NIST GCR 02–841
Between Invention and Innovation
An Analysis of Funding for Early-Stage Technology Development

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PART I: 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)]

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 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.
- **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 Washington, 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 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 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.

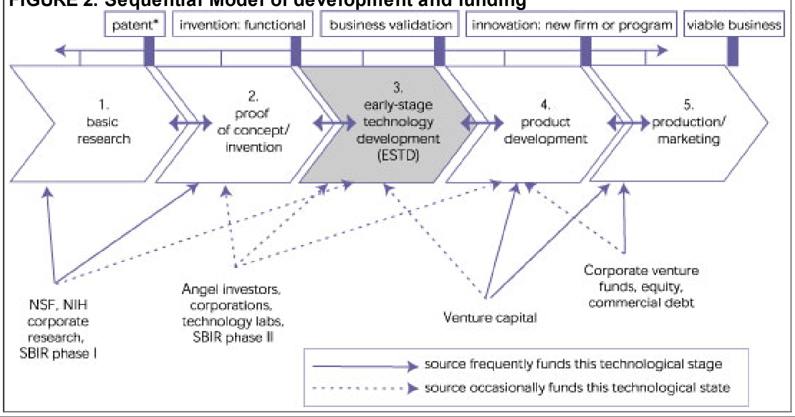
2. FROM INVENTION TO INNOVATION

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 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.

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.

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."

B. THREE ELEMENTS OF STAGE 3

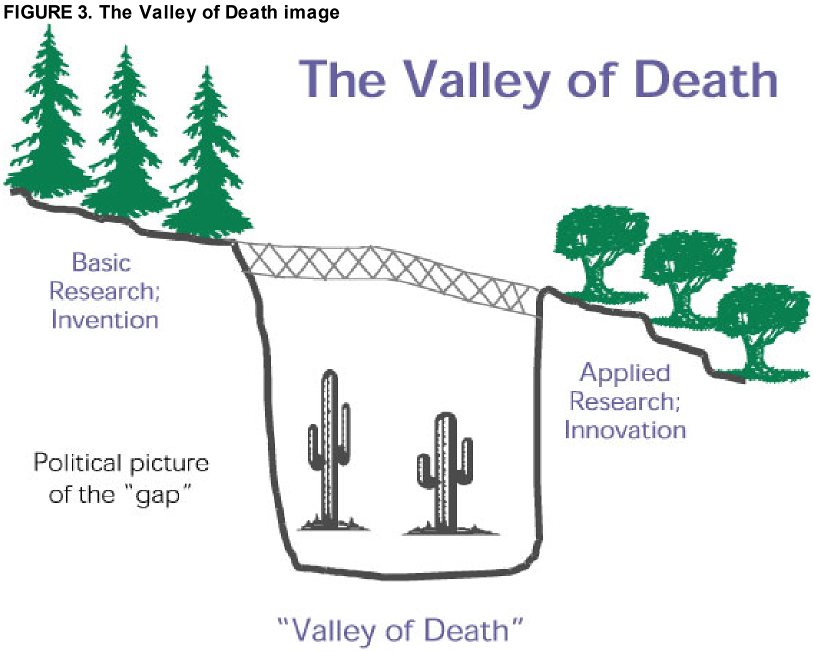
The specific region of the innovation space in which we are most interested is bounded at the earliest stage with the verification of a commercial concept through laboratory work, through the identification of what looks like an appropriate market, and perhaps the creation of protectable intellectual 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:

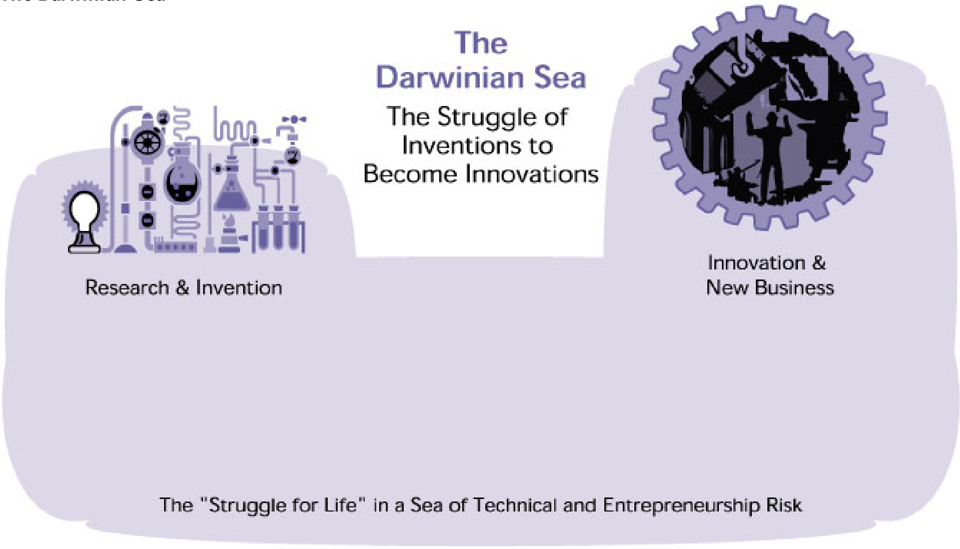
Motivation for research: Initially an innovator demonstrates to *his or her own satisfaction* that a given scientific or technical breakthrough could form the basis for a commercial product (proof of principle). However, a substantial amount of difficult and potentially costly research (sometimes requiring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

FIGURE 3. The Valley of Death image



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

FIGURE 4. An alterative metaphor for the investion-to-innovation transition:
The Darwinian Sea



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 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 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 Magnetoelectronics 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 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.

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)

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 "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 research[(47)] 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.

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 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."

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 payoff 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 Ampersand 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, 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.

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)

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 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."

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)

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).

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.

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:

> 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.

____________________ [Click on image to go back to text.]

27. Branscomb (2001). Traditionally, management innovations were considered a different meaning of the word "innovation" from a new product in th 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 engineeering ideas.

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).

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.

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).

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.

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).

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.

41. Ehlers (2000).

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 can 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.

43. We emphasize, however, that both the Palo Alto and Washington, D.C., 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).

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.

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 closed 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.

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

52. Porter and vanOptsal (2000: 39).

53. Moore and Davis (2000).

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

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.

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.'"

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/NewsandReports/publications.htm>.

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).

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).

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

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