The Role of Public Research Institutions in a National Innovation System: An Economic Perspective

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I. Introduction

This White Paper discusses the economic role of public research institutions in a national innovation system. Among the many interrelated elements of such a system are education, university research, and property rights.[1] Public research institutions are a part of a nation's education and research environment with a focus on generic research – that has to varying degrees the attributes of a public good – that is especially useful for industry and commerce and for which property rights and private provision are problematic. Projects from selected U.S. public research institutions are discussed to illustrate the underlying theoretical concepts related to market failure and the matching of each appropriate public policy with the specific source of underinvestment in research. A few limited examples of research projects underway in Latin American countries are also described. We contacted representatives of these Latin American projects to see if we could discern useful contrasts with the U.S. cases with which we have had first-hand experience. Our impressions from the responses are used in the exposition of the key point about the role of public research institutions – their projects' outputs and outcomes should efficiently address market failures that would cause underinvestment in socially desirable research. .

Prescriptive analysis, based on the case studies of public research projects, identifies:

• circumstances when public research institutions need research capability and need to perform research,

• circumstances when the public's desired research is better performed privately but with partial public funding and oversight by the public research institution,

[1] See Nelson (1993).

• a method of leveraging public funding of research when the private sector can do the research better than the public research laboratories but does require some partial public funding,

• procedures for on-going evaluation of public research institutions.

Fundamental to our discussion is the following framework for analysis:

R&D → *knowledge* → *innovation* → *technological advancement* → *economic growth*

Although simple, this framework underscores two important points. One, research and development (R&D) activity is the primary input into the production of new technical knowledge. And two, the relevant output from the R&D-based innovation process is economic growth. A national innovation system, and its elements, should be viewed in this framework; and thus, we focus on the role for public research institutions within the framework. The knowledge-generating activities of the public research institutions address market failures that would – absent the public research activities – result in underinvestment in R&D and hence a shortfall of innovation and growth from socially desirable levels.

II. Government's Role in Innovation

The theoretical basis for government's role in market activity is based on the concept of market failure. Market failure is typically attributed to market power, imperfect information, externalities, and public goods. The explicit application of market failure to justify government's role in innovation – in R&D activity in particular – is a relatively recent phenomenon within public policy.

Many point in the United States to President George Bush's 1990 *U.S. Technology Policy* as that nation's first formal domestic technology policy statement. Albeit an important initial policy effort, it however failed to articulate a foundation for government's role in innovation and technology. Rather, it implicitly assumed that government had a role, and then set forth the general statement (1990, p. 2):

> The goal of U.S. technology policy is to make the best use of technology in achieving the national goals of improved quality of life for all Americans, continued economic growth, and national security.

President William Clinton took a major step forward from the 1990 policy statement in his 1994 *Economic Report of the President* by articulating first principles about why government should be involved in the technological process (1994, p. 191):

> The goal of technology policy is not to substitute the government's judgment for that of private industry in deciding which potential 'winners' to back. Rather, the point is to correct market failure …[2]

Subsequent Executive Office policy statements have echoed this theme; *Science in the National Interest* (1994) and *Science and Technology: Shaping the Twenty-First Century* (1998) are among the examples.

Relatedly, Martin and Scott (2000, p. 438) observe:

> Limited appropriability, financial market failure, external benefits to the production of knowledge, and other factors suggest that strict reliance on a market system will result in underinvestment in innovation, relative to the socially desirable level. This creates a *prima facie* case in favor of public intervention to promote innovative activity.

[2] The conceptual importance of identifying market failure for policy is also emphasized, although without any operational guidance, in Office of Management and Budget (1996).

A. Underinvestment in R&D

Market failure, as we address it in this paper and of the type which could specifically be termed "technological or innovation market failure," refers to a condition under which the market, including both the R&D-investing producers of a technology and the users of the technology, underinvests, from society's standpoint, in a particular technology. Such underinvestment occurs because conditions exist that prevent organizations from fully realizing or appropriating the benefits created by their investments.

The following explanation of market failure and the reasons for market failure follow closely Arrow's (1962) seminal work in which he identified three sources of market failure related to knowledge-based innovative activity – "indivisibilities, inappropriability, and uncertainty" (p. 609).[3]

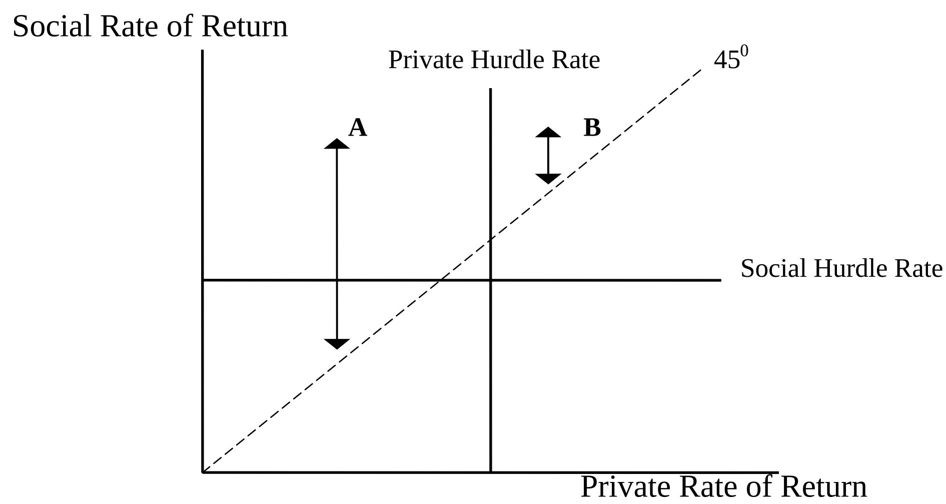
To explain, consider a marketable technology to be produced through an R&D process similar to that in the schematic above where conditions prevent full appropriation of the benefits from technological advancement by the R&D-investing firm. Other firms in the market or in related markets will realize some of the profits from the innovation, and of course consumers will typically place a higher value on a product than the price paid for it. The R&D-investing firm will then calculate, because of such conditions, that the marginal benefits it can receive from a unit investment in such R&D will be less than could be earned in the absence of the conditions reducing the appropriated benefits of R&D below their potential, namely the full social benefits. Thus, the R&D-investing firm may underinvest in R&D, relative to what it would have chosen as its investment in the absence of the conditions. Stated alternatively, the R&D-investing firm may

[3] Although Arrow does not elaborate on indivisibilities and inappropriability in his paper, the concepts are well understood in the innovation literature. Recalling that Arrow defines innovation "as the production of knowledge" (1962, p. 609), the market does not price knowledge in discrete bundles and thus because of such indivisibilities market prices may not send appropriate signals for economic units to make marginal decisions correctly. Below, we talk primarily about inappropriability and uncertainty.

determine that its private rate of return is less than its private hurdle rate and therefore it will not undertake socially valuable R&D.

The basic concept can be illustrated with the following figure, which follows from Tassey (1997) and Jaffe (1998). The social rate of return is measured on the vertical axis along with society's hurdle rate on investments in R&D. The private rate of return is measured on the horizontal axis along with the private hurdle rate on R&D. A 45-degree line (dashed) is imposed on the figure under the assumption that the social rate of return from an R&D investment will at least equal the private rate of return from the same investment. Two separate R&D projects are labeled as project A and project B. Each is shown, for illustrative purposes only, with the same social rate of return.

Spillover Gap Between Social and Private Rates of Return to R&D



For project A, the private rate of return is less than the private hurdle rate because of barriers to innovation and technology. As such, the private firm will not choose to invest in project A, although the social benefits from undertaking project A would be substantial.

The principle of market failure illustrated in the figure relates to appropriability of returns to investment. The vertical distance shown with the double arrow for project A is called the spillover gap; it results from the additional value society would receive above what the private firm would receive if project A were undertaken. What the firm would receive (along the 45-degree line) is less than its hurdle rate because the firm is unable to appropriate all of the returns that spill over to society. Project A is the type of project in which public resources should be invested to ensure that the project is undertaken.

In comparison, project B yields the same social rate of return as project A, but most of that return can be appropriated by the innovator, and the private rate of return is greater than the private hurdle rate. Hence, project B is one for which the private sector has an incentive to invest on its own or, alternatively stated, there is no economic justification for public resources being allocated to support project B.

For projects of type A where significant spillovers occur, government's role has typically been to provide funding or technology infrastructure through public research institutions that lowers the marginal cost of investment so that the marginal private rate of return exceeds the private hurdle rate.

Note that the private hurdle rate is greater than the social hurdle rate in the figure. This is primarily because of management's (and employees') risk aversion and issues related to the availability and cost of capital. These factors represent an additional source of market failure that is related to uncertainty. For example, because most private firms are risk averse (i.e., the penalty from lower than expected returns is weighted more heavily than the benefits from greater than expected returns), they require a higher hurdle rate of return compared to society as a whole that is closer to being risk neutral.[4]

To reduce market failures associated with inappropriability and uncertainty, government typically engages in activities to reduce technical and market risk (actual and perceived). These activities include, but are not limited to, the activities of public research institutions, as discussed below. The following section discusses several circumstances – termed barriers to technology – that cause market failure and an underinvestment in R&D.

