Modeling and Measuring the Economic Roles of Technology Infrastructure

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Abstract

Designing and managing an economy's technology infrastructure requires both accurate economic models and data to drive them. Previous models treat technology as a homogeneous entity, thereby precluding assessing investment barriers affecting infrastructure elements. The model presented overcomes this deficiency by disaggregating the knowledge production function into key elements of the typical industrial technology based on the distinctly different investment incentives associated with each element. Without such a model, the economist's ability to assess important market failures associated with investment in the major technology elements, including those with infrastructure (public-good) characteristics, is compromised. Unfortunately, even with the correct knowledge production function, the required data are difficult to collect. This forces government agencies, which fund a majority of technology infrastructure research, to use second-best approaches for economic analyses. The second half of this paper therefore presents an analytical framework that can be driven by more accessible data and provide reasonable impact assessments until better data become available.

Modeling and Measuring the Economic Roles of Technology Infrastructure

Gregory Tassey[1]

The first part of this paper presents a disaggregated or “multi-element” model of technological change. Such a model allows examination of the roles and impacts of the major elements of technology, each of which is distinguished by a different degree and type of public-good content. This distinction implies unique investment behavior with respect to each element with consequent public-policy implications. The second part draws upon the considerable experience of the US National Institute of Standards and Technology (NIST) in designing and conducting practical approaches to estimating the economic benefits from public and private investment in these quasi-public-good technology elements.

1 DISAGGREGATING THE KNOWLEDGE PRODUCTION FUNCTION

The typical industrial technology is composed of three elements: the generic technology base (also, technology platform), supporting infratechnologies, and proprietary market applications (innovations and subsequent improvements). The first two have public-good content and therefore embody infrastructure characteristics. These critical quasi-public technology goods are supplied by a combination of firm-specific assets and sources external to the innovating unit of the firm, such as central corporate research labs, government labs, and, increasingly, universities. The fundamental relationships among these elements require a technology production function that captures the interactive nature of the two quasi-public-good elements with each other and with private-sector investments in the third element, proprietary technologies. Most important, each element responds to different sets of investment incentives (Tassey 2005a).

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[1] The author is indebted to Daniel Josell and an anonymous referee for constructive comments regarding characterization of several elements of the model.

The failure to disaggregate the technology variable based on the distinctly different character of each element and its associated unique investment incentives has limited economists' ability to explain R&D investment behavior and the subsequent relationships with economic growth. Both macroeconomic and microeconomic growth models have made technology an endogenous explanatory variable. However, the vast majority of this literature has treated technology and the process that creates it, R&D, as homogeneous entities. Only a few efforts have attempted even a partial disaggregation and those have been limited to separating scientific research from technology research. In other words, the *technology* variable remains aggregated.

This failure has also inhibited government technology investment policies by prohibiting assessments of the distinctly different incentives associated with each of these three elements. This policy analysis problem is becoming more severe for several reasons: (1) corporate laboratories have reduced their share of national spending on the quasi-public elements, in particular, early-phase research on new, radical technologies; (2) in many countries, such as the United States, government spending on such research has been erratic and skewed toward a few technologies tied to specific social objectives; and (3) universities in many economies are assuming a larger role in such early-phase technology research, with implications for intellectual property (IP) and research portfolio management.

1.1 The three elements of industrial technology

The enabling role of generic technologies for the development of market applications (innovations) has been discussed qualitatively (Link and Tassey, 1987; Nelson, 1992; Tassey, 1997, 2007).[2] Dosi (1982, 1988) defines a "technology paradigm", which is portrayed as a "pattern" of solutions to selected technoeconomic problems based on highly selected principles derived from the natural sciences. Such "highly selected principles" form a generic technology base from which market applications are drawn. A generic technology provides in essence a "proof of concept" which reduces technical risk sufficiently to enable applied R&D investments to be rationalized.[3]

Infratechnologies are the other quasi-public technology element. They include research tools (measurement and test methods), scientific and engineering data, the technical basis

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[2] A generic technology is not the same thing as a "general purpose technology" as defined by Bresnahan and Trajtenberg (1995). The latter refers to a technology with multiple market applications (i.e., market economies of scope exist), a distinctly different concept from the generic base from which a particular set of technology applications is developed.

