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PB2007-105379

Advanced Technology Program

Economic Analysis of Research Spillovers Implications for the Advanced Technology Program

NIST-GCR-97-708

Economic Assessment Office (EAO)

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ECONOMIC ANALYSIS OF RESEARCH SPILLOVERS IMPLICATIONS FOR THE ADVANCED TECHNOLOGY PROGRAM

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Prepared for the
Advanced Technology Program December 1996

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Economists and other social scientists have demonstrated that the R&D activities of private firms generate widespread benefits enjoyed by consumers and society at large. As a result, the overall economic value to society often exceeds the economic benefits enjoyed by innovating firms as a result of their research efforts. Th excess of the *social rate of return* over the *private rate of return* enjoyed by innovating firms is described by economists as a positive externality or spillover. These spillovers imply that private firms will invest less than is socially desirable in research, with the result that some desirable research projects will not be undertaken, and others will be undertaken more slowly, later, or on a smaller scale than would be socially desirable.

These spillovers flow through a number of distinct channels. First, spillovers occur because the workings of the market or markets for an innovative product or process create benefits for consumers and non-innovating firms ("market spillovers"). Second, spillovers occur because *knowledge* created by one firm is typically not contained within that firm, and thereby creates value for other firms and other firms' customers ("knowledge spillovers"). Finally, because the profitability of a set of interrelated and interdependent technologies may depend on achieving a critical mass of success, each firm pursuing one or more of these related technologies creates economic benefits for other firms and their customers ("network spillovers").

The ATP would like to invest in projects that have a high social rate of return, but that would be underfunded, delayed or otherwise inadequately pursued in the absence of ATP support. This objective can be furthered by pursuing projects for which the gap between the social and private rates of return ("the spillover gap") is large. Existing ATP analyses--including examination of broad-based economic benefits, consideration of whether a technology is "enabling," and consideration of the need for ATP funding-- implicitly address the likely extent of the spillover gap for proposed projects. Better understanding of the pathways of spillovers can improve this process.

Researchers have identified characteristics of the market and technological environment that make spillovers more or less likely. Explicit consideration of these characteristics can be used to improve the likelihood that the ATP will fund high-social-return projects that would otherwise have been underfunded. These considerations include:

- competitiveness of the market or markets in which the innovation will be commercialized
- the role of "lead time" and "learning curves" in conveying advantages that are likely to permit innovators t reap a large fraction of the benefit of their innovations
- the role of marketing, sales and service, regulatory expertise and other "cospecialized assets" in

determining whether the returns to innovation can be captured by the innovator

- benefits of coordinated research that may arise if the returns to specific research investments are dependent on success by a "critical mass" of related projects
- the likelihood of ***negative*** spillovers through obsolescence of existing technology
- attributes of "enabling" technologies
- need for licensing for successful commercialization
- role of legal mechanisms for intellectual property protection in protecting returns

Further research could help clarify and expand the extent to which these and other factors can be used to predict the spillover potential of proposed projects. As experience with ATP projects accumulates, research can document the extent of spillovers created, the extent to which the factors listed above do predict spillovers, and the existence of other factors that are associated with the realization of large spillover benefits.

I. INTRODUCTION AND OVERVIEW

Economists use the term "spillover" to capture the idea that some of the economic benefits of Research and Development (R&D) activities accrue to economic agents other than the party that undertakes the research. Purchasers of better or cheaper products, competing firms that imitate a successful innovation, and firms whose own research benefits from observation of the successes and failures of others' research efforts all garner such spillover benefits. As these examples suggest, these spillovers are created by a combination of the new knowledge resulting from an R&D effort, and the commercialization of the new technology in terms of a product or process that is successfully implemented in the marketplace. Thus a complete understanding of the R&D spillover phenomena requires an unusual combination of scientific/technical and business/economic analysis.

Standard economic analysis postulates that economic agents try to maximize their self interest. In the context o R&D, this implies that firms make decisions about the level and focus of their R&D efforts based on maximizatic of their long-run profit. Firms deciding whether or not to pursue a particular line of research, or deciding on the margin what level of resources to devote to a research project, try to balance, in some rough way, the cost of th R&D against the future profits that the effort might yield, taking into account the tremendous uncertainty about both the overall costs and benefits. Because of research spillovers, there are benefits that are created for the economy and for society when a firm undertakes a research project (or increases its level of commitment to an ongoing project) that are ignored in this cost/benefit calculation.(1) The social rate of return to R&D will generally exceed the private rate of return.(2) Since firms make their decisions based only on the private rate of return, they will fail to undertake some projects that are socially desirable, and they will generally pursue the projects th they do undertake at a level of resource commitment that is lower than is desirable from the point of view of society as a whole. In economists' jargon, there is a "market failure" with respect to R&D that results in market forces allocating fewer of society's overall resources to R&D than is desirable.

R&D spillovers are thus an example of a positive externality. Other examples of activities that generate positive externalities (and hence are underprovided by a laissez-faire market system) include prompt garbage removal, inoculations and employee training. The concept of positive externalities is very closely related to the concept o "public goods." In the limit, the benefits of an activity may be so diffuse that no individual or firm would undertak the activity on their own, such as national defense. R&D (and the other examples in this paragraph) fall in an intermediate range in which the activity generates sufficient benefit to the party undertaking it that market forces generate some, but not enough, of the activity.

The market failure created by R&D spillovers is one of the primary justifications for government policies designe to encourage R&D. This report will describe what is known by economists about the phenomenon of R&D spillovers, and assess the relevance of this knowledge for the ATP. A thorough understanding of the spillover process is important to the ATP for at least three reasons. First, since a large fraction of aggregate R&D expenditures are funded by other government programs, and the U.S. tax code creates significant incentives to privately-funded R&D, the policy justification for the ATP rests on a demonstration that the program incrementally increases social returns, relative to what would occur in its absence. In other words, it is insufficie simply to cite the existence of spillovers. The ATP must be able to show that the government policy portfolio including the ATP is more effective at correcting the R&D market failure than the portfolio without the ATP woul be.

Second, better understanding of the spillover process will facilitate selection of projects for funding by the ATP so as to maximize the social rate of return to the ATP expenditures. While there is inherently much uncertainty regarding the spillover potential of particular projects (just as there is much uncertainty about their technical potential), it is possible to identify generic features that will tend, on average, to be associated with a greater likelihood of spillovers.

Finally, to the extent that the policy justification for the ATP lies in creating spillovers, then any attempt to evaluate the ATP's success must try to measure those spillovers. Hence a better understanding of the process will foster the development of data collection and research efforts that are appropriate to quantification of the spillovers generated by the ATP investments.

The spillover phenomenon is not the only factor that may cause socially desirable research efforts to be underfunded. In particular, capital market imperfections have the effect that risk and financial factors may also impede socially desirable research and development efforts. This report does not provide an explicit analysis of these other factors, but does consider their likely interaction with the spillover process, and the consequences o this interaction for the ATP.

The next section of this report will discuss the analytical underpinnings of the spillover concept in more detail, and relate this analytical framework to analyses already undertaken by the ATP. Section III will discuss the findings of economic research regarding the magnitude of spillovers, and the circumstances that make them more or less likely. Section IV then suggests ways in which the current ATP analysis of spillovers could be expanded, and considers the difficult issues raised by the interaction of spillovers, risk, and private decisions regarding R&D expenditures. Section V discusses the issue of designing research and data collection to measure spillover impacts and improve the ability of the ATP to assess the likely spillover potential of project proposals. Section VI provides concluding comments.

II. ECONOMIC ANALYSIS OF R&D SPILLOVERS

A. Sources of Spillovers

Spillovers have been of interest to economists since at least the nineteenth century. At that time, organized scientific research was uncommon in industrial firms. Technological knowledge was built more by informal "tinkering" and learning by doing. Alfred Marshall, one of the founders of modern microeconomics, made such informal learning a centerpiece of his analysis of the evolution of the modern, large industrial firm. He wrote tha

Many of those economies in the use of specialized skill and machinery which are commonly regarded as within the reach of very large establishments, do not depend on the size of individual factories. Some depend on the aggregate volume of production of the kind in the neighborhood; while others again, especially those connected with the growth of knowledge and the progress of the industrial arts, depend chiefly on the aggregate volume of production in the whole civilized world. (Marshall, 1920)

He argued that R&D spillovers were on the rise, remarking, "the secrecy of business is on the whole diminishin and the most important improvements in method seldom remain secret for long after they have passed from the experimental stage."

Analytically, it is useful to distinguish several different mechanisms by which R&D generates spillovers. For convenience, I refer to these as "knowledge spillovers," "market spillovers," and "network spillovers." In order to think through the implications of spillovers for the ATP, it is useful to consider each of these separately, and the to note that they also interact in a way that tends to increase their combined effect.

1. **Knowledge spillovers**

The quote from Marshall refers to the phenomenon of knowledge spillovers. Knowledge created by one agent can be used by another without compensation, or with compensation less than the value of the knowledge.