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[4] There are two parts to the answer to the twin questions of how the social hurdle rate is determined and why it is represented as being less than the private hurdle rate. The first is grounded in the practice of evaluations, and the second is grounded in the theory of public policies to address market failure. (1) Regarding practice, for our U.S. case studies described below, the U.S. Office of Management and Budget has mandated that we use a specified real rate of return as the rate for evaluation studies -- i.e., the rate to be considered the opportunity cost for the use of the public funds in the investment projects we evaluate. The Office of Management and Budget (1992, p.9) has said that: "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent." Now, that real rate of return (and the related nominal rates derived by accounting for expected inflation rates in various periods of analysis) has been far less than what our respondents tell us is the private hurdle rate for comparable investment projects in industry during comparable time periods for the public investments we have studied. (2) Regarding theory, when we evaluate public investment projects, we are invariably looking at cases where there has been some sort of market failure. To improve upon the market solution, the government has become involved (in a variety of ways, in practice) with an investment project. Just as market solutions for the prices of goods may not reflect the social costs for the goods (because of market failure stemming from market power, imperfect information, externalities, or public goods), the private hurdle rates that reflect market solutions for the price of funds – the opportunity cost of funds to the private firms – may not reflect the social cost of the funds. The government may decide that the appropriate social cost – the opportunity cost for the public funds to be invested – differs from the market solution. Typically, in practice, the government believes that it faces less risk than the private sector firms doing similar investments; hence it will believe a lower yield is satisfactory since the public is bearing less risk than the private sector firm going it alone with a similar investment. More generally, government must decide what the opportunity costs of its public funds will be in various uses, and in general that will not be the same as the market rate. However, all that said, clearly we know from Arrow's thinking about social choice that the government's decision about what the rate should be cannot possibly reflect the diversity of opinion in the private sector regarding the decision (Arrow, 1963). Consequently, as a logical matter, one could not prove that the government's choice of the right hurdle rate is obviously correct because diversity of opinion about the correct rate will not be reflected in the government's choice.

B. Barriers to Innovation and Technology

There are a number of factors that can explain why a firm will perceive that its expected private rate of return will fall below its hurdle rate.[5] Individuals will differ not only about a listing of such factors because they are not generally mutually exclusive, but also they will differ about the relative importance of one factor compared to another in whatever taxonomy is chosen.

First, high technical risk (that is, outcomes may not be technically sufficient to meet needs) may cause market failure given that when the firm is successful, the private returns fall short of the social returns. The risk of the activity being undertaken is greater than the firm can accept, although if successful there would be very large benefits to society as a whole. Society would like the investment to be made, but from the perspective of the firm, the present value of expected returns is less than the investment cost and is thus less than the amount yielding its acceptable return on investment.

Second, high risk can relate to high commercial or market risk (although technically sufficient, the market may not accept the innovation – reasons can include factors listed subsequently such as imitation or competing substitutes or interoperability issues) as well as to technical risk when the requisite R&D is highly capital intensive. The project may require too much capital for any one firm to feel comfortable with the outlay. The minimum cost of conducting research is thus viewed as excessive relative to the firm's overall R&D budget, which considers the costs of outside financing and the risks of bankruptcy. In this case, the firm will not make the investment, although society would

[5] As Arrow (1962) explained, investments in knowledge entail uncertainty of two types – technical and market. The technical and market results from technology may be very poor, or perhaps considerably better than the expected outcome. Thus, a firm is justifiably concerned about the risk that its R&D investment will fail, technically or for any other reason. Or, if technically successful, the R&D investment output may not pass the market test for profitability. Further, the firm's private expected return typically falls short of the expected social return as previously discussed. This concept of downside risk is elaborated upon in Link and Scott (2001a).

be better off if it had, because the project does not appear to be profitable from the firm's private perspective.

Third, many R&D projects are characterized by a lengthy time interval until a commercial product reaches the market. The time expected to complete the R&D and the time until commercialization of the R&D results are long, and the realization of a cash flow from the R&D investment is in the distant future. If a private firm faces greater risk than society does, and as a result requires a greater rate of return and hence applies a higher discount rate than society does, it will value future returns less than does society. Because the private discount rate exceeds the social discount rate, there may be underinvestment, and the underinvestment increases as the time to market increases because the difference in the rate is compounded and has a bigger effect on returns further into the future.

Fourth, it is not uncommon for the scope of potential markets to be broader than the scope of the individual firm's market strategies so the firm will not perceive or project economic benefits from all potential market applications of the technology. As such, the firm will consider in its investment decisions only those returns that it can appropriate within the boundaries of its market strategies. While the firm may recognize that there are spillover benefits to other markets, and while it could possibly appropriate them, such benefits are ignored or discounted heavily relative to the discount weight that would apply to society. A similar situation arises when the requirements for conducting R&D demand multidisciplinary research teams; unique research facilities not generally available with individual companies; or "fusing" technologies from heretofore separate, non-interacting parties. The possibility for opportunistic behavior in such thin markets may make it impossible, at reasonable cost, for a single firm to share capital assets even if there were not R&D information sharing difficulties to compound the problem. If society, perhaps through a technology-based public institution, could act as an honest broker to coordinate a cooperative multi-firm effort, then the social costs of the multidisciplinary research might be less than the market costs.[6]

Fifth, the evolving nature of markets requires investments in combinations of technologies that, if they existed, would reside in different industries that are not integrated. Because such conditions often transcend the R&D strategy of firms, such investments are not likely to be pursued. That is not only because of the lack of recognition of possible benefit areas or the perceived inability to appropriate whatever results, but also because coordinating multiple players in a timely and efficient manner is cumbersome and costly. Again, as with the multidisciplinary research teams, society may be able to use a technology-based public institution to act as an honest broker and reduce costs below those that the market would face.

Sixth, a situation can exist when the nature of the technology is such that it is difficult to assign intellectual property rights. Knowledge and ideas developed by a firm that invests in technology may spill over to other firms during the R&D phase or after the new technology is introduced into the market. If the information creates value for the firms that benefit from the spillovers, then other things being equal, the innovating firms may underinvest in the technology. Relatedly, when competition in the development of new technology is very intense, each firm, knowing that the probability of being the successful innovator is low, may not anticipate sufficient returns to cover costs. Further, even if the firm innovates, intense competition in application can result because of competing substitute goods, whether patented or not. Especially when the cost of imitation is low, an individual firm will anticipate such competition and may therefore not anticipate returns sufficient to cover the R&D investment costs. Of course, difficulties appropriating returns need not always inhibit R&D investment (Baldwin and Scott 1987). First-mover advantages associated with customer acceptance and demand as well as increasing returns as markets are penetrated and production expanded can imply

[6] See Leyden and Link (1999) on the role of a federal laboratory as an honest broker.

that an innovator wins most (or at least a sufficient portion to support the investment) of the rewards even if it does not "take all."

Seventh, industry structure may raise the cost of market entry for applications of the technology. The broader market environment in which a new technology will be sold can significantly reduce incentives to invest in its development and commercialization because of what some scholars have called technological lock-in and path dependency.[7] Many technology-based products are part of larger systems of products. Under such industry structures, if a firm is contemplating investing in the development of a new product but perceives a risk that the product, even if technically successful, will not interface with other products in the system, the additional cost of attaining compatibility or interoperability may reduce the expected rate of return to the point that the project is not undertaken. Similarly, multiple sub-markets may evolve, each with its own interface requirements, thereby preventing economies of scale or network externalities from being realized. Again, society, perhaps through a technology-based public institution, may be able to help the market's participants coordinate successful compatibility and interoperability.

Eighth, situations exist where the complexity of a technology makes agreement with respect to product performance between buyer and seller costly. Sharing of the information needed for the exchange and development of technology can render the needed transactions between independent firms in the market prohibitively costly if the incentives for opportunistic behavior are to be reduced to a reasonable level with what Teece (1980) calls obligational contracts. Teece emphasizes that the successful transfer of technology from one firm to another often requires careful teamwork with purposeful interactions between the seller and the buyer of the technology. In such circumstances, both the seller of the technology and the buyer of the technology are exposed to hazards of opportunism. Sellers, for example, may fear that buyers will capture the know-how

[7] See David (1987) for detailed development of the ideas of path dependency in the context of business strategies and public policy toward innovation and diffusion of new technologies.

too cheaply or use it in unexpected ways. Buyers may worry that the sellers will fail to provide the necessary support to make the technology work in the new environment; or they may worry that after learning about the buyer's operations in sufficient detail to transfer the technology successfully, the seller would back away from the transfer and instead enter the buyer's industry as a technologically sophisticated competitor. Once again, if society can use a technology-based public institution to act as an honest broker, the social costs of sharing technology may be less than market costs.

These eight factors that create, individually or in combination, barriers to innovation and technology and thus lead to a private underinvestment in R&D are listed in the following table. While we have discussed these factors individually above, and have listed them in the table as if they are discrete phenomena, they are interrelated and overlapping, although in principle any one factor could be sufficient to cause a private firm to underinvest in R&D.