[3] The classic example of a generic *product* technology is Bell labs' proof in the late 1940s and early 1950s of the concept that the principles of solid state physics can be used to construct a semiconductor switch or amplifier, resulting in the creation of the transistor (Nelson, 1962). One of the best examples of a generic *systems* technology is the Internet. As a system (the communications network), technological advances were first required in its major underlying network technologies, such as queuing theory, packet switching, and routing. Demonstration of such in the 1960s led to prototype networks in the 1970s (ARPANET) and 1980s (NSFNET), which eventually led to the Internet. See National Research Council (1999). Occasionally, a generic technology can take the form of a "method of inventing". Examples are methods for manufacturing hybrid corn seeds and research methods for developing nanotechnologies (Darby and Zucker, 2003).

for interface standards, quality control techniques, etc. Collectively, they constitute a diverse technical infrastructure, various types of which are applied at each stage of economic activity. Infratechnologies often are implemented as industry standards (Tassey, 1997, 2000,).[4]

Both generic technology and infratechnology elements are drawn upon by competing firms to create proprietary technology. However, although attainment of partial property rights is possible, spillovers and other sources of market failure are prominent. In fact, widespread use of generic technologies is desirable from a public policy perspective because the more firms draw upon a technology platform, the larger the number and variety of innovations produced. When infratechnologies are adopted as the technical basis for standards, uniform as well as widespread use is mandatory. These characteristics result in various degrees of underinvestment across technologies and over each technology's life cycle. Consequently, every industrialized nation provides funds to leverage generic technology and infratechnology research and subsequent assimilation by domestic industries. Such funding policies constitute recognition of the public-good content, even though identifying and measuring this content remains difficult conceptually and empirically.

1.2 The multi-element knowledge production function

The microeconomics literature has partially recognized the need for a disaggregated technology framework to address these phenomena but has not progressed beyond a dichotomous model in which technology is separated into scientific and technological stocks of knowledge. In such models, scientific information is appropriately characterized as a pure public good (Nelson, 1959) with external (to the industry) sources of supply. However, in such models, technological knowledge is implicitly assumed to be a purely private good, even while acknowledging the existence of spillovers.[5]

The following disaggregated knowledge production function separately specifies the key public and private technology elements and thereby allows the explicit representation of the critical elements of an industrial technology, specifically generic technologies and infratechnologies. Such an investment-based model of innovation allows assessment of the productivity of private-sector applied R&D, as determined by both private and public-sector expenditures that precede or concurrently support it.[6]

As a point of departure for explicitly separating the proprietary technology element from the quasi-public-good elements, the following generalized model is used:

$$Q_i = S \cdot F(KN_j, KE_i, \phi_j, X) \qquad [1]$$

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[4] Note that infratechnologies are part of an industry's technology base in contrast to what are referred to as "infrastructure technologies." The latter are produced by industries whose primary role is to provide an economic infrastructure function for other industries (electricity, transportation, and communications).

[5] A number of studies have attempted to empirically test this general specification by separately including basic research and applied R&D variables in a modified production framework. See Mansfield (1980, 1991); Link (1981); Griliches (1986); Jaffe (1989); Leyden and Link (1991); and Toole (1999).

where Q is a firm's output of technology-based goods and services. *KN* represents the non-excludable (and hence public-good) portion of the industry's generic technology and is assumed equally available to all firms in the industry. *X* is a set of factors that affect output/performance in addition to the public and private technology elements. ϕ represents the innovation infrastructure of the industry, which consists of a set of infratechnologies and associated standards, as well as other infrastructure elements such as the availability of risk capital, intellectual property laws, technical support for entrepreneurs, etc. This infrastructure affects all three stages of economic activity: R&D, production, and commercialization. *S* is the science base upon which the industry's generic technology is based. Because the vast majority of science is developed outside the industry by universities and government research institutes and because major breakthroughs in science occur infrequently, the science base is considered to be externally determined and constant and therefore is entered in the model as a shift parameter.