Knowledge spillovers are particularly likely to result from basic research, but they are also produced by applied research and technology development. This can occur in obvious ways, such as "reverse engineering" of products, and also in less obvious ways, such as when one firm's abandonment of a particular research line signals to others that the line is unproductive and hence saves them the expense of learning this themselves. The spillover beneficiary may use the new knowledge to copy or imitate the commercial products or processes of the innovator, or may use the knowledge as an input to a research process leading to other new technologies

In some circumstances the creation of knowledge spillovers is intentional on the part of the innovator; the publication of scientific papers is, at least in part, intended to spread new knowledge so that it can be used by the widest possible audience. In the case of patented inventions, society requires disclosure of new knowledge as a quid pro quo for the granting of monopoly rights in the commercial use of an invention. The effect of this disclosure is, in principle, to make the new knowledge available to others for the purpose of facilitating new and different applications, while at the same time protecting the inventor against copying.

Knowledge spillovers also occur when researchers leave a firm and take a job at another firm (or start their own While trade secret law gives firms some ability to protect knowledge they have created, it is extremely difficult tc effectively protect tacit knowledge about successful and unsuccessful approaches, mechanisms etc. Further, important innovative successes are likely to increase the incentives for researchers to capitalize on their tacit knowledge by moving to another firm or starting their own.

More generally, commercial development and use of new knowledge will tend to cause it to spread, despite any desire of the inventor to prevent such spread. Economic exploitation of new knowledge requires the sale of new commercial products embodying that knowledge or the incorporation of that knowledge into new commercial production processes. Such commercialization tends, in general to reveal at least some aspects of the new knowledge to other economic agents. Hence the very process of economically exploiting the knowledge that research creates tends to pass that knowledge to others. Because the spread of knowledge is greatly affected by the commercial use of new technology, even the analysis of "knowledge" spillovers must be informed by an understanding of the market mechanisms that govern the spread of new technology.

2. **Market spillovers**

Market spillovers result when the operation of the market for a new product or process causes some of the benefits thereby created to flow to market participants other than the innovating firm. It is this "leakage" of benefits through the operation of market forces, rather than the flow of knowledge itself, that distinguishes market spillovers from knowledge spillovers. Any time a firm creates a new product, or reduces the cost of producing an existing product, the natural operation of market forces will tend to cause some of the benefits thereby created to be passed on to buyers.

Consider first the case of new or improved products. It is likely that a firm that sells a better mousetrap will charg a price that is higher than that being charged for ordinary mousetraps. But innovative products, even those that are patented or otherwise protected from direct competition, will generally be sold at prices that do not ***fully*** capture all of the superiority of the new product relative to what was available before. As a result, consumers wi be made better off by the introduction of the new product. This increase in consumer welfare is a social benefit from a new product that is not captured by the innovator.[(3)] Similarly, if a company does R&D to lower its production cost, it will typically lower its selling price as a result. Again, the innovator's customers are better off, and a benefit is created that is not captured by the innovator. Of course, innovation often results in both higher quality/performance and lower prices; thereby benefiting customers even more.

3. **Network spillovers**

Network spillovers result when the commercial or economic value of a new technology is strongly dependent on the development of a set of related technologies. An example of network spillovers exists among all of the different developers of application software for use with a new operating system platform. If one firm develops a particular application, people will buy it only if many other firms develop other sufficient applications so that the platform itself is attractive and widely used[(4)]

If the commercial payoff to ***each*** of a set of related research projects is dependent on *all* or a significant fraction of the projects being completed successfully, then private firms might hesitate to undertake any one of the projects, for fear that the others will not be undertaken. Conversely, if any one firm decides to undertake such a project, it creates a positive externality for all the other firms, by increasing the probability that the "critical mass" will be achieved. Note that this positive externality or spillover exists even if there is no knowledge spillover among the firms (although it is likely that knowledge spillovers would also be occurring).

The existence of network externalities creates a "coordination problem" that is another possible market failure associated with research. Where network externalities are important, it is possible that firms' inability to coordinate their efforts will lead to a misdirection of research effort, away from the activities associated with network externalities, even if firms are in the aggregate undertaking a socially efficient ***level*** of research effort.

It is important to emphasize that the coordination problem only arises if there are reasons why a single firm cannot develop all of the necessary related components (or contract with others for their development) and thereby internalize the network externality. Thus while you cannot run a computer without an operating system, the need for the operating system software does not create an important coordination problem, as the hardware manufacturer can either write the operating system itself or contract for its creation. What distinguishes the operating system (which does not create a significant network externality) from the need for applications programs (which might) is the likelihood that ***many*** different applications will ultimately be necessary, and that it is unlikely that one firm would have all the capabilities to create all of these different applications, or even to knc what the set of necessary applications will ultimately look like. To put it differently, synergistic market interaction among a small number of technologies is unlikely to create a coordination problem, but when the number of technologies that must be developed is large and the necessary capabilities are diverse, the coordination problem may become severe.

There are a number of different mechanisms by which the coordination problem created by network externalitie can be handled. Research joint ventures, in which a number of companies combine forces, can be used to pursue the interrelated approaches whose commercial success is interdependent. By fostering the creation of such joint ventures, the ATP assists this process. In addition, the formation of focused programs targeted at a set of interrelated technologies can be used to try to ensure that a critical mass will be reached. Focused programs are discussed in section IV.C.

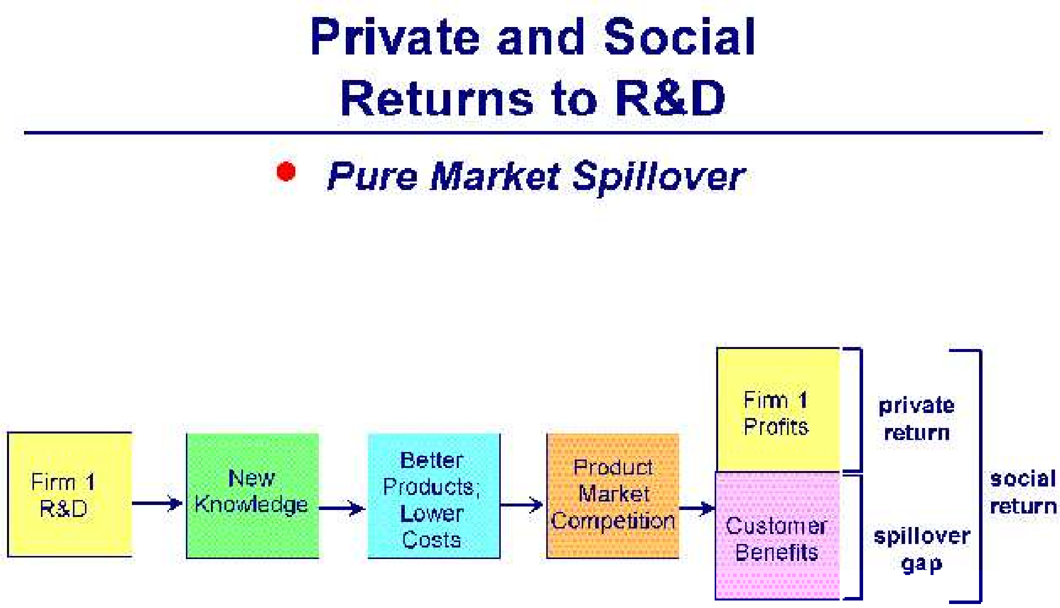
B. Private and Social Returns to R&D

1. **Pure market spillovers**

As noted above, the effect of spillovers is to create a gap between the private rate of return to R&D (the return c profit earned by the firm undertaking the research) and the social rate of return, which includes the private returi but also includes benefits to the firms' customers and to other firms. The nature of this spillover gap in the context of market and knowledge spillovers is illustrated in Figures 1, 2, and 3.

Figure 1 illustrates a "pure" market spillover. If "firm 1" invests in R&D, this generates new knowledge, leading eventually to improved products or lower production costs for firm 1.[(5)]

Figure 1



The operation of competition in the markets where firm 1's products are sold will divide the economic benefit of these improvements between firm 1's profits and benefits captured by customers in the form of lower prices or higher quality. The total social return to the innovation is comprised of the customer benefit plus the profits accruing to firm 1; the private return is only firm 1's profits, and hence there is a "spillover gap" consisting of the customer benefit.[(6)] The more competitive are the markets in which firm 1's products are sold, the greater will be the share of the economic benefit that will be driven out of firm 1's profit and into the benefits captured by firm 1' customers.

Economists would say there is an "appropriability" problem, because firm 1 is not able to appropriate to itself all of the benefits created by its investment in research. Of course, firms will attempt to solve the appropriability problem, using various mechanisms to try to capture the fruits of research. Economists studying the innovation process have identified a number of such appropriability mechanisms, and have identified market conditions tha tend to make them more or less successful. This research is discussed in Section III.B.

It is obvious from Figure 1 that the market spillovers will not be realized unless the innovation is commercialized successfully. Market spillovers accrue to the customers that use the innovative product; they will not come to pass if a technically successful effort does not lead to successful commercialization.

An interesting case -- and one that illustrates the dividing line between knowledge spillovers and market spillovers -- occurs when a firm invests its resources in developing an improved input to its own production process, such as a new material or a new machine tool. Often, the firm will then work with its supplier firms to produce this new input. The innovator will get the benefit of the innovation in its own production (and its ***customers*** will enjoy market spillovers), but the supplier may, in turn, sell the improved input to other firms, creating profits for itself and benefits to those purchasing firms (and their customers).