Factors Creating Barriers to Innovation and Technology

1. High technical risk associated with the underlying R&D
2. High capital costs to undertake the underlying R&D
3. Long-time to complete the R&D and commercialize the resulting technology
4. Underlying R&D spills over to multiple markets and is not appropriable
5. Market success of the technology depends on technologies in different industries
6. Property rights cannot be assigned to the underlying R&D
7. Resulting technology must be compatible and interoperable with other technologies
8. High risk of opportunistic behavior when sharing information about the technology

III. The Role of Public Research Institutions

Public research institutions – their intramural research as well as their focused extramural research activity – could overcome many of the barriers to innovation and technology discussed in the previous section.

For the purpose of describing the rationale for public research institutions that provide, intramurally or extramurally, infrastructure technology needed by industry, we use a definition of risk that is focused on the operational concern with the downside outcomes for an investment. The shortfalls of the private expected outcomes from society's expected returns reflect appropriability problems. There are several related technological and market factors that will cause private firms to appropriate less return and to face greater risk than society does. These factors underlie what Arrow (1962) identified as the non-exclusivity and public good characteristics of investments in the creation of knowledge. The private firms' incomplete appropriation of social returns in the context of technical and market risk can make risk in its operational sense unacceptably large for the private firm considering an investment.

Operationally and with reference to the figure above, Tassey (1992, 1997), for example, defines risk as the probability that a project's rate of return falls below a required, private rate of return or private hurdle rate (as opposed to simply deviating from an expected return).[8] As illustrated in Link and Scott (2001a) – both in concept and in terms of the specific projects performed by the private sector with subsidies and oversight from the Advanced Technology Program within the U.S. National Institute of Standards and Technology (NIST) – for many socially desirable investments, the private firm faces an unacceptably large probability of a rate of return that falls short of its private hurdle rate. Yet, from society's perspective, the probability of a rate of return that is less than the social hurdle rate is sufficiently small that the project is still worthwhile.

We have presented in section II.B a specialized subset of circumstances in which markets fail to provide adequate infrastructure technology and where public standards and technology laboratories can provide the infrastructure technologies that would not be

[8] Tassey (1992, 1997) has developed and applied the idea of barriers to innovation and technology, using the idea to advance knowledge about appropriate technology policy for the U.S. National Institute of Standards and Technology (NIST).

provided adequately by private markets. The role of these public institutions is then to address, and to the extent possible correct, what we term technological or innovation market failure.

Martin and Scott (2000, pp. 438-439) make the point that the design of appropriate public policy should match the policy with the specific source of underinvestment. In that light, they identify several roles for public research institutions. Given the types of research they perform, such institutions could be called standards and infrastructure technology institutions, and we focus in this paper on their role in a national innovation system. Specific activities of those institutions are matched with specific sources of underinvestment in research, and the various activities are illustrated with examples from case studies.

One role for a public research institution is to facilitate the promulgation and adoption of standards and thereby, for example, reduce the risk associated with standards for new technology as inputs are developed for using industries such as in the sectors developing software, equipment, and instruments. We are using the term “standards” in a general sense to refer to voluntary performance protocols and interoperability standards, test methods, and standard reference materials. We distinguish among these when we provide specific project examples. Although one can find examples where observers have thought that product standards were used in anticompetitive ways, the role for public research institutions is quite general and important, encompassing several types of standards that we shall discuss with examples below. The examples illustrate the variety of useful roles of public research institutions with regard to standards. The public institutions with research capability can respond to industry’s needs for standards, working with industry to develop them while serving as an honest broker providing impartial mediation of disputes that could not be provided by a private firm with a proprietary interest in the outcomes.[9] We shall provide several examples where in the absence of the public research institution, industry would have incurred higher costs to replace the public standards activities than the actual costs to the public institution for those activities. Further, the quality of the more costly private standards activities would have been less than the quality of the public standards activities. We document the facts about the effective use of public research institutions to address market failures by using the evaluation methods that are discussed in Section VIII.

For another role, public research institutions can oversee extension services to facilitate technology transfer in sectors such as light industry or agriculture when, for example, small firms, facing limited appropriability from their investments in new technologies yet providing large external benefits to the economy as a whole, apply inputs developed in supplying industries. Such extension services can make possible a vibrant entrepreneurial sector of smaller firms that stimulate the adoption and diffusion of new technology and also innovation, technological advance, and economic growth. The positive impact of such an entrepreneurial sector has been documented by many scholars – for example, Audretsch (1995) – and in the last two decades recognition of its importance for economic growth has increased and become widespread. Imperfections in credit markets, opportunistic behavior by larger firms that might provide resources to small entrepreneurial businesses, and the unappropriated external benefits from entrepreneurial businesses may require public support of extension services to avoid underinvestment in the transfer technologies. Although the argument for public research institutions with research capability is not as strong as it is in the foregoing role with standards, public research institutions such as the U.S. National Institute of Standards and Technology are in a good position to foster the technology transfer provided by extension programs. Such public institutions have knowledge of the key technologies, have working relationships with the industries supplying the technologies (indeed in many

[9] Industry's scientists and engineers frequently interact with the scientists of the public research institution in conferences and workshops and together they enable the public research laboratories to develop the standards needed as the technological requirements for industry to remain competitive evolve. See the several examples described in Link and Scott (2004).

cases the technologies were developed with the cooperative activities of the public research institution and industry – as discussed below), and can assist with the transfer the technologies without opportunistic exploitation of the small firms, allowing them to grow as independent sources of initiative and growth.[10]

For a third role, a public research institute can serve as the coordinator and facilitator for cooperative R&D efforts joining industry, universities, and government in research that is subsidized by the government. The several projects studied by Hall, Link, and Scott (2003) provide examples of such cooperative R&D efforts. Such cooperative research with a public research institution as the facilitator is often necessary to coordinate the development of infrastructure technologies as well as pre-competitive generic technologies that are at the heart of the development of complex systems involving high cost, risk, and limited appropriability. These complex systems are developed, for example, in aerospace, electrical and electronics technology, and telecommunications and computer technologies. While the coordination of cooperative efforts that transcend the solely market-based activities of industry is arguably an important and central role for government, the key question is whether a public research institution playing that coordinating role actually needs to have a research capacity itself. Based on our case studies, we believe that in many cases the answer is "Yes." For example, the Advanced Technology Program (ATP) at NIST relies on the research capability of NIST to ensure not only sound oversight of the competitions for the government's chosen research

[10] Private organizations with some public funding have evidently been successful in transferring technology to smaller businesses. For example, Chile's Fundación Chile is largely private with some public funding, and it introduces and develops new technologies and disseminates them. Fundación Chile is a nonprofit organization created in 1976 by the government of Chile and the ITT Corporation of the United States. Its mission is to increase the competitiveness of Chile's economy by promoting and developing innovations, technology transfer, and technological management. See http://www.fundacionchile.cl/ . Although coordinated by a public research institution, there is substantial private funding for the Malcolm Baldrige National Quality Award Program through NIST (discussed in Section B.7). The Program is focused on improving management and competitiveness. The pattern of shared funding among government and private organizations is common to many of the activities of public research institutions – most prominently activities largely performed by the private sector with oversight from the public institution and with some partial public funding of the projects.

projects that will be performed by industry with partial public funding, but to provide as well coordinated research developing infrastructure technologies that support the advances in technology that the ATP hopes to foster through its awards for publicly subsidized and privately performed research. An example of privately performed research with partial public funding and with the oversight of a public research institution is provided by the ATP's TIMA project discussed below. We document the social value of the project using the "spillovers method" for project evaluation that is discussed in Section VIII. Examples of the use of the public research capability to support the ATP's mission are provided in the SRM 2517a case, the ICM case, and the dielectrics case that are all discussed in Section IV. We document the social value of these publicly performed research projects using the "traditional method" for project evaluation discussed in Section VIII.

Finally, for industrial applications of technologies with high science content, where the knowledge base originates outside of the commercial sector, the creators of the knowledge may not recognize the potential applications or effectively communicate the new developments to potential users. As a fourth role in a national innovation system, a public research institution can facilitate the diffusion of advances from research in these cases – such as in biotechnology, chemistry, materials science, and pharmaceuticals – where the applications have high science content. This fourth role is one of facilitating communication and dissemination of ideas from science that can then be used by many sectors to advance applied research and development. In many cases, government funds will have been used by universities to develop the basic science, because the ideas have a strong public good component and there would not have been sufficient incentive to develop them without government funding. Once the basic science is available, the knowledgeable public research institution with expertise in both research and connections to industry can help to disseminate the information widely. An example is provided by the dissemination of basic science about the properties of chemicals in various mixtures in the alternative refrigerants case discussed below.

