an independent consultant by a number of European companies. Mr. Demos is fluent in French and speaks Spanish. He holds an M.B.A. from New York University's Leonard N. Stern School of Business where he majored in Finance and International Business. He also holds an M.S. with honors from L'Ecole des Hautes Etudes Commerciales in Paris and a B.A. in Letters from Wesleyan University.

Maryann Feldman, *The Jeffrey Skoll Professor of Innovation and Entrepreneurship, Rotman School of Management, University of Toronto*

[See biographies for Washington, D.C. workshop.]

Michael T. Horvath, *Associate Professor of Business Administration, Amos Tuck School of Business Administration, Dartmouth College*

Michael Horvath, associate professor at the Tuck School of Business at Dartmouth, is engaged in the study of the effects of venture capital, entrepreneurship, and innovation on regional and macroeconomic growth. Michael teaches electives on high-tech entrepreneurship and venture capital. He is also a co-founder of Kana Communications, Inc., a leading provider of web-architected enterprise relationship management solutions. Michael received a Ph.D. in economics from Northwestern University (1994), and a B.A. in economics from Harvard University (1988). Prior to joining The Tuck School, Michael taught macroeconomics at Stanford University for six years.

David Hsu, *Doctoral Candidate, Sloan School, M.I.T.*

David H. Hsu is a Ph.D. candidate in technology strategy and entrepreneurship at the MIT Sloan School of Management, where he is the David and Lindsay Morgenthaler Fellow. His research focuses on high-tech start-up commercialization strategies and the role of venture capital in new firm development. He received his A.B. from Stanford in economics and political science and his M.P.P. in public policy from Harvard.

Adam Jaffe, *Professor of Economics, Brandeis University*

A former senior staff economist for the President's Council of Economic Advisers, Adam Jaffe's interests include the effect of incentives and regulations on the diffusion of technologies, and the role of R&D and innovation in economic growth. In cases against the tobacco industry in Minnesota and Massachusetts, Jaffe was the primary economic expert in demonstrating conspiracy among tobacco companies to suppress competition, health research, and other activities revealing harmful effects of smoking. He currently serves as coordinator of the National Bureau of Economic Innovation Policy and the Economy Group. His consulting clients include the National Institute of Standards and Technology, Proctor & Gamble, and PacifiCorp. He teaches courses in microeconomics, industrial organization, and environmental economics. He holds a Ph.D. from Harvard University.

Dale W. Jorgenson, *Department of Economics and Kennedy School of Government, Harvard University*

Dale Jorgenson is the Frederic Eaton Abbe Professor of Economics at Harvard University. He has been a professor in the Department of Economics at Harvard since 1969 and director of the Program on Technology and Economic Policy at the Kennedy School of Government since 1984. He served as chairman of the department of economics from 1994 to 1997. Jorgenson received his Ph.D. degree in economics from Harvard in 1959 and his B.A. in economics from Reed College in Portland, Oregon, in 1955.

Jorgenson was elected to membership in the American Philosophical Society in 1998, the Royal Swedish Academy of Sciences in 1989, the U.S. National Academy of Sciences in 1978 and the American Academy of Arts and Sciences in 1969. He was elected to Fellowship in the American Association for the Advancement of Science in 1982, the American Statistical Association in 1965, and the Econometric Society in 1964. He was awarded honorary doctorates by Uppsala University and the University of Oslo in 1991.

Jorgenson is president of the American Economic Association. He has been a member of the Board on Science, Technology, and Economic Policy of the National Research Council since 1991 and was appointed chairman of the board in 1998. He is also chairman of Section 54, Economic Sciences, of the National Academy of Sciences. He served as president of the Econometric Society in 1987.

Jorgenson received the prestigious John Bates Clark Medal of the American Economic Association in 1971. This medal is awarded every two years to an economist

under forty for excellence in economic research. He is the author of more than two hundred articles and the author and editor of twenty books in economics. His collected papers have been published in nine volumes by The MIT Press, beginning in 1995. The most recent volume, *Econometric Modeling of Producer Behavior*, was published in 2000.

Joshua Lerner, *Associate Professor of Business Administration,
Harvard Business School*

Josh Lerner is an associate professor at Harvard Business School, with a joint appointment in the finance and the entrepreneurial management units. He graduated from Yale College with a special divisional major which combined physics with the history of technology. He worked for several years on issues concerning technological innovation and public policy, at the Brookings Institution, for a public-private task force in Chicago, and on Capitol Hill. He then undertook his graduate study at Harvard's Economics Department. His research focuses on the structure of venture capital organizations, and their role in transforming scientific discoveries into commercial products (*The Venture Capital Cycle*, MIT Press 2000). He also examines the impact of intellectual property protection, particularly patents, on the competitive strategies of firms in high-technology industries. He is a faculty research fellow in the National Bureau of Economic Research's Corporate Finance and Productivity Programs.