One could think of this as a knowledge spillover, in the sense that the knowledge created by the innovator has leaked to its supplier. But the transfer of knowledge to the supplier is not an accident, it is a necessary step in implementing the innovation. In theory, one could imagine the innovator writing a contract with the supplier that ensures that all of the benefits of future sales are captured by the innovating customer. In practice, such a contract is impossible to write; the inability to write such a contract is a market imperfection that creates the market spillover. In other words, knowledge spillovers can be thought of as benefit leakages that occur in the absence of a market interaction between the innovator and the spillover beneficiary, whereas market spillovers result from a market interaction between them.

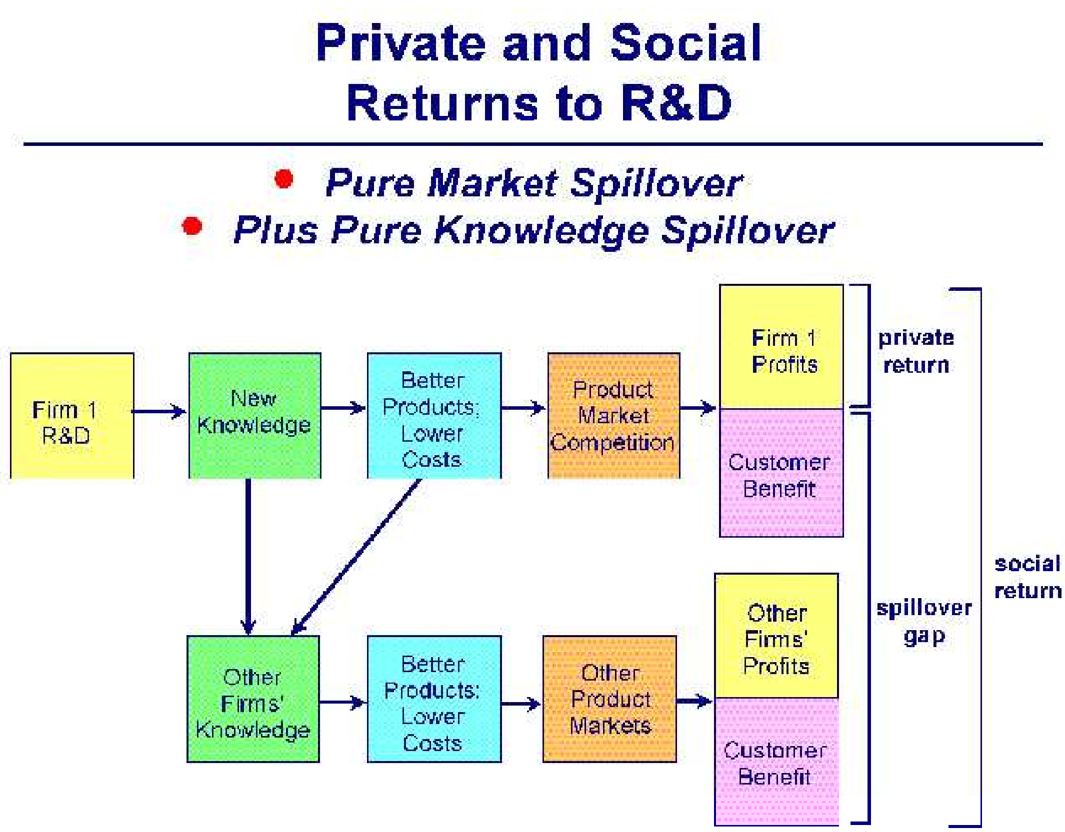
Note that market spillovers occur whether the purchaser of the new product is a household or another firm. In the case of improved intermediate products, then the market spillover benefits will be passed to the purchasing firms, which will in turn tend to pass at least some of this benefit to their customers. For example, if a supplier to the auto industry develops a better material, that material will be sold to auto companies at a price that does not fully reflect its improved properties. In turn, the auto companies will sell the better autos to consumers at a price that is either lower than before (if the new material significantly reduced production costs) or else results in a price/quality combination that is superior from the consumers' point of view. Such a chain of spillovers can be quite long; a new catalyst could permit economic production of a new polymer that results in a better fiber that is used in better fabric that is eventually incorporated in a better garment.

An important case of market spillovers associated with intermediate goods is where the innovation is an input to the research process, such as a new material or instrument. The purchaser is another researcher, who will typically use the new device in ways that create further spillovers. This case of "infratechnologies" is discussed further below.

2. **Pure knowledge spillover**

Figure 2 illustrates the effect of adding a "pure" knowledge spillover. By "pure," I mean a knowledge spillover that flows to firms that do not compete in firm 1's markets. Their increase in knowledge as a result of firm 1's research allows them to improve their products or lower their costs, increasing their profits and customer benefits in their markets.[7] Both these profits and the consumer benefits are part of the social return, but are not captured by firm 1, and so the spillover gap is increased.

Figure 2



Note that even in the case of knowledge spillovers, the social return is created by the ***commercial use*** of a new process or product, and the profits and consumer benefits thereby created. The difference between market spillovers and knowledge spillovers is that in the former case the commercial benefits are created in the market for the new product or process that is the direct "output" of the research effort, while in the case of knowledge spillovers the commercial benefits are created indirectly through the creation of new or improved products or processes in other markets. Though as a society we value "knowledge for knowledge's sake," I am not including such non-economic value within the concept of knowledge spillovers used here.

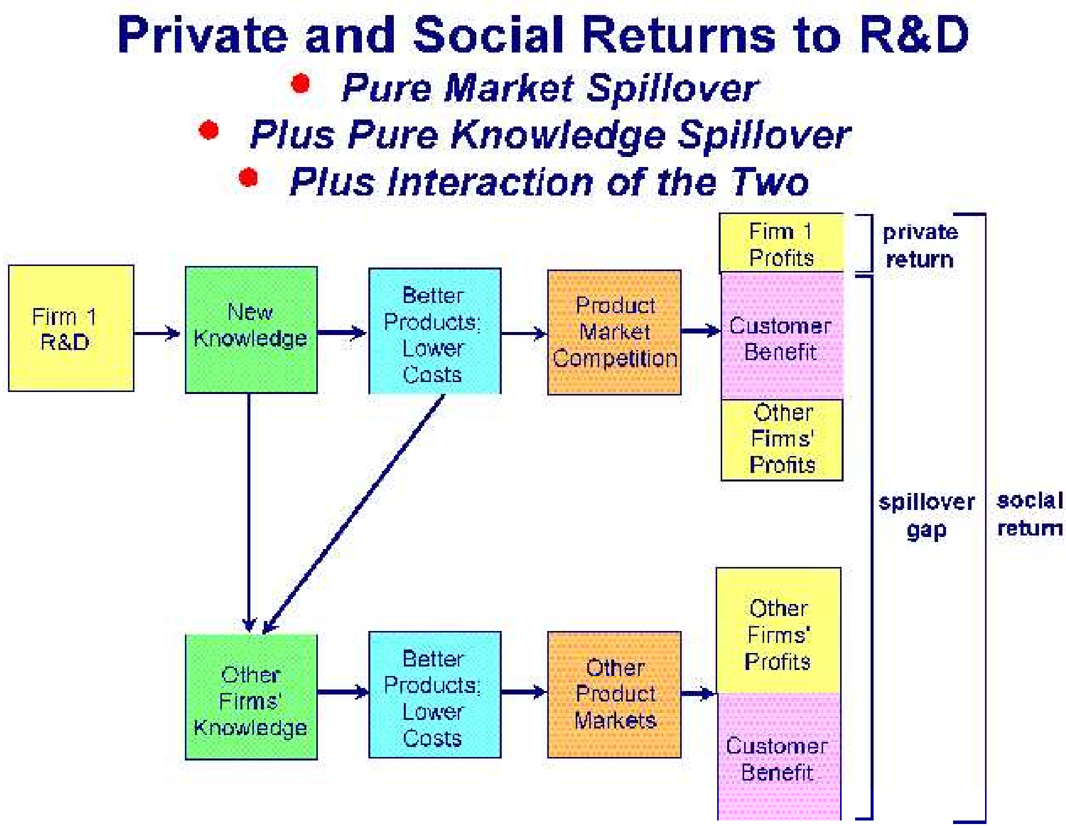
Figure 2 indicates that the knowledge spillovers flow to some extent from firm 1's creation of new knowledge, and to some extent from firm 1's commercialization efforts. This reflects the idea that other firms may learn to some extent from papers, patents, departing employees, and other disembodied outputs of firm 1's research, but they are likely to learn more when firm 1's research results are actually embodied in new commercial products and processes. The relative importance and the speed of these two pathways will vary, depending on the nature of the research. In general, knowledge spillovers from more basic research would be expected to flo mostly from the research results themselves, and to take a fairly long time to have the commercial impact indicated in the lower part of Figure 2.[(8)] On the other hand, knowledge spillovers from applied research and development are more likely to flow from the products or processes embodying the research results, and thereb have a quicker economic impact.