KE_i is a firm's stock of excludable (proprietary) knowledge that is used to create new products and services, i.e., innovations. At any point in time, a firm's proprietary technical knowledge creation is equivalent to the growth in KE_i, represented by

$$[2] \qquad \Delta KE_i = \delta_i RE_i^{\lambda}$$

where *RE* is applied R&D expenditures targeted at developing innovations, λ is a scale parameter, and δ is a firm's R&D productivity factor.[7]

The productivity factor is represented by

$$[3] \qquad \delta_i = \eta_j e^{-KN_j / RE_i}$$

An important point from a policy perspective is the negative sign on *KN*. It implies a hurdle for investment in innovations, specifically an initial technical-risk barrier that must be overcome before substantial private investment in *RE* will be forthcoming. The negative sign may seem counter intuitive because generic technology does in fact enable the conduct of applied R&D, which, in turn, produces innovations. However, it is a barrier to applied R&D in the sense that (1) it must be available for innovation effort to occur and (2) on average, the greater the potential of a new technology, the greater the required advance in early-phase proof-of-concept research, i.e., the greater the initial barrier to innovative effort posed by the needed investment in the generic technology.

η_j is an efficiency parameter that represents the portion of an industry's technical infrastructure that supports knowledge production. This infrastructure is the collective

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[6] See Tassey, 2005b for a comprehensive treatment of this model, including comparisons with endogenous growth theory and alternative output/performance functions.

[7] *KE* is assumed to be largely determined by *KN*, so the rate of growth is d/dt(KE). To the extent the existing stock of proprietary knowledge influences the growth of *KE* over the technology's life cycle, the rate of growth is more appropriately 1/*KE* • d/dt(*KE*). Further, some models assume that the rate of growth of *KE* is equivalent to the rate of innovation. However, equation [1] shows that this is not the case which further complicates public policy.

effect of an industry's (or supply chain's) infratechnologies and associated standards that affect R&D efficiency. For example, the development and characterization of biomarkers and the ability to detect and interpret them in the human body greatly increases the productivity of biotechnology R&D. Similarly, the ability to accurately image biological activity and transmit the results for analysis also increases R&D efficiency. In general, the availability of such techniques increases potential economic benefits from inventive activity and thereby provides incentives to create proprietary technical knowledge. Such technical infrastructure only changes occasionally (i.e., slower than proprietary technologies). Moreover, because of their large public-good content, they often become industry standards, which themselves are only changed periodically. They therefore can be considered constant relative to the firm's R&D investment aimed at invention and then innovation (*RE* in equation [3]).[8] Thus, η_j is assumed to be a process constant over a technology life cycle in industry j.

The above model shows how industries based on radically new technologies require larger initial generic technology research expenditures. They will therefore experience lower rates of technical knowledge production for a given level of private R&D expenditures for some time. This phenomenon helps explain the S-shaped growth curve that characterizes the typical technology life cycle. In particular, a "risk spike" is created by the need for investment early in the R&D cycle in a technology platform (generic technology) that enables subsequent innovation; that is, its existence blocks private investment in innovation early in the life cycle (Tassey 2005a, 2005b, 2007).[9] In this early phase of the technology life cycle when the generic technology is immature, initial attempts at innovation through applied R&D typically fail miserably.

The exponential function in equation [3] is, in effect, a measure of the risk faced by investors at different points in the R&D cycle. When the targeted technological advance is large, as is the case for a radically new technology, the risk is also high that expenditures for developing innovations (through expanding *KE*) will fail. That is, the hump or risk spike in Figure 1 will be larger than for investment in new but less advanced technologies (for example, a next-generation generic technology, as opposed to one based on new scientific principles).

In all cases, investment in expanding the generic technology base is required to overcome the risk spike, *RS*, and allow private investments in *KE* to proceed. Such a risk profile explains why rates of innovation based on emerging technologies can languish for years, even decades. However, once the risk spike is overcome, private investment in R&D can reduce private risk, *RP*, to levels that permit commercialization.[10]

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[8] Critical measurement methods, interface specifications, etc. are typically required to be in place before substantial R&D can be conducted efficiently, but once adopted as standards they tend to remain unchanged for extended periods of time.

[9] The large size of total risk and subsequent investment barrier created at this point also has been referred to as the "valley of death".