Mark Myers, *Xerox Corporation (ret.) and Wharton School,
University of Pennsylvania*

[See biography for Washington, D.C. workshop.]

Paul D. Reynolds, *Paul T. Babson Professor of Entrepreneurial Studies,
Babson College*

Paul Reynolds is a professor in entrepreneurship at the London Business School, the Paul T. Babson Chair in Entrepreneurial Studies at Babson College (Wellesley, Massachusetts), and the director of the annual Babson—Kauffman Entrepreneurship Research Conference (1996–2000). He was the Coleman Foundation Chair in Entrepreneurial Studies at Marquette University for five years (1990–1995). He has been very active in research involving new firms, entrepreneurship, and their role in economic change and development since 1983. This has included the development of several state-wide (Minnesota, Pennsylvania, Wisconsin) samples of new firms with follow-ups. With regional economist Wilbur Maki (University of Minnesota), he has analyzed the effect of the local context on firm births and the effect of firm births on job growth. He worked with a European team (coordinated by David Storey, University of Warwick, UK) to

develop U.S.–Western European comparisons on the role of regional factors affecting entrepreneurial activity. Reynolds is now coordinator of the Entrepreneurial Research Consortium [ERC], an international collaboration of thirty-four university units, government agencies, and foundations implementing national longitudinal studies of business start-ups in the United States and eight other countries. As coordinating principal investigator of the Global Entrepreneurship Monitor project, he is coordinating thirty-one national teams in an ongoing analysis of the contributions of the entrepreneurial sector to national economic growth.

Reynold's educational background includes degrees in engineering (B.S., University of Kansas, 1960), business (M.B.A., Stanford, 1964), psychology (M.A., Stanford, 1966), and sociology (Ph.D., Stanford, 1969). He is the author or co-author of three conference proceedings, four books, four data sets in the University of Michigan ICPSR public archives, twenty-five project reports and research monographs, sixty peer-reviewed journal articles or conference proceeding reports, and several hundred professional conference presentations.

Hans Severiens, *Coordinator, Band of Angels*

[See biographies for Palo Alto workshop.]

Karl Shell, *Robert Julius Thorne Professor of Economics, Department of Economics, Cornell University*

Karl Shell has been the Robert Julius Thorne Professor of Economics at Cornell University since 1986 and has been the editor of the *Journal of Economic Theory* since 1968. (In 2000, Jess Benhabib joined Shell in the *JET* editorship.)

Professor Shell received his A.B. in mathematics from Princeton University in 1960, where he was a student of William Baumol, Ralph Gomory, and Harold Kuhn. He received his Ph.D. in Economics from Stanford University in 1965, where he was a student of Kenneth Arrow and Hirofumi Uzawa.

Shell was a member of the MIT faculty from 1964 to 68. He was a member of the University of Pennsylvania faculty from 1968 to 87.

In work inspired by Kenneth Arrow and stemming from his 1965 Stanford dissertation, Shell, in papers published 1966 and 1967, introduced a macroeconomic theory of inventive activity in which technological knowledge is a non-conventional factor of production. It follows that there are increasing returns to scale in all factors (including the non-conventional factor) taken together. Hence purely competitive

provision of inventive activity is not possible. Also because of increasing returns, the growth process is history-dependent and permits both explosive growth and contractionary growth. In a paper published in 1973, Shell provided the first growth model in which inventive activity depends on the prevailing industrial organization.

Andrew Toole, *Department of Economics, Indiana University*

Andrew Toole received his Ph.D. in economics from Michigan State University and a B.A. in economics and business administration from Kalamazoo College. His areas of interest include evaluating the effects of government science and technology policies on private industry investment and innovation, analyzing the key factors affecting the supply and demand of high-skilled labor, and competitive strategies in the pharmaceutical and biotechnology industries.

Richard J. Zeckhauser, *Frank Plumpton Ramsey Professor of Political Economy, J. F. Kennedy School of Government, Harvard*

Richard Zeckhauser, Frank Plumpton Ramsey Professor of Political Economy, pursues a mix of conceptual and applied research. The primary challenge facing society, he believes, is to allocate resources in accordance with the preferences of the citizenry. Much of his conceptual work examines possibilities for democratic, decentralized allocation procedures. His ongoing policy investigations explore ways to promote the health of human beings, to help labor and financial markets operate more efficiently, and to foster informed and appropriate choices by individuals and government agencies. Zeckhauser's current major research addresses the performance of institutions confronted with inadequate commitment capabilities, incomplete information flow, and human participants who fail to behave in accordance with models of rationality (for example, by engaging in herd behavior). Financial markets, health risks, and college admissions are the subjects of his major empirical investigations. Zeckhauser is the author or coauthor of 180 articles and eight books or edited books. He was U.S. pairs contract bridge champion in 1966 and finalist in the World Pairs Championship in 1998. He is a frequent investor in technology startups, many run by former students or colleagues, and serves on the board of three high-technology companies.