Thus, for the kinds of applied research and development projects that are the focus of the ATP, the realization o spillover benefits, and social returns more broadly, is strongly dependent on successful commercialization of the new technology. This is true both for market spillovers (which depend entirely on commercialization) and knowledge spillovers (which are likely to be largely dependent on and speeded by commercialization). New technology that remains "on the shelf" does not benefit customers, and hence does not create market spillovers and the knowledge spillover impact is likely to be limited. Basic research of the sort that is the mission of other federal agencies besides the ATP is likely to create knowledge spillovers that are more diffuse and slower to materialize.

3. **The interaction of market and knowledge spillovers**

It will often be the case that at least some of the firms that benefit from the knowledge spillover will be competitors or potential competitors of firm 1. The extreme case of this is pure imitation, where other firms copy the innovations of firm 1; more generally, firms making similar or related products may be able to improve their products or lower their costs on the basis of things they are able to learn as a result of firm 1's research. As shown in Figure 3, this complicates the picture in two ways. First, the introduction of these cheaper or better products into firm 1's markets creates some additional customer benefits, and some profits for these other firms both of which constitute social returns not captured by firm 1. These increase the spillover gap.

Figure 3



At the same time that this increased competition increases social returns, it will likely ***reduce*** firm 1's profit from its own innovation. That is, the combination of knowledge spillover with competitive interaction increases the spillover gap both by *raising* the social return and *lowering* the private return. Thus "pure" knowledge spillovers increase the social rate of return to R&D, but they do so in a way that at least does not reduce the private return. When knowledge spillovers are combined with competition, however, the effect is likely to be an actual reductio of the private rate of return. Put differently, the interaction of knowledge spillovers and market spillovers aggravates the firm's appropriability problem: not only does the firm create benefits that it cannot capture, but its own profits from marketing its innovation are competed away. Understanding this interaction has important implications for identifying which research projects are likely to have large spillovers. In Section III.B, I discuss t factors that economists have identified that affect firms' ability to deal with this appropriability problem.

Finally, Figure 3 can also be used to illustrate the possibility that research effort of any given firm can create a ***negative*** externality for other firms. Suppose that the improved products of "other" firms in Figure 3 came from their own research, rather than from a spillover of knowledge from firm 1. In this case, there would still be a diminution of firm 1's profits as a result of this new competition. This ***reduction*** in profits of other firms is a negative spillover, just as the increase of profits of other firms in Figure 2 is a positive spillover.

To make this concrete, consider the market for anti-ulcer drugs. In the 1970s, the drug Tagamet was introduced, which, for the first time, reduced the stomach's production of acid rather than just neutralizing acid once produced. This was an important medical advance that generated large social benefits and also large expected profits for the firm that introduced it. Subsequently, Zantac was introduced, a drug that accomplishes the same objective as Tagamet, though with somewhat fewer side effects. The maker of Zantac has made large profits, because its slightly superior performance has allowed it to take much of the market away from Tagamet.

From a social point of view, the introduction of Zantac had 3 effects. On the plus side, the maker of Zantac has earned large profits, and consumers have gotten some benefit from Zantac's superior features and price competition between the two firms. On the minus side, the maker of Tagamet has ***lost*** a large stream of profits that it otherwise would have enjoyed. Altogether, it is quite possible that the incremental social value of Zantac has been quite modest, despite the fact that its maker has earned large profits. Hence, in this case, the private rate of return to innovation likely ***exceeded*** the social rate. Given that significant research resources were devoted to the introduction of this marginally valuable (from a social point of view) innovation, it is quite possible that the social rate of return to this innovation was actually negative.

More generally, the introduction of a new technology will often make some previous investment in R&D obsolete Part of the profits to the innovator can be thought of as being taken away from the previous technological leade This is a negative externality, i.e. it is a negative social effect of research that is not considered when a firm makes its own R&D decisions. At a purely theoretical level, it is possible that this effect dominates the other two so that the laissez-faire level of private R&D is too high rather than too low. In reality, the empirical evidence is overwhelming that such is not the case, i.e. the net effect of the positive and negative externalities is positive.[(9)] Nonetheless, the existence of this negative effect has some implications. In particular, if we can identify situatio where it is likely to be unusually large, then we can surmise that these are situations where the net spillover benefits are likely to be small or even negative, suggesting that this would not be a good area for ATP funding.

C. Relationship of Spillover Concepts to Existing ATP analysis

Spillovers are already very much a part of ATP discussions and analysis, although different words are sometime used. In this Section, I will relate the terms and analyses that are currently used to the spillover concepts as I have described them.

1. **Broad-based economic benefits**

One explicit criterion of project selection is the creation of broad-based economic benefits. Under this criterion, the ability of a proposed project to enable new economic activity is evaluated. The significance of potential market applications, and their impact on productivity, employment, output and quality of life (if applicable) are considered. Applicants are asked to discuss timing issues, and to explain why ATP assistance is needed, what difference it will make, and why taxpayer support is justified. The overall incremental benefits created by the project are compared to its overall incremental costs. Although economic benefits include purely private benefit and thereby encompass much more than spillovers, this analysis is also closely related to the kinds of impacts on productivity, employment and output that determine the magnitude of market spillovers.

As shown in Figures 2 and 3, knowledge spillovers also lead, eventually, to economic benefits. One way to thin of this is to view market spillovers as creating ***direct*** economic benefits, and knowledge spillovers as creating ***indirect*** economic benefits. Thus, at least in principle, both of these effects would be a part of what is currently analyzed under the rubric of broad economic benefits.

2. **Enabling technology**

The concept of "enabling" technology is widely used as a general description of the mission of the ATP, and as criterion for discussing individual projects. I believe that the notion of enabling technology can be related to the concepts of market and knowledge spillovers, and the important interactions between the two. There are a number of different ways in which a technology can be thought of as enabling. In this subsection, I consider different ideas of enabling technology that are used within the ATP, and how each relates to the spillover concepts that I have elucidated.

Multi-use technology. A multi-use technology is defined within the ATP as "a technology that has many distin applications." In the framework that I have presented, a multi-use technology can be thought of as one that generates many distinct paths of knowledge spillover. Referring to figure 2, if the lower pathway that begins wit "Other firms' knowledge" being augmented by spillovers from the research of firm 1 is replicated many times over, then firm 1 is generating multi-use technology. The many different and distinct applications of a multi-use technology make knowledge spillover likely, because the original developer of the technology is unlikely to be able to pursue all of these distinct applications, suggesting that others will likely pick up the idea and commercialize (and hence profit from) many of the resulting applications.

One way a technology can have multiple uses is where "proof of concept" is important. For example, the attem to develop a catalyst for a certain polymerization reaction that is based on an entirely new mechanism could be multi-use technology; the successful demonstration of the validity of the new mechanism may well allow others to develop new catalysts for a whole range of other polymerization reactions. Another form of multi-use technology is where improved performance of a specific component is the "bottleneck" preventing higher performance in many different applications. The proponent wants to make a quantum improvement in this component, and redesign ***one*** of these applications to exploit the improved performance. But once the improved component is available, all the other applications can be improved as well. Thus a multi-use technology has significant knowledge spillovers because it has a wide variety of distinct applications, not all of which are likely to be implemented by the firm that successfully demonstrates the first application.

The ***distinctness*** of the applications is important. If I invent a better automobile windshield wiper, one might argue that this is a multi-use invention, as it can be used on every car, truck, and tractor in the world. But these are not distinct applications, by which I mean no significant additional research has to be done to adapt the idea to these different uses. There is little to stop me from making all of these sales myself (assuming I have adequa manufacturing capacity). In contrast, when there are numerous distinct applications, the time and application-specific knowledge that it takes to undertake the application-specific research necessary to implement the generic idea in different areas will make it difficult for any one firm to capture all of these areas. This makes spillovers likely.

Pathbreaking technology. Another way in which a technology can be enabling is to be "pathbreaking," defined as "a technology that induces revolutionary change in existing fields or that promises to open up new fields of activity." Whereas a multi-use technology can be thought of as one for which the knowledge spillover impact is likely to be "wide," we can think of a pathbreaking technology as one whose knowledge spillover impacts are "deep." That is, the solution to certain stubborn technical problems can be expected to open up a new line of technological developments, creating in the process entire new markets or even new industries. It is extremely unlikely that the firm that originally opens up this line will capture all or even most of the economic benefits thereby created. As discussed below, for example, the firm that invented the "CAT" scanner did not last long in the commercial market, as subsequent products that built upon but improved the original idea were marketed by other firms.

Infratechnologies. Tassey (1995) defines "infratechnologies" as "a set of 'technical tools' for making the entire economic process more efficient, or, in some cases, possible in the first place." Examples given by Tassey of infratechnologies include standards, scientific and engineering data, measurement and test methods, production practices and techniques, and interfaces. Clearly, infratechnology as relevant to the ATP is a narrower concept. The ATP defines infratechnology as "technology that supports the R&D, production, and business of entire industries."