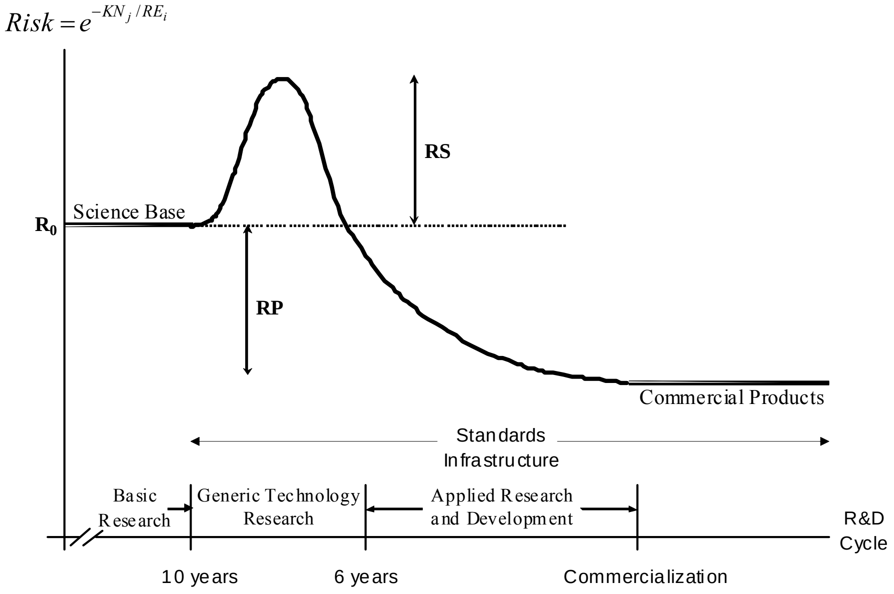
[10] More radical technologies present higher risk spikes. However, once such spikes are overcome, commercialization risk actually can be reduced to a greater extent than is the case for less radical technologies because the superior performance attributes enhance market penetration. See Tassey (2005b, 2007).

The extreme case is no generic technology ($KN = 0$). Under this condition, applied R&D has very low productivity and will likely not be attempted. Growth in the stock of technical knowledge and hence the rate of innovation is then determined by $\delta = \eta$. This case could be called the "natural rate of innovation" because it is driven solely by the general economic environment included in η. Such inventions fall into "Pasteur's quadrant"; that is, inventions that occur through trial-and-error or "inspiration" processes.[11] This source of invention is increasingly rare for today's science-driven and complex technologies.

Substituting equation [3] into [2] gives the technology production function:

$$[4] \qquad \Delta KE_i = \eta_j e^{-KN_j / RE_i} RE_i^{\lambda}$$

Equation [4] shows that the growth rate of technical knowledge is negatively related to the magnitude of initial technical and market risk associated with prospective investments in "killer apps". Thus, the efficiency parameter, η_j, is a critical factor in knowledge production because it can help compensate for the risks that companies face when deciding to commit to new technologies and/or markets.



Source: Tassey [2005a, 2005b, 2007]

FIGURE 1 Risk Reduction in the R&D Cycle

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[11] See Stokes (1997). The term "Pasteur's quadrant" refers to Louis Pasteur's invention of the vaccine, which preceded subsequent discovery of some new principles of microbiology. More recently, packet switching – the basis for computer networks including the Internet – evolved to a significant degree ahead of network theory (National Research Council, 1999).

1.3 Investment implications of the model

For corporate R&D decision making, the amount of generic technology, *KN*, and the quality of the infratechnologies and standards available to an industry directly determine the adequacy of an industry's technical infrastructure. The efficacy of this infrastructure directly affects the technical and market risk associated with R&D project selection, i.e, *RE*.

The requirement for firms to estimate both technical risk associated with market-driven attributes and market risk associated with variations in expected market demand is especially critical in the early phases of the R&D cycle. The impact is to retard private investment in the generic technology research that produces *KN*. Similarly, the unavailability of sufficient technical efficiency, η, contributes to this risk spike and, in fact, risk over the entire R&D cycle. Increasing η through better and more timely standardization improves the efficiency of research by defining and measuring interactions of specific performance attributes with the overall product technology and with complementary products in a technology systems (Tassey, 2005a, b).