Granted that basic research with economy-wide implications and very long time horizons is unlikely to be undertaken by private firms, are there reasons – incentive problems and market failures – that would require that the basic research should be *performed* by the government and not by, for example, the government's financing of private universities? That is, are there reasons that the fourth role for the public research institution would include not only working to communicate basic science, transferring it to industry in ways that focus on the industrial usefulness of the basic science, but the public laboratory would actually do basic science itself. Although, in our experience with the work done in the U.S. government laboratories, we have observed some fairly basic research (such as in the materials science involved in the dielectrics case discussed in Section IV), even the most basic research is quite applied – using the basic science created in universities to develop new measurement technology for example. Conceivably there are incentive issues that may dictate the performance of certain types of basic research in the laboratories of public research institutions. By their nature, the research objectives of the government may differ from the interests of universities and their researchers, and it is possible that some goals of the government's basic research agenda would not align well with the current "academic" interests. Stated differently, academic researchers might find it beneath them to do the science that the public happens to want at a particular time. Another possibility is that academic researchers cannot always take the long view (especially given that the "long view" can change as political administrations change) needed to develop a government-mandated strand of science in the detail needed, simply because of the constraints of turning out sufficient publications of sufficient variety and quality in the context of review and promotion for the researchers. Laboring in some public service vineyard for a decade or more may not have the necessary academic rewards to ensure survival in the university system. A public laboratory scientist is freed from such constraints and the public laboratory can set its own reward structure that is sensitive to the fact that political administrations change and the scientific imperatives of government can change. Finally, national security may dictate that some types of research are performed in government laboratories with heightened security rather than in the more open environment of university laboratories.

In all of the foregoing roles for the public research institution, the institution is not only an "honest broker" providing technological services – standards, standard reference materials, calibrations traceable to the standards, technology transfer and diffusion of scientific advances – without a proprietary, rivalrous, market-based interest. As well, the public research institution's research capability is an integral part of developing and maintaining the standards and other technological services. The institution is not just an administrator, but an organization with real scientific and engineering expertise. In matters of generic and infrastructure technology, the institution is an honest broker with leading-edge research capabilities and close working relationships with industry allowing it to understand industry's needs and continually develop and maintain the standards and services that industry relies on for its productivity. We have observed that role for a public research institution in many case studies such as those described briefly in Section IV below and those described fully in Link and Scott (1998, 2004) and in many others as well. We have in those cases documented the efficacy of the public research performance using both the "counterfactual method" and the "traditional method" of project evaluation as described in Section VIII.

The theoretical foundation for public sector involvement in any aspect of the innovation process, as illustrated generally in the schematic above, logically leads to a discussion of public accountability, meaning that the public sector is also responsible for evaluating the social benefits of its actions. Alternative frameworks for approaching such an evaluation are discussed below in Section VIII. Those alternative methods for evaluating projects have entered the foregoing discussion already and will also be cited in the case studies of Section IV because the project evaluations ultimately are the only way to verify a priori theories about the need for public research institutions with research capabilities. Further, given the ways in which we have developed those evaluation methods, they are the ultimate way to answer the question: Once we have discussed the list of technology and innovation market failures, what needs to be done by the government versus what needs to be paid for (in part) by the government? The answer ultimately is that certain types of activities – such as the provision of standards of measurement and the calibration services to ensure traceability of measurements to standards – are provided by the public research institution with higher quality and at lower cost than the services could be provided by the private sector. To document that statement in numerous cases (some of which are discussed briefly in Section IV), we have developed and used the "counterfactual method" for project evaluation that is discussed in Section VIII. In cases where the most efficient solution is private performance of the public's desired research projects, then the public research institution will in many cases have a role overseeing the performance of the project – for example, deciding which private firms will perform the research and perhaps using its own research capabilities to develop infrastructure technologies to support the success of the new, publicly mandated technologies being developed by the private sector with subsidies from the government. We discuss such cases in Section IV.

IV. Examples of Projects from Public Research Institutions in the United States

A. Funding of Extramural Research

A.1. The TIMA Focused Research Program

The Advanced Technology Program (ATP) was established within the U.S. National Institute of Standards and Technology (NIST) through the Omnibus Trade and Competitiveness Act of 1988, and modified by the American Technology Preeminence Act of 1991.[11] The goals of ATP, as stated in its enabling legislation, are to assist U.S. businesses in creating and applying the generic technology and results necessary to

[11] For background information about NIST see www.nist.gov.

"[c]ommercialize significant new scientific discoveries and technologies rapidly, and refine manufacturing technologies."[12]

ATP has sponsored a number of focused program competitions in addition to its general competitions. One such focused program (in 1995 and in 1997) is the Technologies for the Integration of Manufacturing Applications (TIMA) Program. This program is one example of overcoming market failure through a public/private partnership using the resources of a public research institution.

The overall goal of the TIMA focused program was to develop and demonstrate the technologies needed to create affordable, integrable manufacturing systems. Many manufacturing companies need to respond more rapidly to changing markets and evolving opportunities if they are to remain competitive in global markets. Although this need is widely recognized, manufacturers find it difficult to implement the technologies needed for them to become more agile producers. Even highly automated plants and factories struggle to adapt successfully and efficiently and reconfigure production processes to accommodate design changes and new product lines. Customized systems integration efforts are often needed to achieve such changes, but they are not undertaken primarily because of idiosyncrasies in manufacturing software and incompatibilities among software applications.

Typically, factory-floor information systems focus on the operation of production equipment and the control of processes. The systems communicate neither directly nor regularly with administrative information systems, or with design and engineering systems. As a result, upstream information systems are unaware of important

[12] The term "generic technology" does not have a generally accepted definition. It is not a National Science Foundation reporting category of R&D spending (Link 1996a, 1996b, 1996c). Tassey (1992, pp. 98-99) offers the following definition: "generic technology research is a major step in the sequential evolution of a typical industrial technology. It is the organization of scientific principles into a *functional technical concept.*"

manufacturing details. Middle-level information systems, known as manufacturing execution systems (MES), bridge this critical information gap.

MES solutions, complex and burdensome as they may be, can be solved by contracting with a large systems provider or integrator. However, once a manufacturer has incurred such a substantial investment it is likely to become dependent on that single vendor and thereby become unaware of, or if aware likely ignore, other vendors that may have more economical or innovative solutions. Because the initial solution involves re-engineering the manufacturer's business processes to be compatible with the vendor's requirements, even large manufacturers that can afford the up-front investment cost will by-pass the use of MES technology.

TIMA technologies benefit a range of companies: companies that employ MES by providing them with a wider range of powerful, integrable applications that will dramatically improve the manufacturer's ability to reconfigure, scale, and adapt their processes; small- and medium-sized manufacturers by making MES more affordable and by providing a direct path toward greater automation through incremental addition of compatible applications; and vendors of MES products by expanding the market, lowering barriers to entry, stimulating innovation, and allowing technical specialization. Consumers benefit from the adoption of these technologies in at least two ways – a higher quality product and a lower priced product to the extent that greater automation increases competition.

The TIMA projects illustrate cases where although the social rate of return was quite high and justified the R&D investments, the private sector would not have made the investments without the subsidies from the public because in the absence of the partial public funding, barriers to innovation and technology would have kept the expected private rate of return below the private hurdle rate. The primary barriers were a long time to complete the R&D and commercialize the resulting technology, and high technical risk associated with the underlying R&D. The TIMA projects also illustrate the way that public support for industrial R&D projects with large social value can be managed through a public research institution.

As reported in Link and Scott (2001a), this project was successful from an economic perspective as evidenced, with reference to the figure above, by an estimated social rate of return for an average TIMA project of 63 percent with ATP funding compared to a private rate of return without ATP funding of 20 percent, less than the private hurdle rate of 25 percent. The "spillovers method" of project evaluation, described in Section VIII, was used to compute the rates of return. The partial public funding increased the private rate of return above the private hurdle rate for the project. Thus, the private sector was willing to perform the research for the project that had a social rate of return exceeding the social hurdle rate. The performance of the project by the private sector with the oversight of ATP provided a socially desirable outcome.

B. Public Research Institutions' Performance of Research: Intramural Funding of Infrastructure Technology Outputs

B.1. Standards: Internet Commerce for Manufacturing (ICM)

The goals of this project, performed at the U.S. NIST with oversight from NIST's ATP, were to assist industry in developing open standards to enable exchange of business and product data for all supply chain participants, to provide a flexible testbed for industry and government to collaborate in testing and evaluating standards-based tools and integration technologies, and to demonstrate business-to-business E-commerce. In 1996, the Software Diagnostics and Conformance Testing Division of the Information Technology Laboratory and the Electricity Division of the Electronics and Electrical Engineering Laboratory began a three year study. In November 2001, as a direct result of the research on this project, several Product Data eXchange (PDX) standards were adopted. The standards benefited original equipment manufacturers (OEMs) in the computer industry and contract manufacturers in the electronics manufacturing services (EMS) industry.   The standards were used to communicate data for the engineering and manufacturing of components to be used in printed circuit boards. Significant cost savings were realized by OEM and EMS companies as a result of improved data communications related to E-commerce.

As reported in Link and Scott (2004), this project was successful from an economic perspective as evidenced by a prospectively calculated internal rate of return of 220 percent, a benefit-to-cost ratio of 33 to 1, and a net present value of over $23 million. The "traditional method" of project evaluation, described in Section VIII, was used to compute these evaluation metrics.