In my view, infratechnologies can be thought of as generating two kinds of spillovers. First, development of measuring and testing methods, interfaces, and certain production practices have elements of network externalities. That is, these technologies often have features that depend on the establishment of *standards* that are shared by multiple industry participants. It does me no good to develop an interface unless many others are going to use it. Similarly, the value of measuring and testing methods is greatly enhanced when the same methods are widely used, so that test results can be shared and used as the basis for market transactions. For the reasons discussed above, activities that have this element of the creation of standards, with the attendant network externalities, are likely to be underprovided by competitive markets.

The idea of infratechnologies appears, however, to be broader than just standards. Another dimension is the development of technologies that are essentially ***inputs*** to the research process. Even without the issue of standards, the development of certain kinds of scientific and engineering data, or the creation of measuring and testing instruments, facilitate the research process. One way to think of this is to view infratechnologies as inventions whose "market" is the research process itself. That is, the customers are other researchers, and the market spillovers come in the form of increases in the efficiency of others' research programs. Now, to the extent that the research process ***generally*** involves the creation of spillovers, the generation of market spillovers that come in the form of more efficient research ought to generate particularly large social returns, since the research endeavors that benefit will typically go on to generate further spillovers.

Overall, then, the various notions of "enabling" technologies can be thought of as capturing several specific mechanisms by which market and knowledge spillovers operate and interact. As discussed in Section IV, understanding the significance of these spillover pathways provides an analytical basis for evaluating the spillover potential of proposed projects.

3. **Necessity of ATP support**

Finally, an additional element of the existing review process that relates to spillovers is the necessity of ATP support. Conceptually, the existence of large spillovers is one obvious explanation why a technically important project with significant economic benefits might not be carried out without ATP support. Often, the spillover connection is implicit rather than explicit: proponents and/or reviewers will cite the diffuse and high-risk nature o the potential benefits as reasons why private capital is not forthcoming, or note that the project is not part of the proponent's core business.

III. REVIEW OF ECONOMIC LITERATURE RELATING TO SPILLOVERS

A. Estimating rates of return and the magnitude of spillovers

A possible excuse for the delay between the time Alfred Marshall talked about spillovers and the time economis made serious efforts to measure them is that they are inherently difficult to observe. As Paul Krugman has note "knowledge flows...are invisible; they leave no paper trail by which they may be measured and tracked, and the is nothing to prevent the theorist from assuming anything about them that she likes" (Krugman, 1991, p. 53). As a result, empirical measurement of spillovers is necessarily somewhat indirect. Most analyses take the form of measuring the innovative effort or output of one agent or set of agents, and looking for a correlation between thi measure and the innovative output of another agent or set of agents.

To make such an analysis tractable and meaningful, one must identify which agents are the likely recipients of spillovers from particular research efforts. This typically involves developing a metric for measuring the "closeness" of different agents -- either in terms of technological similarity, geographic proximity, or economic relationships, such as vendors and their customers. To infer the existence of spillovers from a correlation between the research effort of one group of agents and the research output of other agents that are somehow "close," it is necessary to control for (1) the innovative ***effort*** of the second group, and (2) variations in "technological opportunity" that might be affecting the productivity of research effort for both the "spilling" and "receiving" agents, inducing a correlation between an agent's research success and the effort of other firms that need not be related to spillovers.

Studies of this sort allow the calculation of the "excess return" to R&D investment, i.e., the difference between the rate of return calculated including the effects of the investment on the recipients of spillovers, and the rate o return calculated excluding spillover effects. Depending on the nature of the study, this excess return or spillove gap may encompass knowledge spillovers, market spillovers, or both. In general, the spillover gap is found to b positive, suggesting that the negative competitive externality is generally outweighed by positive effects of knowledge and consumer surplus externalities.

1. **Measurement of market spillover**

The oldest line of work focuses on spillovers embodied in products and measures closeness using supplier-customer relationships. For example, Terleckyj (1974) looked at industry data, constructing a measure of "borrowed" R&D for each industry on the basis of the R&D of the industries from which it purchased intermediate inputs, including capital equipment. He found that the productivity effects of R&D in downstream industries implied an excess return to industry R&D of 20% to 50% (compared to a private rate of return of abou 30%). This measure of market spillovers may also contain an element of knowledge externalities, to the extent that the downstream firms are engaged in their own research and benefit indirectly from the research of their suppliers.

Scherer (1982 and 1984) took another cut at this problem. By examining patent data, he estimated the fraction of inventions *originating in* each industry that would be *used by* each industry. This allows the creation of a "technology flow" matrix which can be used to allocate industrial research by the industry in which it will be "used" regardless of the industry in which it is performed. He shows that this "used" R&D variable is more strongly correlated with industry productivity growth than is a variable measuring R&D performed in the industry

Mansfield, et al (1977) used a case study approach instead of looking at aggregate industry R&D statistics. The identified 17 specific innovations, and attempted to estimate the actual cost and overall social benefits of each. particular, they took great care to analyze the impact of the innovations on customers, and also on competitors. They did not, however, specifically seek to identify knowledge externalities. For this group of innovations, the median private rate of return was about 25% and the median social rate of return was about 50%.

Bresnahan (1986) and Trajtenberg (1990) have quantified the consumer surplus spillover from mainframe computers in the 1960s and the CT scanner in the 1970s. Bresnahan calculates that between 1958 and 1972 financial service firms paid $68 million for computing services, but received benefits equal to $200 to $400 million. This difference between the cost of the computers and the benefits they created is a measure of market spillovers, and suggests that the social rate of return to this innovation was several times the private rate. Trajtenberg calculates that the social rate of return to ***improvements*** in CT scanners averaged between 180 and 350 percent per year, depending on how foreign R&D investments are treated. While Trajtenberg does not calculate private rates of return, approximately half of the producers, including EMI, the original innovator, eventually left the business, apparently because of mounting losses.

2. **Measurement of knowledge spillovers**

In my 1986 paper, I used patent data for about 500 manufacturing firms to characterize the "technological proximity" of all pairs of firms on the basis of the extent of overlap of technological classification of their patents. then constructed a measure of the "spillover pool" for each firm, as the sum of all other firms' R&D, weighted by their proximity to the receiving firm. I found that the pool variable had positive effects on firms' patents, profits ar market value, all controlling for the firm's own R&D. For patents -- a purely technological measure of research output -- roughly half of the aggregate impact of R&D was in the form of spillovers, or, conversely, the social productivity of research was roughly twice as great as the private productivity. For economic measures of research output such as profits, productivity and market value, I found that the spillover effect was roughly half as large as the private return[(10)]

Interestingly, the effect of the pool was found to be itself a function of firms' own R&D. The more R&D a firm does itself, the more it benefits from spillovers from others. With respect to profits and market value, firms that have significantly less than the mean R&D level actually suffer a negative effect from the spillover pool. This is interpreted as saying that both knowledge and competitive externalities are present, with the former outweighing the latter on average, but the latter outweighing the former for firms that do little R&D themselves.

3. **Summary of estimates of spillover magnitudes**

Griliches (1992, Table 1) summarizes the results of many of these studies. He concludes "R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates." While all of this work carries econometric limitations and presents only indirect evidence that spillovers exist, the weight of the evidence does seem to be increasingly convincing that spillovers create a large gap between the private and social rate of return. There are two ways to look at this gap. In absolute terms, it appears that the ***excess*** of the social rate of return over the private rate --the rate of spillover -- is something like 15 to 30 percer with some estimates much higher than that. Another way to look at this is relative to the private rate of return.[(11)] Again, estimates vary somewhat, but spillovers seem to create a gap between the private and social return that equal to 50 to 100% of the private rate of return. Note that the individual studies underlying these ranges tend to emphasize either knowledge externalities ***or*** market externalities. I can think of no study that, at a conceptual level, is designed to capture both, although relationships between the two in the data make it likely that each kir of study picks up some of the other effect. Hence it is likely that these estimates have some tendency to underestimate the combined effects.

B. Mechanisms of Appropriation

In parallel to the efforts to measure rates of return, economists have worked to understand how firms respond to spillovers. U.S. firms spent about $100 billion of their own money on R&D in 1995, so they obviously think that there are significant private returns to capture. This does not mean, as discussed above, that the social return is not even higher, but it does suggest that understanding the mechanisms by which firms "appropriate" the returns to R&D is likely to be helpful in understanding where and when spillovers are likely to be large. From this point of view, spillovers are likely to be largest when the mechanisms of appropriation are unavailable or do not work well.

At a broad conceptual level, there are 4 important ways that firms appropriate the returns to R&D.[(12)] First, to minimize knowledge spillovers, they can try to legally preclude others from using knowledge that they create, through the use of intellectual property protections such as patents, copyrights, and employment contracts that attempt to prevent scientists and engineers who leave the firm from using knowledge they take with them. Second, for certain kinds of new knowledge, secrecy can be effectively maintained. Third, in some cases, simpl being first conveys sufficient advantage that an innovator can capture a significant share of the benefits to innovation, even if the knowledge is otherwise unprotected Finally, despite the simple model of knowledge as a public good, economic exploitation of new knowledge often requires other assets or abilities that may not be easily obtained or duplicated. Investment in these "cospecialized" assets (Teece, 1986) may allow an innovating firm to capture a larger share of the overall returns to a new technology.