Because both *KN* and η are widely and commonly used, their inadequacy in effect creates "public risk". Thus, all technology-based economies subsidize generic technology and infratechnology research (the latter providing the technical basis for standards).[12] If the risk spike is overcome by subsidizing *KN* and η, then private investment, *RE*, can sufficiently reduce aggregate (technical and market) risk to enable commercialization of new technology.

Note that the i firms in industry j draw upon the same industry-level infratechnology endowment. This is particularly the case the greater the extent of standardization. The non-excludable generic technology endowment KN_j available to each firm in an industry is also assumed to be approximately identical to the industry endowment because, by definition, the non-excludable character of this technology element and its role as a platform for innovations within the industry leads to both approximately equal access and common use by all firms in the industry.

1.4 Qualifications to the model

The model is complicated by the quasi-public-good nature of generic technologies (and infratechnologies to a lesser extent), which means that some degree of property rights can be attained and maintained by individual firms. Thus, both government and industry fund generic technology research and both private firms and universities patent generic technologies. Companies also develop infratechnologies to varying degrees (some of which contributes to industry standards). Thus, at the R&D stage, *KN* and η represent the nonproprietary segments of these two technology elements.[13]

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[12] With respect to support of generic technology research, DoD/DARPA, NIH, and NIST/ATP are examples in the United States, while the Framework Programme is the major example in the European Union. Infratechnology research is supported by national research institutes, such the US National Institute of Standards and Technology (NIST).

[13] As indicated in footnote 7, *KE* could be included as an explanatory variable in the knowledge production function and would include any proprietary segments of *KN* and η.

Therefore, the quasi-public-good character of these two technology elements and the consequent need to assimilate them from external sources means that endowments are not identical across firms, especially in the early portion of a technology's life cycle. This leads to competitive advantages both among firms within domestic industries and across competing industries in the global economy. Beyond the early phase of the technology life cycle (i.e., movement up the S-shaped performance/cost curve), competitive advantage is increasingly influenced, not only by efficiency in producing *KE*, but also by various infratechnologies that affect the production market development stages of economic growth (Tassey, 2007).

2 THE RATIONALE FOR GOVERNMENT SUPPORT OF TECHNOLOGY INFRASTRUCTURE

Policy analysis requires providing a framework to identify and characterize R&D underinvestment phenomena. If industrial technologies were homogeneous entities (i.e., the so-called "black box" model prevails), the traditional knowledge production function and output/performance models would be sufficient to inform policy makers. However, for the reasons stated here and in previous papers, the typical industrial technology must be disaggregated into the several major elements implied by equation [4]. The existence of distinctly different investment barriers is the key construct in determining government R&D support roles and is the rationale for the disaggregated model. Two of the elements have significant public-good content and hence have the characteristics of technical infrastructure.

Following the model developed in the previous section, this disaggregation is shown in Figure 2. The shading indicates the degree of public good content in each of the major elements of the typical industrial technology. The technology box is derived from an