B.2. Standard Reference Materials: Wavelength References for Optical Fiber Communications: SRM 2517a

The goal of this project performed at the U.S. NIST was to develop an improved standard reference material (SRM) for the measurement of the wavelength of light in an optical fiber network. In 1998, the Optical Fiber and Components Group of the Optoelectronic Division of the Electronics and Electrical Engineering Laboratory began a two year study of SRM 2517a (to replace SRM 2517). The new SRM benefited industry in the following ways. Its use by test equipment manufacturers brought about: production related engineering and experimentation cost savings and calibration cost savings, increased production yields, negotiation (with customers over performance attributes) cost savings, and reduced marketing costs.

As reported in Link and Scott (2004), this project was successful from an economic perspective as evidenced by an internal rate of return of 4,400 percent, a benefit-to-cost ratio of 267 to 1, and a net present value of $76 million. As with the ICM case, the "traditional method" was used to compute the metrics for this case. There are two important observations to make about these metrics.

First, in this SRM 2517a case especially, we observe extraordinarily high rates of return to the public's investment in the development of infrastructure technology. The large rates of return are the result of having very small marginal investment costs (small relative to most infrastructure projects) in the context of huge extant investments in the public research institution. Thus, there are relatively tiny costs and some relatively large returns. Of course, we have to have the large public research laboratory that was already in the business of providing standard reference materials and calibration services for the measurement of the wavelength of light to make effective the small incremental investments to develop an improved standard reference material. Having the established public research institution is a given in these project evaluations, and then we ask what the social rate of return is for a new investment project.

A second observation is needed to address the question of why, given the high returns on the investment, firms in the private sector did not undertake the research themselves. The answer is related to the first observation. It is much more efficient for the public laboratory to do the work, and that is not simply because of the extant investment in the public laboratory, although that is part of the reason. Our case studies using the "counterfactual method" described in Section VIII have documented that for the infrastructure technology projects such as those developing standard reference materials and the others that we discuss here and in Link and Scott (1998, 2004), because of various combinations of the barriers to technology that we have described in Section II, the public laboratory produces a higher quality output with more desirable outcomes and at a lower cost that the private sector could achieve. For these projects it is especially costly for the private sector to overcome coordination problems in developing, disseminating, and using the technology in the context of appropriability difficulties and opportunistic self-interested behavior of private firms. In the best of circumstances for alternative solutions (such as using cooperative agreements among the participants in a trade association and contracts with university scientists) the results are, according to our respondents in industry, of lower quality and higher cost than the results for the public laboratory's performance of the research and services.

B.3. Calibration Services: Thermocouple Calibration Program

The thermocouple calibration program at the U.S. NIST resides within the Chemical Science and Technology Laboratory (CSTL), one of seven research laboratories at NIST. CSTL's mission is to provide the chemical measurement infrastructure for enhancing the productivity and competitiveness of U.S. industry, assuring equity in trade, and improving public health, safety, and environmental quality. Such measurement technology is germane to industrial research and development, product application, improvements in the design and manufacturing of quality products, proof of performance, and marketplace transactions that include the successful entry of U.S. products into international markets.

Thermocouple calibration allows accurate measuring of temperature, and NIST's role as the lead U.S. agency for temperature measurement is to overcome technical and business barriers by providing impartial technical positions, expertise in a wide range of measurement areas, direct access to complementary national standards, and the motivation to deliver the technical infrastructure to a wide range of supplier and user industries.

All temperature measurements must ultimately trace back to a national standard to provide consistency and accuracy across disparate organizations and industries. NIST has the legal mandate in the United States for providing the national standards that form the fundamental basis for all temperature measurements made in domestic industries. Realizing and maintaining national temperature standards in terms of the scientific first principles and the constants of nature that define the International Temperature Scale is difficult technically and requires a dedicated laboratory capability. The CSTL develops and maintains the scientific competencies and laboratory facilities necessary to preserve and continuously refine the basic physical quantities that constitute the national temperature standard. Further, NIST has a mandate to apply these basic measurement standards to develop uniform and widespread measurement methods, techniques, and data.

As reported in Link and Scott (1998), this program was successful from an economic perspective as evidenced by an internal rate of return of 32 percent and a benefit-to-cost ratio of 3 to 1. These evaluation metrics were calculated using the "counterfactual method" of evaluation described in Section VIII. That method allows the documentation of the higher costs for alternative solutions for the thermocouple calibration services. With the thermocouple case, impartial technical positions that span many sectors are often necessary and hence cannot reasonably be coordinated by the private sector.

B.4. Test Methods: Polymer Composite Dielectrics for Integrated Thin-Film Capacitors

The goals of this project performed at the U.S. NIST were to establish new metrology – test methods – to characterize electrical properties of the dielectric films used as embedded capacitance in printed circuit boards (PCBs) and to advance knowledge about the limits of this new system. In 1999, the Polymers Division of the Materials Science and Engineering Laboratory began the three year study to develop the new test method.

Dielectric films can be used in the new packing solutions for the high performance chips combining resistors, capacitors, and microstrips with integrated circuits in PCBs. As a result, systems operate at higher frequencies and the PCBs are more functional. The new test method for characterizing dielectric films is valuable to the PCB industry. Respondents reported that the new test method will reduce the costs of characterizing materials, increase production yields, and enable industry to move forward into new products with higher frequencies, thus allowing for broader bandwidth communications technology.

As reported in Link and Scott (2004), this project is expected to be successful from an economic perspective as evidenced by prospectively calculated lower-bound metrics showing an internal rate of return of 35 percent, a benefit-to-cost ratio of 7 to 1, and a net present value of about $11 million. Although the “traditional method” of evaluation is used for these metrics, they are just conservative lower-bound estimates because of data constraints that are explained in Link and Scott (2004).

B.5. Verified Data Bases: Phase Equilibria Program

Scientists discovered the usefulness of phase diagrams for describing the interactions of inorganic materials in a given system more than 100 years ago. Phase equilibria diagrams are graphical representations of the thermodynamic relations pertaining to the compositions of materials. Ceramists have long been leaders in the development and use of phase equilibria diagrams as primary tools for describing, developing, specifying, and applying new ceramic materials.

Phase diagrams provide reference data that represent the phase relations under a certain limited set of conditions. A ceramist conducting new materials research will invariably conduct experiments under different conditions than those that underlie the phase diagram. The reference data in the phase diagram provide the user with a logical place to begin experimentation for new research and to bypass certain paths that would lead to a dead end.

For over 60 years, the U.S. NIST and the American Ceramic Society (ACerS) have collaborated in the collection, evaluation, organization, and replication of phase diagrams for ceramists. This collaboration began in the late 1920s between Herbert Insley of the National Bureau of Standards and F.P. Hall of Pass and Seymour, Inc., a New York-based company. Since that time, over 10,000 diagrams have been published by ACerS through its close working relationship with NIST. The collaboration between these two organizations was informal until December, 1982, and successive formal agreements have extended the program to the present.

This program, within the Materials Science and Engineering Laboratory (MSEL), is known as the Phase Equilibria Program. Its purpose is to support growth and progress in ceramics industries by providing qualified, critically-evaluated data on thousands of chemical systems relevant to ceramic materials research and engineering. This information serves as an objective reference for important statistical parameters such as melting points and chemical reactivity. In short, the database is a valuable source of infrastructure technology for ceramists in research- and application-oriented organizations.

The intention of the Program is to overcome problems that researchers have in using ceramic phase equilibria diagrams that appear in the various technical journals. For example, the original source of a diagram is often obscure or not available readily to all ceramists. Diagrams are also published with inconsistent styles and units, and some diagrams are published with obvious, at least to expert ceramists, errors in thermodynamic data. Those errors could cause design failures. Maintaining currency of the diagrams is another concern of ceramists. Hence, the objective and scope of the NIST/ACerS program is to compile an accessible, accurate, systematic, and current set of phase diagrams that have already appeared in the archival literature.

In the absence of phase diagrams, ceramists would incur greater costs for internal research and experimentation. These additional costs would likely be passed on to downstream manufacturers and ultimately on to consumers of ceramic-based products. Without the public investments, there would be additional costs from additional trial and error experimentation and literature search contemporaneous with product development, raising production costs of customized products and hence increasing prices.

As reported in Link and Scott (1998), this program was successful from an economic perspective as evidenced by a calculated internal rate of return of 33 percent and a benefit-to-cost ratio of 9 to 1. The "counterfactual method" was used to calculate the metrics, documenting the higher costs for the project that would have occurred if the public laboratory had not been involved in the project.

B.6. Specialized Research, Technical Advice, and Dissemination of Ideas from Basic Science in Support of Public Initiatives: Alternative Refrigerant Program

The U.S. NIST is often called upon to contribute specialized research or technical advice to initiatives of national importance. The U.S. response to the international environmental problem of ozone depletion required such a contribution.