Intellectual property protection is most successful with knowledge that can be easily described and codified. Thus patents tend to be most effective in the chemical industries, including drugs, and in some industries based on relatively simple mechanical technologies (Levin, et al, 1987).[(13)] Also, patents are generally viewed as more effective at protecting *product* innovations than *process* innovations. Conversely, secrecy is most effective in protecting tacit knowledge that is difficult to codify (and hence difficult to copy), and is more useful in protecting process innovations than product innovations.

First-mover advantages possessed by an innovator derive from two primary sources. First, being the first to market a new technology may allow a firm to create customer loyalty that protects profits to some degree even i other firms eventually are able to imitate the new product. Second, for production technologies where "learning curve" effects cause production costs to fall as production experience is accumulated, the first firm to market may garner a cost advantage that is dynamically self-sustaining. That is, the first firm acquires production experience first, leading to lower cost; this lower cost allows the first-mover to maintain a large market share which serves to increase production experience and lower cost further.

Finally, the need for cospecialized assets, such as large-scale production capability, a network of sales and service organizations, a reputation for reliability within a line of products, or the ability to navigate a maze of regulatory approvals necessary to market some products may allow some innovating firms to protect themselve from the more serious competitive effects of knowledge spillovers. Conversely, for products where these assets are important, firms that do ***not*** possess them are likely to have difficulty appropriating a large fraction of the returns to their research. They will either have to license their technology to a firm that does possess the other assets (giving up a significant chunk of the profits in the process) or else knowledge spillovers make it likely tha they will soon face competition from other firms that can benefit from the knowledge they have created, and which possess significant competitive advantages in the marketplace.

IV. FRAMEWORK FOR EXPLICIT EVALUATION OF SPILLOVER POTENTIAL OF ATP PROPOSALS

A. The Underlying Criterion for Project Selection

It is a generally accepted criterion of public policy that expenditure programs should seek to maximize the socia rate of return of the expenditures they make. In the case of the ATP, this basic objective is qualified by a numbe of constraints, including a need to identify projects that produce enabling technologies, that entail overcoming challenging technical difficulties requiring a research agenda that pushes the state of the art of industrial practic in the fields in question, and have the potential for significant economic benefits to parties other than the project proponents. Among projects satisfying these constraints, however, the ATP would like to spend its funds to create the greatest possible social return.

Maximizing the social return on the ATP's investment is complicated by the possibility that ATP funds may be partially or wholly displacing private R&D resources, implying that the social benefits of the research would have come about without the ATP.[(14)] The possibility of displacement induces a distinction between the social rate of return to the project and the social rate of return to the ATP expenditure. If ATP funds a project with a high social rate of return, but in so doing largely displaces private funds, then the social return *to the ATP expenditure* (the public rate of return on the government investment) will be low despite the high social return ***to the project***.[(15)] Thus the danger of displacement means that what the ATP must try to do is fund projects that have a high social rate of return, ***and*** a low probability that ATP funds are displacing private funds. Of course, the ATP can never know for sure the extent to which it is displacing private funds, and project proponents have an inherent incentive to understate the likely extent of displacement.

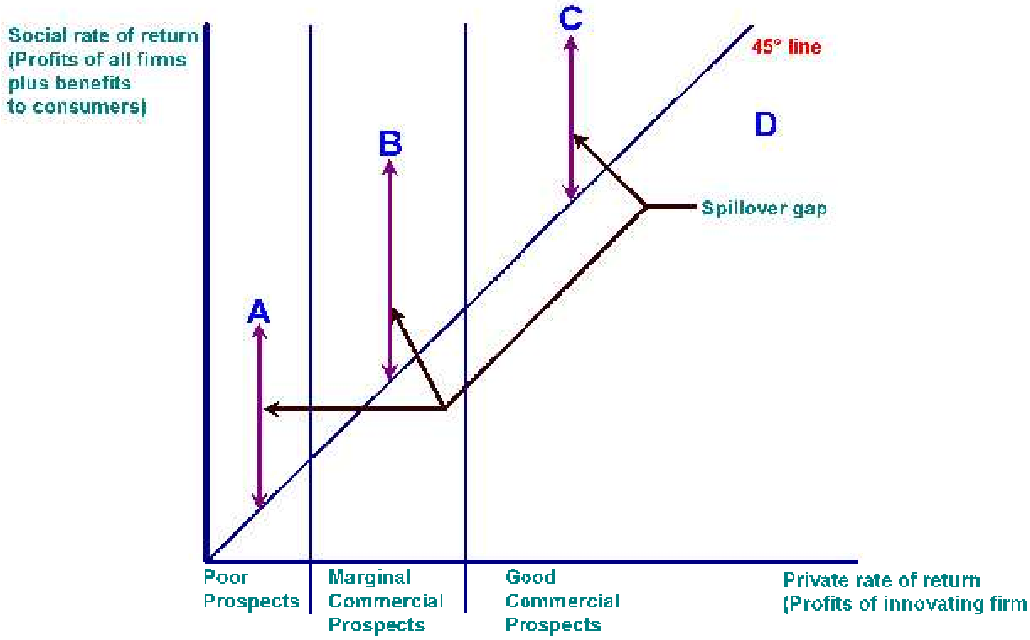
The difficulty with simultaneously seeking projects with high social returns and low probability of displacement is that many factors pointing toward high social returns also point towards higher likelihood of displacement; conversely, factors pointing towards low probability of displacement may signal low social returns. The reason fo this connection is that the likelihood and extent of private investment in a project are going to be affected by its ***private*** rate of return. Any factors that tend to simultaneously increase both the private and the social rates of return will tend to make the danger of displacement high on projects with high social rates of return.

1. **Minimizing displacement by maximizing the spillover gap**

The path through this dilemma is to look for factors that cause the social and private rates of return to diverge: the presence of such factors signals the possibility that social returns may be high at the same time that the risk of displacement is low. Strong likelihood of research spillovers is just such a factor. Hence by trying to identify project proposals where the likelihood of spillovers is particularly high, the ATP will fulfill its statutory mandate, and do so in a way that will yield a high social return by minimizing the extent of displacement.[(16)]

The relationships among the social rate of return, the private rate of return and the danger of displacement are illustrated by Figure 4, which graphs the social and private rates of return for various hypothetical projects. Obviously, there will always be tremendous uncertainty ***ex ante*** about the private and social returns to a project. Conceptually, Figure 4 should be thought of in terms of the ***expected*** returns, i.e., the magnitude of the return if successful, times the probability of success. The public sector seeks to maximize the expected social return, an the private sector seeks to maximize the expected private return.

Figure 4



Since projects higher up on the diagram have higher social returns, in the absence of the displacement concern and other constraints, the ATP would simply seek to find projects that are as far up as possible. From the privat sector point of view, projects to the right (higher private return) are more likely to be funded, all else equal. Of course, the likelihood of private funding for any particular project will depend on its riskiness and the financial environment of the project proponents. Although it is a gross oversimplification, for the purposes of discussion I have arbitrarily divided the projects into 3 groups: "good" commercial prospects that are likely to be well-supported by the private sector, "marginal" commercial prospects that are less likely to be funded and may be funded at inadequate rates, and "poor" commercial prospects.

All projects such as "A," "B," and "C" that lie above the 45° line generate spillovers. (Their social rates of return exceed their private rates.) If the ATP seeks to choose projects with the highest social rate of return, then projec "C" is the most desirable of these projects, and ought to be the prime candidate for funding. If society as a whol faced an all or nothing choice among these projects, we might want to choose C, since its overall social rate of return is higher. But it is likely that C will be funded by the private sector, whereas it is likely that A and B will no be, or will be underfunded. If the ATP ranks projects based on the "spillover gap," then projects A and B would indeed be favored over C. Hence if we want the ATP to generate high returns from projects that would not otherwise be funded, then we would be better off looking at the spillover gap than the overall social return.

Project D illustrates the extreme version of this problem. This hypothetical project generates high social and private returns, but its net spillovers are negative. This might be the profile of a product like Zantac that is highly successful but drives out a close substitute technology. If we were to seek to select projects only on the basis o social returns, this project would rank as higher than A, despite the fact that its private rate of return exceeds its social rate. The government has no business funding this project, given that its net effect on all parties, other than the firm performing it, is negative.

In reality, of course, we will have only coarse estimates of the social rate of retur***or*** the spillover gap. The fact that these prospects can only be known with great uncertainty strengthens the superiority of the spillover gap over the social rate of return as a decision criterion. Although projects like A do exist, there will in general be some correlation between the private and social rates of return. For example, all else equal, both rates will be higher for projects with higher success probabilities and projects whose product (if successful) serves a larger market. If we focus only on the social rate of return, then there is a danger that we will fund projects that appear to have a high social rate of return, where the only reason the private sector is not pursuing this project is because its overall prospects (affecting both the private and social returns) are being overestimated or overstated by the project proponents. If we focus on the spillover gap rather than the apparent overall social rat of return, we are less likely to step in to fund projects for which the explanation for lack of private funding is that they are not really very promising projects.