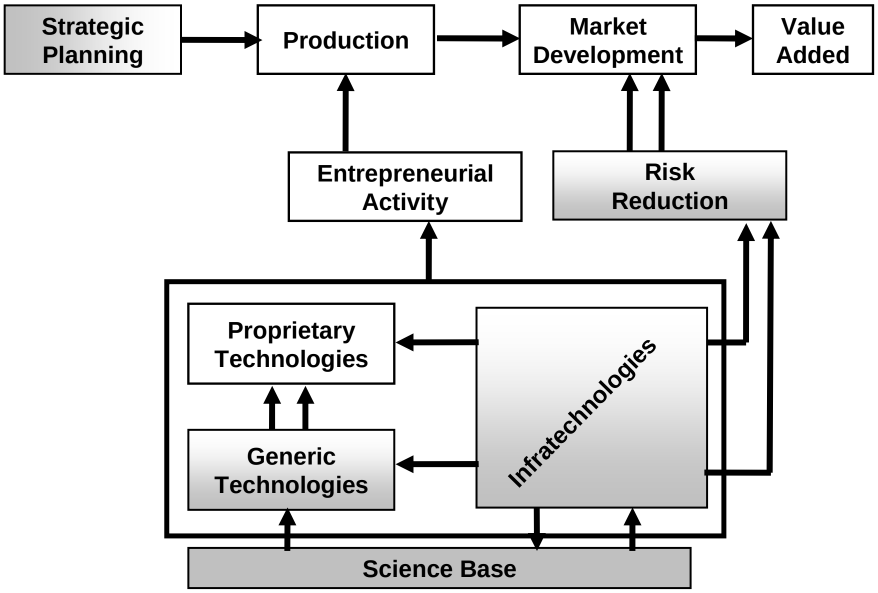

FIGURE 2 Technology-Based Industry Model

underlying science base (a pure public good). The existence of the three distinct elements comprising industrial technologies defies the notion that technologies are “black boxes”. Instead, the three technology elements shown arise from different sources in response to distinctly different investment incentives and research processes. It is the differences in investment incentives that create the need for disaggregation, which then drives policy analysis.

Specifically, an industrial technology is based on a set of fundamental or generic concepts. Although examples can be found of technologies emerging before significant proof of concept, an industry’s generic technology increasingly must evolve (basic concepts demonstrated, prototypes developed and tested) before industry is willing to commit significant funds to the more applied R&D required for market applications of the technology. This linearity in the R&D cycle occurs for two reasons. First, modern technologies are increasingly dependent on prior scientific advances. Second, the associated increase in technological complexity means that proving the overall technology concept is essential to enabling the much larger subsequent applied R&D that results in a stream of innovations.

Generic technologies are not widely recognized as an important element of industrial technology and they are not perceived as a type of technical infrastructure. However, such technology platforms have definite infrastructure characteristics. First, they are subject to substantial spillovers due to the tacit character of the knowledge created. Second, they also typically exhibit economies of scope, frequently well beyond the strategic scope of most firms. Both factors lead to underinvestment (Tassey, 2005a).

In Figure 2, the arrows convey the linear character of progressive knowledge application from basic science to generic technology development to proprietary products, processes, and services. Further, the diagram indicates that this evolutionary process (which is more complicated than shown because of feedback loops) is facilitated and in many cases made possible by a set of infratechnologies (included in η in equation [4]). As previously indicated, these tools include measurement methods for R&D and production control, technical support for interfaces between components of systems technologies, scientific and engineering databases, techniques such as quality assurance procedures, and test methods for facilitating marketplace transactions of complex technology-based products. They are ubiquitous in technology-based industries and often exert their impacts the form of industry standards. This technology element suffers from extensive spillovers. In fact, spillovers in the form of widespread use of standards are actually essential if this form of technical infrastructure is to be effective.

Which quasi-public good technology element is the target of the government research program/project determines the analytical and data collection approaches to strategic planning and retrospective impact assessment. Assuming the target has been determined by underinvestment analysis (i.e., the policy rationale has been determined), the analyst will choose an analytical framework with the appropriate set of metrics. Doing so will allow accurate determination of the nature of the prospective/retrospective technical outputs from the research, the specific outcome (economic impact) metrics to be estimated/measured, the relevant types of qualitative analyses of the impact, and summary economic role assessments that will provide feedback/justification to government managers and other stakeholders (in particular, industry and government).

3 ANALYTICAL TOOLS FOR ECONOMIC IMPACT ASSESSMENT

Pressures to conduct systematic strategic planning for and retrospective impact assessments of research projects and programs are of relatively recent vintage, so most government agencies have not acquired the internal capability to select appropriate models and impact metrics and then to develop the necessary data sources or to find contractor support with the appropriate economic assessment skills. Moreover, R&D agencies are for the most part managed by technically trained people who are unfamiliar with economic assessment tools and have difficulty understanding the imperative for such analysis or who are uncomfortable with the use and interpretation of information produced by a distinctly different discipline. And, while some universities have curricula that include impact assessment techniques, little of it is designed for government research program evaluation.