Historically, chemical compounds known as chlorofluorocarbons (CFCs) have been used extensively as aerosol propellants, refrigerants, solvents, and industrial foam blowing agents. Refrigerants are chemicals used in various machines, such as air-conditioning systems, that carry energy from one place to another. Until the past decade, most refrigerants used throughout the world were made of CFCs because of their desirable physical and economic properties. However, research has shown that the release of CFCs into the atmosphere can possibly damage the ozone layer of the earth. In response to these findings, international legislation was drafted that resulted in the signing of the Montreal Protocol in 1987, a global agreement to phase out the production and use of CFCs and replace them with other compounds that would have a lesser impact on the environment.

In order to meet the phase-out schedule in the Protocol, research was needed to develop new types of refrigerants, called alternative refrigerants, that would retain the desirable physical properties of CFCs, but would pose little or no threat to the ozone layer.

Possible candidates for alternative refrigerants must have a number of properties and meet a number of criteria to be judged as feasible replacements for CFC refrigerants.

Since 1987, the United States and other nations have forged international environmental protection agreements in an effort to replace CFCs with alternative, more environmentally neutral chemical compounds in order to meet the timetable imposed by the Protocol.

NIST became involved in alternative refrigerant research in 1982 and has continued to support U.S. industry in its development and use of CFC replacements. The Physical and Chemical Properties Division of NIST's Chemical Science and Technology Laboratory (CSTL) has been the focal point for this research effort.

The Physical and Chemical Properties Division has more than 40 years of experience in the measurement and modeling of the thermophysical properties of fluids. The Division has been involved with refrigerants since the mid-1980s. Early work was performed at NIST in conjunction with the Building Environment Division, and this work led to the development of early computer models of refrigerant behavior. In addition, research performed by Division members serves as a basis for updating tables and charts in reference volumes for the refrigeration industry.

Research on alternative refrigerants falls broadly into three areas: (1) effects of man-made chemicals on the atmosphere, (2) chemical and physical properties of alternative refrigerants, and (3) methods to place chemicals in machines. The first area is referred to by NIST scientists as "understanding the problem," and the other two areas are referred to as "solving the problem." The primary focus of the Physical and Chemical Properties Division is on the properties of refrigerants.

The results from NIST's properties research were made available to industry in various forms. The most effective form for dissemination of information has been through the

REFPROP program, a computer package that is available through NIST's Standard Reference Data Program. The REFPROP program is used by both manufacturers and users of alternative refrigerants in their respective manufacturing processes. A particular benefit of the REFPROP program is its ability to model the behavior of various refrigerant mixtures, and this has proven to be a key method in developing CFC replacements.

NIST's research efforts on characterizing the chemical properties of alternative refrigerants and how these refrigerants perform when mixed with other refrigerants potentially averted a very costly economic disruption to a number of industries. According to interviews with industry and university researchers, NIST served critical functions that were important to the timely, efficient implementation of the Montreal Protocol. The formal evaluation of the REFPROP program shows a very high return on the public's investments to use the expertise at the national laboratory to provide the specialized research and technical advice in support of industry's adaptations to the international initiative embodied in the Montreal Protocol.

As reported in Link and Scott (1998), this project was successful from an economic perspective as evidenced by an internal rate of return of 435% and a benefit-to-cost ratio of 4 to 1. The "counterfactual method" was used for the metrics; costs for the project would have been much higher if alternatives to NIST had been used to perform the project. NIST created a program to determine properties for refrigerants that were mixtures of chemicals; the project then created an R&D data base (much as the data base in the ceramics phase-diagrams case could be used for R&D) to be available for use by all firms. For the development of such generic, infrastructure technology, there would be incentive problems for industry because of appropriability problems. Further, proprietary interests of firms could cause opportunistic behavior that limited both the data developed and the usefulness of the data developed. For universities, there would have been a greater incremental cost for developing the project, because NIST already had an extant research presence that allowed it to efficiently develop the data that industy needed.

Thus, we see again the influence of the extant investment in the public research institution on the decision of whether to use a public laboratory to perform research or instead industry or universities. One lesson is that for such cases – that do not involve standards or the need for an honest broker – a country that did not already have an established public laboratory with expertise in an area could probably do as well or better contracting the research to universities (or to firms if the problems of proprietary interests and opportunistic behavior could be overcome).

B.7. Technical and Business Assistance to Firms through Manufacturing Extension Programs and Quality Management Advice

The U.S. NIST's mission is to promote U.S. economic growth by working with industry to develop and apply technology, measurements, and standards. It carries out this mission through four major programs, the first two of which we have discussed indirectly in the foregoing cases of projects in the NIST laboratories and projects sponsored by ATP. Those first two programs are: (1) measurement and standards laboratories that provide technical leadership for vital components of the nation's technology infrastructure needed by U.S. industry to continually improve its products and services; and (2) a rigorously competitive ATP award process providing cost-shared awards to industry for development of high-risk, enabling technologies with broad economic potential.

There are two other major programs at U.S. NIST. They are: (3) a grassroots Manufacturing Extension Partnership with a network of local centers offering technical and business assistance to smaller manufacturers; and (4) a highly visible quality outreach program associated with the Malcolm Baldrige National Quality Award that recognizes continuous improvements in quality management by U.S. manufacturers and service companies.

As reported in Link and Scott (2001b), the National Quality Award Program was successful from an economic perspective as evidenced by a benefit-to-cost ratio of 207 to 1. The "counterfactual method" (discussed in Section VIII) for project analysis was used; the results document the efficacy of using the public research institution to coordinate the quality program, which as noted in Section III uses a substantial amount of private funding.

V. Examples of Projects from Public Research Institutions in Latin America

Three examples of Latin American public research institution projects were identified as background for this White Paper. These examples are summarized briefly to illustrate parallel activities between the United States and the selected Latin American countries. After the brief summary of these examples, we offer in the next section a critical, overarching observation based on correspondence with those with knowledge about the projects.

A. Technologies to Prevent and Mitigate Natural Disasters in High-Risk Areas

This project, like the Alternative Refrigerant REFPROP Program discussed as an example of a U.S. program, is aimed at major environmental problems that have become the focus of public initiatives. It is coordinated by the Escuela Superior de Ingenienría Mecáica y Eléctric, which is associated with the Instituto Politécnico Nacional de México. Colombia, El Salvador, Honduras and Venezuela are participating in this project that has the goals of encouraging training and exchange of theoretical and practical knowledge on environmental issues and transferring knowledge about how to address those issues in high-risk urban areas.

B. Technology Transfer to Ecuador and Bolivia of Colombian Sericulture

The Centro de Desarrollo Tecnológico de Sericultura (CDTS) located in Colombia coordinates and implements this project to offer assistance to governments and private sectors of Ecuador and Bolivia to develop sericulture (i.e., silk production). The program provides training and know-how transfer to government and private technicians, as well as to leading producers in order to enable the transfer of up-to-date technology for production and handling of silkworm cocoons to small farmers. In a broad sense, this program parallels the programs (discussed in section IV.B.7) at NIST that provide technical and business assistance to firms.

C. Strengthening of the Central American Capacity in Technological Management for the Small and Medium-Size Company

This project, which parallels the National Quality Award program at NIST, is from Comisión para el Desarrollo, Científico y Tecnológico de Centro América y Panamá (CTCAP) in El Salvador. It aims to strengthen the capacity to incorporate technological management as a tool to increase entrepreneurial productivity and competitiveness and to increase as well the productivity and competitiveness of small and medium-size companies in each of the Central American countries. The project will work to foster the transfer of managerial techniques and methods to improve the technological management of companies.

VI. Lessons Learned from the Case Studies

The case studies illustrate ways that specific activities of public research institutions can address specific types of market failures. Without the public research institution's activity, there would be an underinvestment in socially desirable research, and the institution's activity provides the desired investment yielding outputs that have outcomes that have desirable social impacts. We have focused on U.S. case studies with which we have had first-hand experience and then worked to draw out lessons that may be of general importance. Martin and Scott (2000) have several examples from other nations that are consistent with the general conclusions we have drawn, yet illustrate the international variety of approaches to public research. In addition to our focus on cases that we have actually studied in detail, we have contacted representatives of a few public research projects – briefly described in Section V – in Latin America to learn how the approach to those projects compares with what we have observed first-hand in the U.S. context.

The lessons to be learned are of two types. The first is a general observation about the importance of identifying outputs and outcomes and understanding how they fill a market-failure void that would occur without the public investment. The second is a listing of circumstances in which activities of public research institutions with a research capability are socially valuable.

First, as a general observation, we emphasize that the activities of public research institutions are most likely to be successful in correcting underinvestment when the institutions think about those activities in terms of outputs and outcomes and measured impacts for research projects that address market failures.

Examples of outputs include contributions to underlying science, developed generic technology or infrastructure technology, documented use in industry of generic technology or infrastructure technology, intellectual property, and the promulgation of industry standards. Examples of outcomes include industry R&D investment decisions, market access and entry decisions, industry cycle time, productivity, market penetration of new technology, product quality, product and systems reliability, and reduced transaction costs. The impacts are the social benefits that we measure with metrics such as rates of return, net present values, and benefit-to-cost ratios.

In Section VIII, we explain alternative approaches that public research institutions can use to track their inputs, outputs, outcomes, and impacts and thereby maintain useful evaluation of their investments. Those alternative approaches to project evaluation were used to calculate the rates of return and other evaluation metrics discussed for the cases in Section IV.