To state this point slightly differently, the ATP decision process should recognize that its information is imperfec and that errors are going to be made. Further, information that is available about a project ought to be examinec not only for what it says explicitly about social returns, but also for it what it ***implies*** about the probability of errors being made. In some cases, the "facts" being put forth to support the likelihood of large social returns for a project are facts that equally well support the likelihood of large private returns (e.g., a large market for the resulting product). If these purported facts are true, then both private and social returns from the project will be high, i.e. we will be at points like C (or even D) in Figure 4. Now, the ATP cannot know with certainty if the "facts are really true, and cannot know why, if they are true, the private sector would not fund the project on its own. Logically, there are several possibilities: (1) the facts as presented are actually false, i.e., the market is not really large or else the probability of success is so low that the expected (social) net present value of the investment is negative;[(17)] (2) the facts as presented are true, and the private sector knows it and would, indeed, fund the project with or without government help; or (3) the facts are true, and there is some reason why the private sector will not fund the project (or will not fund it adequately or in a timely way) despite the potential payoff.

Some projects will, of course, fall into category (3), but the ATP should be worried about possibilities (1) and (2) This worry can be minimized by seeking a large spillover gap, not just a large social return. If projects with apparently high potential private returns are to be funded, there should be a careful analysis of the reasons as t why the project is not being funded despite its large potential payoff.

2. **Commercialization, business risk and the spillover gap**

Point "A" in Figure 4 raises additional issues. This hypothetical project has good social returns, but very low private returns. Because market size, success probability and other factors tend to affect both private and socia returns, projects like "A" will come about only in cases where there are particularly strong problems with appropriating the returns, leading to a large spillover gap and low private returns. It is unclear what the ATP's attitude towards a project like A should be. There is a large spillover gap, and a very low risk of displacement, s this would appear to be a particularly good funding prospect. The qualification of this conclusion rests on the observation made above that the realization of spillover benefits from R&D projects will likely be dependent to a large extent on successful commercialization of the output. Projects like A with very poor commercial prospects are not likely to be commercialized, even if technical success is achieved. Hence the danger with funding projects like A is that ***few*** spillover benefits will actually be achieved, because commercialization will never occu

Again, the realization that information is imperfect complicates this analysis. Faced with a proposal with apparently poor commercial prospects, the ATP will not know for sure whether the project is really an "A" or a "B". In principle, rational profit-maximizing companies obligated to share the cost of ATP projects are not likely t propose projects like A. To the extent that the cost-sharing burden is real, and the proponents can be trusted to be acting to maximize profits, the ATP ought to ignore the danger of points like A in its decision-making, seek to maximize the spillover gap, and rely on the proponents to screen out projects where the private returns are so low that commercialization is unlikely even if technical success is achieved.

On the other hand, to the extent that companies cannot be relied upon to screen out projects like "A," then the ATP must be concerned both with seeking a large spillover gap ***and*** expected private returns sufficient to make commercialization likely. For example, R&D labs or research divisions of large companies may not be discipline effectively by their management to pursue only commercially tenable projects. This means that the ATP has to undertake the analysis necessary to ensure that proposals from such organizations are not projects like "A" that are unlikely to be commercialized and hence unlikely to produce significant spillover benefits.[(18)]

This issue is important because, holding constant the size of the market for the potential output, factors that inhibit innovators' ability to protect their innovations will simultaneously increase the spillover gap ***and*** reduce private returns. Thus, as discussed above, a project proponent that has the ability to manufacture and market a new product successfully is more likely to appropriate the returns than one that would have to license the technology to others, or else become a competitor in a market where it does not have a historical market presence. From the point of view of spillover analysis, the proponent's lack of manufacturing and marketing ability ought to increase the ATP's interest in a project (all else equal), because it increases the likelihood of spillovers. On the other hand, the lack of these other abilities may make the likelihood of commercialization so low that the spillovers will never come about.

There is no resolution to this dilemma except to separate the two issues. Analytically, the spillover gap is important, and factors that are likely to inhibit a proponent's ability to capture the returns to its innovations make spillovers more likely. At the same time, it may be true that, in combination with other factors affecting the business risk of a particular project, limitations on the ability of the proponent to capture the returns could eventually tip the balance toward a decision that the project, despite its spillover potential, has too low a probability of commercial success for ATP involvement.

B. Factors Pointing Towards Large or Small Spillover Gaps

In practice, of course, we cannot, *ex ante,* "measure" the spillover gap as shown in Figure 4. But we can, based on the discussion in Sections II and III, identify factors that will tend to be associated with high probability or magnitude of spillovers. All of these will be a matter of degree, and apply in a relative, "all else equal" sense. It \ not be possible to identify any particular characteristic that definitively identifies or rules out spillovers. Nonetheless, a systematic analysis of these factors should give a reasonable overall evaluation of a proposal's spillover prospects.

Factors making market spillovers larger or more likely:

- market in which innovation will be used or sold is highly competitive
- lead time and learning curves are not likely to give innovator strong market advantages
- technology is infrastructural, i.e., other researchers are a significant component of the market for the new technology
- output is product innovation that would be difficult to patent or copyright
- cospecialized assets are important in the relevant markets, and project proponents do not possess important assets
- need for regulatory approvals
- sales/service important
- reputation/market presence important
- licensing of the technology to others is likely to be important
- multi-use innovation, where many uses are likely to be commercialized by others
- process technology, proponents are small (or not) producers in relevant markets
- capital needs for ultimate commercialization beyond proponents' reach
- other cospecialized assets important (as above)

Factors making market spillovers smaller or less likely:

- Proponents have market power in the relevant markets
- Lead time and learning curves can be expected to convey significant advantages on the innovator if the project is successful
- output is product innovation that can be protected by patent or copyright
- Proponents possess important cospecialized assets
- Technical success will lead to a large negative profit impact on another firm or firms whose technology wi thereby be made obsolete.

Factors making knowledge spillovers larger or more likely:

- "multi-use technology"
- "proof of concept" that would point the way for other researchers to try related ideas in other applications
- key component that will facilitate redesign and improvement of multiple distinct systems using that component
- "pathbreaking" technology: success will open an entirely new line of technological development with

apparently significant economic benefits

- subsequent technical developments require expertise in applications technologies in which proponents do not have relevant expertise (applies to both "multi-use" and "pathbreaking" technologies
- useful knowledge would be gained even if project fails to achieve its technical objectives

Factors making knowledge spillovers less likely:

- output is process innovation that can be kept secret, and project proponents can use in their own production process
- project proponents have special technical expertise that would position them to be the most likely developer of many of the follow-on technologies

Factors making interacting knowledge and market spillovers likely:

- output is "infratechnology:"
  - technology has attributes of a "standard" and thereby generates network spillovers
  - output is a product that would be sold to other researchers
- output is product innovation that would be difficult to patent or copyright

C. Implications for the Focused Programs

As discussed above, there are some areas of technology where, in addition to the market and knowledge spillovers, there is an additional externality due to the dependence of profitability for each of a set of related projects on some "critical mass" of projects being successful. The existence of an area of technology where projects interact via these network externalities yields an argument for government action to solve the coordination problem that might otherwise prevent any of the different research projects from being undertaken.

Analytically, the possible existence of network externalities can be seen as part of the motivation underlying the creation of focused programs within the ATP. Thus, the justification for the Component-Based Software program is not that there is too little research effort devoted to developing new software. Rather, there may be "enough" software development going on, but firms are unlikely to expend significant resources on developing tools and capabilities for the development of software "components," since the economic payoff to the creation of such components is largely dependent on a wide range of component availability, so that users can solve the overall applications needs through the selection of such components rather than custom programming. By creating a focused program, the ATP attempts to solve this coordination problem, assuring each of the participants that the overall program activities will create a reasonable chance that the component-based approach can fly.

It is difficult, however, to assess the validity and importance of the network spillover arguments for focused programs in a general way. The mere observation that uncoordinated action is not likely to be optimal does not, by itself, reveal what the coordinated action should be. There is a danger that government intervention, despite the best of intentions, can lead to "lock-in" of a certain approach that is not in fact optimal. Further, although the theoretical possibility of network externalities is real, markets do manage to solve many coordination problems. other words, to determine whether and to what extent the network externality phenomenon would justify a focused program in a particular technical area requires careful analysis.

By noting the connection between network externalities and the possible government role in solving the resulting coordination problem, I do not mean to suggest that this coordination role is the only reason for the existence of focused programs. There may be other benefits to focused programs besides addressing the network spillover problem. The effect of knowledge spillovers may be magnified by having a number of researchers working on distinct but related projects. There may be administrative efficiencies to having a set of related projects, and developing the in-house expertise to understand and manage them. Finally, in a world of extremely imperfect information, focused programs may be necessary to ensure that potential industry participants are sufficiently aware of the ATP and what it does in order to maximize the quality of the proposals that the ATP receives. Because of these other considerations, the value of focused programs need not ultimately rest on the network externality argument.

In any event, the existence of focused programs does not eliminate the desirability of choosing individual projec that are likely to yield high spillovers. To the extent that the conditions listed above will be the same for the various proposals in any given focused competition, they will not serve to discriminate among the proposals in a focused competition. Other considerations will differ, however, so that the need to identify the spillover potential of individual proposed projects is not eliminated by evaluating them in the context of a focused program.