Thus, without an understanding and acceptance of the appropriate economic models, inadequate and inappropriate data are collected. Ideally, economists and policy analysts would like to estimate a fully specified performance function of the form represented by equation [1]. Doing so requires the estimation of a number of functions, including a technology production function such as equation [4]. The latter is the focus for R&D policy analysis because it shows the relationships among potential investment targets (KN, η, and RE) and the subsequent output of technical knowledge with innovation potential, KE.[14] Unfortunately, the quantity and quality of data required to drive the multi-element technology production function are not yet available.

The implication is that the policy analyst must look for a second best approach until better data are made available. An alternative, which is frequently used by many government policy groups, is to simply collect descriptive statistics through surveys. Examples would be the number of companies that (1) changed their investment behavior (say, increased generic technology research) in response to an R&D subsidy, (2) adopted an infratechnology from a government laboratory and experienced a production productivity improvement, or (3) achieved a commercialization objective in a shorter period of time due to increased R&D efficiency resulting from some combination of government-supported generic technology and infratechnology research and an integrated innovation infrastructure. Unfortunately, descriptive statistics only provide general qualitative indicators of impact and therefore do not provide cause-and-effect information. Moreover, because of their lack of specificity, the results are frequently misinterpreted. That is, the efficiency or relative effectiveness of the specific applications of a policy instrument (direct funding of R&D, tax incentives, etc.) and ultimately the general effectiveness of each instrument for different types of market failures cannot be determined with reasonable accuracy.

A second alternative is to use metrics that provide quantitative measures of an S&T policy's economic impact but for which data are more easily obtained than is the case for

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[14] Economists have focused on production functions that combine labor and capital inputs with technology assumed either to be determined outside the industry being studied or sufficiently constant to allow inclusion in the function as a shift parameter. Totally ignored is the fact that marketing function exists, the output of which combines with the technology created to determine performance in technology-based markets. See Tassey (2005b).

the parametric statistics associated with production and performance functions. Such "compromise" metrics are found in corporate finance, and, while not as potentially robust as parametric statistics, they are compatible with the project or program orientation of government R&D subsidies. If used properly and combined with qualitative assessments, they can provide policy makers with substantial information useful for managing such programs.

4 ANALYTICAL TOOLS

The following describes a set of policy analysis tools that NIST has developed, which (1) enable practical qualitative and quantitative assessments of the economic impacts of ongoing or completed technology infrastructure programs (retrospective studies) and (2) enable identification of new technologies and economic sectors that may potentially be targeted for support in the future (strategic planning studies). The NIST studies have focused on the two quasi-public-good technology elements: infratechnology research (η) conducted in NIST's laboratories and generic technology research supported by the Institute's Advanced Technology Program (KN).[15]

Selection of a framework for economic analysis of R&D projects and programs is confounded by the fact that the output of this investment does not have an explicit market (in contrast to a good or service). Moreover, the results of R&D are neither comparable across projects nor countable (Griliches, 1977). Because of such constraints, it is generally not feasible to directly estimate a knowledge production function. Therefore, selection of an analytical framework for assessing impacts of specific R&D projects frequently is determined by data availability, which results in one of the two above alternative approaches being chosen to approximate equation [1].

In applying the second methodology, the analyst would like to construct a time series of costs and economic outcomes for the affected industries that include a period before government intervention. At some point in the time series, a government-funded project (R&D and technology transfer or technical information dissemination) occurs and the subsequent portion of the time series reflects the technical and economic impacts of the intervention where this intervention affects one or more of the three stages of economic activity (R&D, production, commercialization).

The ability to effectively apply this approach depends significantly on the nature of the R&D project, as well as available data. Generic technologies are typically developed early in a technology's life cycle and hence little technology investment data are generated prior to government intervention. That is, frequently no historical time series exists to allow specification of the intervention. In fact, a major government role in most industrialized nations is to promote early life-cycle (generic) technology research through support policies such as NIST's Advanced Technology Program (ATP) or Europe's Framework Program. In contrast, because certain types of infratechnologies are needed in the middle of a technology life cycle, an increased potential exists for obtaining data on economic activity prior to the government intervention.

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[15] The economic impact assessment methodology described below is discussed in greater detail in Tassey (2003).