We were surprised by the fact that none of our respondents for the Latin American public research projects seemed to think in terms of the outputs and outcomes from public research, although that could simply result from the small number of Latin American projects identified, the time constraints of the study compared to the several years that we studied the cases from the United States, and our prior experience about how policy related scientists think about their projects from a social perspective. Because those with whom we corresponded about the Latin American projects did not think about their public supported projects in terms of outputs or outcomes, we were limited in our ability to identify a public good aspect to their research. However, as our brief history (in Section II) of thought about public research suggests, before the early 1990s, thinking about the market-failure rationale and the outputs and outcomes of publicly funded research was at best not emphasized by government and probably not typical at all. In our experience, those responsible for funding U.S. public-sector research still do not think seriously about market failure as the reason for the public's role in research.

The second broad lesson learned is that there are circumstances where public research institutions with research capabilities can be the most efficient way to address technology and innovation market failures that would result in underinvestment from a social standpoint. We turn now to an enumeration of circumstances – illustrated and discussed in the foregoing sections – where our case studies support the theory that the activities of public research institutions can address market failures and provide socially valuable research. Here, we are drawing together a list of ways that public research institutions can usefully contribute to a national innovation system; the list is more fully discussed and illustrated with examples in the preceding sections of the report. Also, as we explain in our concluding section, the following list of a public research institution's potential contributions must be used selectively when applied for prescriptive purposes to the current policy context for Latin America and the Caribbean.

Standards. The development of the ICM standards provides an example. The public research institution had the knowledge and could act as an honest and knowledgeable broker bringing together the industrial firms to ensure the standards were developed, promulgated, and used.

Standard Reference Materials. The development of the SRM 2517a provides an example. The public research institution had the knowledge of what industry needed, and it had the research capability to develop the appropriate, improved standard reference material.

Calibration Services with Traceability to Standards. The thermocouple case provides an example. The public research institution provided the impartial measurement technology and calibration services traceable to the standards that allowed consistent measurement used across many sectors of the economy.

Verified Data Bases. The phase diagrams for ceramics case and the alternative refrigerants case provide examples of data about the properties of materials in various conditions. In the alternative refrigerants case, the data are combined with a program to predict the properties of different mixtures of refrigerant chemicals. The public research institution was providing impartial, generic pre-competitive technology, making it available for the private sector firms to use in their own proprietary endeavors.

Extension Services to Transfer Technology and Management Techniques. There is often a substantial private component to these services, with the public research institution serving a coordinating role. The Manufacturing Extension Partnership and the National Quality Award Program at U.S. NIST provide examples discussed in Section IV.

Coordinating and Facilitating Cooperative R&D Efforts Joining Industry, Universities, and Government in Research Projects Subsidized by the Government. Hall, Link, and Scott (2003) examine several projects demonstrating such coordination and facilitation, all taken from the projects at NIST's Advanced Technology Program. However, the cooperative R&D efforts among public research institutions and industry and universities span many of the activities of the public institution; indeed, such cooperative activity is pervasive and productive based on our case studies. For example, the dielectrics project (a publicly performed and funded research project in the government laboratory with in-kind contributions of personnel and equipment from industry) discussed in Section IV combined the efforts of the researchers in the public laboratory with the efforts of scientists from industry and from universities.

Communicating and Disseminating Scientific Ideas that Can Be Used by Industry in Many Sectors. Public research institutions can facilitate the dissemination of ideas from basic science (that often are developed with public funds in universities and industry). The ideas are pre-competitive and the public institution can help make them available to all who have use for them in their own proprietary endeavors. The alternative refrigerants case provides an example of the dissemination of knowledge for use in proprietary technologies. In our own experience, the public research institution with a research capability often stands mid-way between the basic science available in universities and the applied needs of industry and is therefore uniquely suited to develop and transfer generic and precompetitive ideas and technologies to those who need to apply them in proprietary technologies. Examples include the use of materials science in the development of new metrology for characterizing the properties of dielectric materials used in high-speed telecommunications (the dielectrics case in Section IV) and the use of optoelectronics science in the development of a new standard reference material (the SRM 2517a case in Section IV) for the measurement of the wavelength of light used in fiber optics communications systems.

Oversight of Partially Publicly Funded and Privately Performed Public Research. Many of the foregoing categories of activities entail this oversight activity, because often the public research institution is working closely with partners in industry who provide both funding and in-kind assistance for the projects. Perhaps the purest example of this present category, however, is the NIST's Advanced Technology Program's projects. The ATP TIMA project provides an example. The public research institution has the research capabilities and industrial knowledge to oversee the awards process that results in the successful private performance of the public research that the government would like to have performed by industry. Industry would have the expertise to perform the research most efficiently in such cases, but the incentives to perform the research must be provided by the public research institution's design of the award process, its subsidies for the research, and its oversight to ensure that the objectives of the research are met. In the following section, we identify a general approach to providing the subsidy for privately performed public research in a way that will minimize the public's expenditure of funds.

VII. Leveraging Public Funding of Private Performance of Public Research.

Public subsidies for privately performed research have often been granted in the context of competition for the awards of public funds to support the research. For example, the U.S. ATP makes its awards in the context of such competitions. The TIMA project discussed above is an example. However, the competition is among organizations to win the award; the proportion of costs covered by the award is determined administratively by various criteria but there is not systematic competition to determine the proportion of a project's total cost that will be taken by public funds – public funds that the winning organization will receive to support the project. Scott (1998) points up that if there were competition to determine the proportion of the costs to be subsidized, the private firms would bid in a way that brought them sufficient public funds to ensure their private hurdle rates were met (see the figure in Section II) but not exceeded. An administratively determined grant of say 50 percent of the project's total funding coming from the public might (and in our experience does) imply a private rate of turn far in excess of the private hurdle rate. In that case a smaller amount of public funding would provide a sufficient subsidy for the private research to meet its private hurdle rate.

Scott (1998) explains that if private organizations bid for the right to receive the award, the public research institution that oversees the process could select an organization that was capable of performing the socially desired research and yet could minimize the expenditure of public funds needed to subsidize the project. Martin and Scott (2000) and Link and Scott (2001a) exposit the idea in the context of the focus of their particular papers. Martin and Scott (2000) emphasize that the bidders for the performance of public research could be venture capital companies. Then, not only would the process minimize the necessary public funding, the process of developing the new technologies and successfully transferring them could be overseen by those with expertise in the development and nurturing of innovations. Link and Scott (2001a) point up that the current procedures for granting awards typically will result in the public spending more than is necessary to ensure the private performance of the research.

VIII. Public Accountability: An Overview of Evaluation Methodologies

It is essential for any public research institution to demonstrate its accountability to the public, from where its resources ultimately come. Public accountability requires that the public research institution first identify market failures before undertaking internally or funding externally investment projects, and second establish an evaluation program. The examples of the activities at NIST and ATP discussed in Section IV included a brief summary of the evaluation metrics for each project. Establishing an ongoing program for evaluation is a hallmark of successful public research institutions. In this section, we review the appropriate evaluation methodologies.

A. Traditional Economic Evaluation Methods

Griliches (1958) and Mansfield et al. (1977) pioneered the application of fundamental economic insight to the development of measurements of private and social rates of return to innovative investments. Streams of investment costs generate streams of economic benefits over time. Once identified and measured, these streams of costs and benefits are used to calculate such performance metrics as social rates of return and benefit-to-cost ratios.

For example, for a process innovation adopted in a competitive market, using the traditional framework, the publicly-funded innovation being evaluated is thought to lower the cost of producing a product to be sold in a competitive market. As the innovation lowers the unit cost of production, consumers will actually pay less for the product than they paid before the innovation and less than they would have been willing to pay – a gain in consumer surplus. The social benefits from the innovation include the total savings that all consumers receive as a result of producers adopting the cost-reducing innovation. Thus, the evaluation question that can be answered from this traditional approach is: Given the investment costs and the social benefits, what is the social rate of return to the innovation?[13]

B. The Counterfactual Evaluation Method

When publicly-funded publicly-performed investments are being evaluated, holding constant the economic benefits that the Griliches-Mansfield model measures, and making no attempt to measure that stream, the relevant counterfactual question to ask is: What would the private sector have had to invest to achieve those same benefits in the absence of the public sector's investments?

[13] For example, the traditional approach of Griliches and Mansfield provided the metrics, reported in Section IV, for the SRM 2517a project.

The answer to this question yields the benefits of the public's investments. The counterfactual method measures as benefits the private sector's costs avoided through the public's investments plus the benefits from the public sector's investments that industry would be unable or unwilling to duplicate.[14] With those benefits—obtained in practice through extensive interviews with administrators, federal research scientists, and those in the private sector that would have to duplicate the investments (i.e., research) in the absence of public performance—counterfactual rates of return and benefit-to-cost ratios can be calculated. Those metrics answer the fundamental evaluation question: Are the public investments a more efficient way of generating the technology than private sector investments would have been?[15]

The answer to this question aligns with the public accountability issues implicit in government mandates for accountability such as the U.S. Government Performance and Results Act (GPRA) of 1993, and certainly addresses a key question of public sector stakeholders, who may doubt the appropriateness of government having a role in the innovation process in the first place.