V. INCORPORATING SPILLOVER CONSIDERATIONS INTO FUTURE RESEARCH

The ATP is unique among government technology programs in its support of R&D with clear commercial focus for the sole purpose of achieving widespread national economic benefits. It is thus imperative that research be undertaken to document and understand the economic impacts of ATP funding. In addition, while the ATP can benefit from spillovers from researchers working on the economics of R&D, the value of such research to the program can be increased by commissioning studies specifically designed to improve our understanding of the R&D process in ways that would facilitate better ATP decision-making.

The foregoing analysis of what is known about the spillover process suggests a number of research areas that should be supported by the ATP:

Better understanding of the mechanisms of appropriation.

- Studies that document the relative potency of specific appropriation mechanisms across different industries or technological areas.
- Studies of particular appropriation mechanisms, to understand better how they work, and what kinds of firms or industries can or cannot use them.

Better understanding of spillover pathways and social/private rates of return .

- Studies of the role of market forces and market structures in determining the magnitude of both market and knowledge spillovers.
- Studies of attributes of technologies that affect the magnitude of market or knowledge spillovers.

Studies of the spillover impacts of ATP-funded projects.

- Mansfield-style analyses of the private and social rates of return of projects, including impacts on customers and competitors.
- Analysis of knowledge spillovers and their pathways, using both technological and market data to identify impacts on the technology of other firms both in and outside of the industry.
- Analyses that test whether the market and technological factors identified above as predictors of spillover potential are associated with larger spillovers from ATP-funded projects.
- Statistical analyses of funded firms, firms requesting but not receiving funding, and firms not interacting with the ATP, to try to estimate the net impact of ATP funding.

VI. CONCLUSION

In order to be effective in achieving its statutory objectives, the ATP must try to determine which projects proposed to it will generate large spillovers, and which will not. Economists and other social scientists have identified certain aspects of a project's technological and market environment that tend to be associated with large or small spillovers. By incorporating the explicit analysis of such factors into both project choice and evaluation of project impact, the ATP can make better decisions

This task is complicated by the interaction of a number of factors that cannot be disentangled from each other. With some loss of important details, the problem can be summarized as follows:

1. The ATP wants to fund projects that will have significant, broad-based economic benefits.
2. The ATP wants to fund projects with minimal "displacement" of private R&D funds.

3. In general, projects with significant broad-based economic benefits will tend to be those that also offer the potential for significant private returns.
4. Project proponents have better information than the ATP about the prospects for private funding, and also have an incentive to conceal this information.
5. The realization of spillover benefits is likely to be heavily dependent on commercialization of the research results, making a clear path to commercialization important to likely success.

Combining points 1-4, the ATP should seek to fund projects that will have a significant economic impact, ***and*** where there are specific attributes of the project and its environment that make spillovers likely. Neither of these conditions is sufficient in itself. Specific features of the technology and the business and economic environment of the proposal that make spillovers likely are crucial, both for ensuring that benefits from this government expenditure will be widely felt, and for reducing the likely extent of displacement. On the other hand, point 5 means that there may be cases where the appropriability problems that create a large spillover gap, when combined with other business aspects of the proposal, make the likelihood of commercial success too low. To oversimplify, the ATP seeks projects with large spillovers, but not projects where the spillovers are so great that the remaining private return is insufficient to maintain commercial momentum.

Thus there is an inherent tension in the ATP decision-making process. We want project proponents to be committed to a project, and to have reasonable prospects for commercial success. A company that is going to do some research but leave it in the laboratory is less likely to generate spillovers or large social returns; hence projects that are unlikely to be commercialized do not achieve the ATP's objectives. All else equal, however, anything that improves the prospects for commercial success increases the expected profits or private returns, thereby decreasing the spillover gap and increasing the likelihood that ATP funding will displace private funds.

There is no way to eliminate this tension, but recognizing it explicitly and separating the issues of spillover potential and business risk should facilitate better decisions. In evaluating business risk and the likelihood of successful commercialization, it is appropriate that factors that support the proponent's likely ability to appropriate the profits from the invention, such as plans to protect inventions with patents, or the existence of a successful marketing organization, would be considered a plus. Within the spillover evaluation, however, it is equally appropriate that the feasibility of patenting the output, or the presence of other appropriation mechanisms such as a strong marketing arm, would be considered a negative factor in determining the extent and likelihood of spillovers.

The ultimate project funding decision in any given case will have to depend on these considerations placed in the context of the overall proposal. For a project whose direct output is likely to be patented, the ATP may still determine that the overall spillover potential is large ***if*** there are other considerations pointing towards large spillovers, such as a technology with strong generic attributes. In the ***absence*** of other spillover indicators, however, a project that produces an easily patented output should be viewed as low spillover potential and hence low priority for funding. On the other hand, in cases where successful patenting is ***unlikely***, this is an indicator of potentially large spillover potential. If this indicator, together with other aspects of the technology, creates a strong case for likely spillovers, then the decision to fund could turn on whether, despite the lack of patent protection, other aspects of the proposal or its proponents provide the basis for concluding that the business risk is manageable and successful commercialization likely. If so, then the project is a good funding prospect; if not, it should be a low funding priority because of the absence of commercialization mechanisms.

This is an inherently difficult and uncertain task, and it is one that requires an unusual combination of technical, business and economic analysis. Perfect prediction cannot be achieved, any more than it can be achieved for the purely technical success of research. We know enough about spillovers to improve the ATP's selection by a more systematic, explicit treatment of spillover effects. Further research can improve and extend our knowledge of spillover phenomena and how to measure them, in order to provide a firmer foundation for a program with the mission, goals, and strategies of the ATP.

The empirical evidence suggests that the ***average*** research project generates spillovers. If the ATP can succeed in targeting projects with ***better-than-average*** spillover potential, then it will generate large social returns that would not otherwise have been achieved.

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ENDNOTES

1. There may also be costs that the firm does not consider. This issue is discussed in Section II.

2. The results of empirical analyses of the magnitude of the gap between private and social rates of return a discussed in section III.A.

3. Economists use the term "consumer surplus" to describe the value that the purchasers of a product derive from a product minus the price paid for it. If the price of a product falls, consumers enjoy greater consumer surplus from its consumption. If the quality of a product rises, and the price does not rise commensurably, there is a similar increase in consumer surplus. Thus what I am calling the "market spillover" amounts to an increasin consumer surplus.

4. The term "network spillover" is chosen because the different related research projects are like the differen users of a network. The value of a network to any one participant is an increasing function of the number of participants; here the expected value of any one research project is an increasing function of the number of different projects undertaken.

5. In some cases, an innovating firm may not be in a position to utilize its new technology, but will need to license or sell the technology to another firm before the product or process can be implemented. In this case, imperfections in the licensing market will generally result in an additional spillover to the licensing firm.

6. Typically firm 1 will have been earning profits and consumers gaining benefits before the R&D was performed; strictly speaking the returns are the *increased* profits and *increased* consumer benefits. The figure ignores this for simplicity.

7. Typically, the other firms would also be doing R&D of their own. The spillover would consist of the

incremental profits and consumer benefits created when other firms' research benefits from the knowledge spillover. Again, this complication is ignored simply to keep the picture clear.

8. Estimates of the lags between basic research and its economic impact range from 5-8 years (Mansfield, 1996) to 15 years or more (Adams, 1990)

9. See Section III.A.

10. At the mean of the data, the private return was about 30% and the social return about 45%.

11. Studies that estimate the highest social rates of return also tend to estimate high private rates. Hence the ratio of social to private may be a more robust indicator of the general pattern of results.

12. For more extensive discussion of these issues see Levin, et al, 1987, and Teece, 1986.

13. This is probably a combination of effects deriving from ease of obtaining the patent with effects related to ease of enforcing against infringement. If I synthesize a molecule that has never before existed, it is presumably relatively easy to satisfy the "novelty" standard necessary to obtain a patent, and also relatively easy to prove th someone else selling the same molecule has infringed. Conversely, it may be hard to show that a complex electronic or mechanical system is or is not substantially different from what has come before.

14. Both third-party surveys sponsored by the ATP and a recent study by the General Accounting Office (GAO) found that company opinion held that the great majority of ATP-funded projects would not have been done or the project schedules would have been slower and achieving goals delayed without ATP funding.

15. Note that even if ATP funding accelerates the project, partial displacement could still be going on. If the private proponents would have spent $500,000 per year, and the budget with ATP support is $600,000 with 50/50 cost sharing, then the project is being accelerated, but $300,000 in public funds are producing only a $100,000 increase in research effort. Each ATP dollar corresponds to only 33 cents of increased project funding.

16. There are, of course, other factors that might cause projects with high social returns to be underfunded by the private sector. By the same logic, funding projects where these other factors are present would yield high social returns.

17. This is not to say that ATP should avoid high-risk projects! What I am saying here is that there are some projects for which the true chances for success are so low that the expected social return (payoff if successful times success probability) is less than the cost.

18. A particular case of proposals that might ignore the need for commercialization potential would be proposals from non-profit organizations. It is for this reason that the ATP does not entertain projects whose lead proponent is not a for-profit firm.

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