C. The Spillover Evaluation Method

There are important projects where economic performance can be improved with public funding of privately-performed research. Public funding is needed when socially valuable projects would not be undertaken without it. If the expected private rate of return from a research project falls short of the required rate called the hurdle rate, then the private sector firm will not invest in the project. Nonetheless, if the benefits of the

[14] In the extreme case where industry would not have made the investments at all, there are no private-sector costs avoided, but because the private-sector performance shortfall is complete, all of the traditional Griliches-Mansfield stream of returns to the R&D investments is valued as benefits. In that special case, the Link-Scott approach is identical to the Griliches-Mansfield approach except that it has the advantage of having pointed out that government could do the work more efficiently—in this special case because industry would not do it at all. See Link and Scott (1998) for more details about the counterfactual evaluation method.

[15] For example, the counterfactual evaluation method provided the metrics, reported in Section IV, for the alternative refrigerants program.

research spill over to consumers and to firms other than the ones investing in the research, the social rate of return may exceed the appropriate hurdle rate. It would then be socially valuable to have the investments made, but since the private investors will not make them, the public sector should. By providing some public funding, thereby reducing the investment amount needed from the private firm or firms doing the research, the expected private rate of return can be increased above the hurdle rate. Thus, because of this subsidy, the private firm is willing to perform the research, which is socially desirable because much of its output spills over to other firms and sectors in the economy.

The question asked in the spillover method is one that facilitates an economic understanding of whether the public sector should be underwriting a portion of private-sector firms' research, namely: What proportion of the total profit stream *generated by the private firm's R&D and innovation* does the private firm expect to capture; and hence, what proportion is not appropriated but is instead captured by other firms that imitate the innovation or use knowledge generated by the R&D to produce competing products for the social good? The part of the stream of expected profits captured by the innovator is its private return, while the entire stream is the lower bound on the social rate of return. In essence, this method weighs the private return, estimated through extensive interviews with firms receiving public support about their expectations of future patterns of events and future abilities to appropriate R&D-based knowledge, against private investments. Then, the social rate of return weighs the social returns against the social investments.[16]

The application of the spillovers model to the evaluation of public funding/private performance of research is appropriate since the output of the research is only partially appropriable by the private firm with the rest spilling over to society. The extent of the spillover of such knowledge with public good characteristics determines whether or not the public sector should fund or partially fund the research.

[16] For example, the spillover evaluation method provided the metrics, reported in Section IV, for the TIMA program.

IX. Conclusion

To conclude this White Paper, we use our analysis to offer answers to several questions of concern to the World Bank's Office of the Chief Economist, Latin America and Caribbean. The overarching question is: How should Latin America restructure the government part of their national innovation system? The subsidiary question of concern for this White Paper is: What are the appropriate roles for public research institutions in the national innovation systems of Latin America?

There are two general categories of answers to be gleaned from our economic analysis based on our experiences with the U.S. public research institutions. First, we have the general lessons learned as summarized in Section VIII and as developed and documented in the earlier sections of the report. Second, there are the proper subset of applicable lessons for Latin America given the reality of the current political economy – namely, in the medium term, Latin America is not going to spend much more on R&D because there are too many competing demands for resources. However, there is great opportunity for use of specialized, applicable lessons, because informed observers believe that the Latin American countries are presently very inefficient in what they do spend for R&D and a great deal of money goes into public research institutes (set up during the import substitution period) that are now considered unproductive. Indeed, some observers believe the institutions are "useless money sinks." That opinion certainly aligns with our impression that the contact individuals for the current publicly supported Latin American technology projects, about which we inquired, did not think of their projects in terms of well-defined outputs and outcomes and did not offer any insights into the public good nature of their projects.

One expert opinion we have encountered is that Finland's approach of expanding co-financing subsidies and reducing the base financing to government think-tanks would be a sensible general policy for Latin America to follow. Note that such a policy is consistent with the effects of the financial leveraging of government funding for innovation policies that has been suggested by Scott (1998) and that we discussed briefly in Section VII. That is, however, just one example of the subset of applicable lessons that we can offer from our analysis based on our practical experience with public research institutions. Therefore, in this concluding, prescriptive section, we offer a subset of lessons applicable to Latin America in its present situation – that is, given the foregoing political economy in which resources are to be devoted to public support of R&D and technology.

Observe first that the objectives of the Office of Science and Technology (OST) within the Organization of American States (OAS) in juxtaposition with the theoretical economic rationale for public support of R&D and technology, and with the evaluation evidence from numerous public sector investments, provide strong support for the use, and continued development, of public research institutions to strengthen economic development and productivity in Latin America and the Caribbean.

The mandated goals as stated in the business plan (dated July 2001 and available at http://www.oas.org/) of the OST within the OAS:

> . . . concern the use of science, technology and innovation for bringing about social development, strengthening the business sector, and protecting the environment through the use of cleaner and less polluting technologies. These substantive mandates require the development of adequate infrastructure for metrology in trade as well as for communications, information technologies, connectivity and the development of policies and strategies on science and technology relative to human resources training. Over the course of the years, both the OAS and the OST, as an integral part of it, have seen an increase in the number of topics needing to be addressed and considered to be of priority by the political leaders of the hemisphere, for the development of their countries.

Those tasks include ". . . preparing and creating standards and patterns of measurement to facilitate trade and to boost consumer and environmental protection." Further, according to the OST's business plan, they include "the development of infrastructure for communications and information technologies, connectivity, metrology infrastructure to support free trade, and the fostering of policies on science and technology for human resources development."

Clearly the goals, regarding science and technology and technology infrastructure, of the Organization of American States motivate needs similar to those that we have documented in the U.S. for public standards and technology organizations. Further, we have reported recent science and technology projects in Latin America and the Caribbean that are similar to the numerous investment projects that we have studied at the U.S. National Institute of Standards and Technology. Taken together, the goals of the OAS and the supporting investment projects underway, when seen in the light of our case studies in the U.S., imply that strong public standards and technology institutions are necessary for the development and productivity of industry in Latin America and the Caribbean.

However, given the economic reality of competing demands for the necessary resources, just a subset of our complete set of lessons are presently practical – that is, presently implementable and useful. The key lessons in the subset are as follows.

One lesson is the foregoing idea about leveraging the public expenditures for R&D and technology by subsidizing private performance of the publicly desired research, but requiring substantial private funding for the projects. As we discussed in Section VII, the essential idea is to supply just enough public funding to allow each project's private rate of return to exceed the private hurdle rate despite the externalities and spillover effects that limit the private appropriability of returns for the socially valuable projects.

Another lesson is that the effectiveness of the public research projects we have studied must be seen in the context of well-established successful public research institutions for which the incremental investments for high-return projects are small relative to the investments that the private sector would have had to make to attempt to replicate the projects without the public research institution. The success stories that we have documented for U.S. public research depend on the extant, experienced, well-developed and well-staffed, public research institution with a history of work in the particular areas of technology with successful interactions with industry and universities. These extant operations often include well-developed and well-staffed services such as calibrations to traceable standards for measuring instruments that are crucial for internationally competitive production. If a public project is in an area of technology where a country does not have such an ongoing public research presence, it may well be more efficient to use a minimal public research bureaucracy to orchestrate two sources of publicly available infrastructure technologies.

First, the minimal bureaucracy would direct and facilitate the use of foreign national standards laboratories in place of the great expense of funding its own national laboratory with research capabilities. The choice of the foreign public laboratories should be made with the goal of minimizing the transactions costs of surmounting economic, cultural, and political barriers to effective use of the foreign laboratories. Our respondents in U.S. industry have often emphasized that, when they are used, foreign laboratories are a much more expensive substitute for the U.S. public laboratories (because of the additional transactions costs of dealing with the foreign laboratories) and would in general be a more costly way to achieve the services provided by the U.S. national laboratories. A well-designed and focused minimal public research bureaucracy could reduce the transactions costs for domestic companies dealing with foreign national laboratories for the standards and technology services necessary to be competitive.

Second, the minimal public research bureaucracy without research capabilities would oversee the publicly-funded private performance of socially desirable public research.

Such research could be performed by industry or by universities or by cooperative ventures joining industry and universities under the oversight of the public research bureaucracy. When industry and universities are joined in the R&D effort, the bureaucracy would need to give special attention to the treatment of intellectual property (Hall, Link, and Scott, 2001). Further, in this role, the goal of leveraging the partial public funding of the privately performed research would be paramount. At the very least, the goal of maximizing the private portion of the funding would be pursued administratively. Ideally, there would be an effective method of overseeing bidding – as described in Scott (1998) and briefly overviewed in Section VII – from the private companies that would perform the publicly desired research or even from private venture capitalists who would then oversee the desired research and innovation.

Implementation of the foregoing recommendations from the prescriptive aspects of the analyses in this paper is one practical path toward both less expensive and more effective public policy toward public research institutions and the standards and technology services that they provide to ensure the competitiveness of domestic industry.

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