However, data on economic activity “before” the intervention is frequently unattainable for either type of government project. Obviously, these data are generated farther back in time than subsequent post-intervention data. Therefore, unless a real-time data collection program is implemented, sources of data degenerate and eventually disappear over time. Consequently, the longer the optimal time series the lower the quality of data obtainable in the “before” period, if it is obtainable at all. Even when an intervention can be clearly defined in the middle of a technology life cycle, the feasibility of collecting accurate data farther back in time than about six years is low in most technology-based industries.[16]

Because availability of data and other difficulties frequently preclude the construction of a time series of economic trends before government intervention, the analyst must often use a “counterfactual” technique to estimate the differential impacts of the government R&D project.[17] In the application of such a technique, industry respondents are asked a series of “what if” questions focusing on the implications of additional costs incurred by industry if the government project did not exist. This approach works well when the government project either is initiated beyond the early phases of the current technology life cycle so that some experience without the government contribution exists, or the project is an intervention in a life cycle that has similarities with related technologies, thereby allowing the respondents to extrapolate from prior experience.

The counterfactual approach has been used extensively by NIST in assessing the economic impacts of its infratechnology research programs. In many cases, a new infratechnology replaces less efficient forms used in the current or previous technology life cycles. Experience with the less efficient infrastructure being replaced or knowledge of similar infrastructure from past life cycles provides industry respondents with an ability to estimate the increased costs that would be incurred if the new infrastructure were not available.

While this approach may sound similar to the time series intervention, the counterfactual approach is a “second best” solution to characterizing costs in the period before interventions because annual cost data cannot be estimated or data collection is judged to be too difficult. As a substitute, the counterfactual approach obtains a rough estimate of annual costs in the pre-intervention period.[18]

NIST’s ATP has also used the counterfactual approach to assess the impacts of its generic technology funding on corporate R&D investment decisions. ATP economic studies use the same counterfactual technique described above for a sample of funded projects. The Program also collects descriptive statistics for all projects together through

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[16] In fact, discussions with managers in some industries put a limit of three years on collections of some types of data due to the dynamic character of their industries (mergers, acquisitions, exits, labor mobility).

[17] A frequently cited early application of the counterfactual technique is Fogel’s [1962] study of “social savings” from the emergence of railroads in the United States. Although much social research involves implicit counterfactuals, Fogel is recognized by economic historians as the first researcher to explicitly state a counterfactual as the basis for analysis.

[18] If the impact of a single project is being assessed, an unambiguous time series of costs may be available from budget records. However, program-level impact assessment typically entails several projects, some of which may have multiple objectives. Moreover, industry assimilation costs, if significant, must also be estimated. Thus, retrospective times series specification will usually be less than ideal.

broad surveys of all grant applicants as well as grant awardees. Here counterfactuals would be no R&D project, a smaller or less ambitious project, or a time delay in funding the same project.

In effect, such impact estimation techniques do not explicitly measure ΔKE, ΔKN or η. Instead, inputs (investments in these variables) are related to outcomes (Q in equation [1]).

5 SELECTION OF METRICS

This step is critical because it drives survey design and eventual impact estimates. Unfortunately, it is frequently mishandled. The general approach requires decisions about the scope and heterogeneity of the technology to be studied, what to include with respect to subsequent categories of investment necessary to achieve commercialization, and how to account for the "cost" of scrapping the existing technology.

Historically, government-funded R&D and subsequent government procurement in areas with social objectives such as national defense and energy independence have jump-started new industries or at least significantly expanded embryonic ones. Digital computers and network communications are examples. The degree to which government R&D programs facilitate the formation of new companies and an effective industry structure will determine the efficiency with which a social objective (such as better health care) is attained. Thus, useful impact assessment in virtually all cases will require economic impact metrics.

In selecting such metrics, the structure and coverage of benefits and costs is particularly important for the ultimate estimation procedure. One of the initial decisions focuses on the desirability of establishing and including a baseline of net benefits from an existing technology. For example, in studies of social rates of return from private-sector innovations, Mansfield *et al* (1977) argued that benefits (profits) to imitators should be added to benefits accruing to the innovating firm and that benefits lost to competitors supplying the old technology should be subtracted. Further, unsuccessful R&D by competing firms should be added to total costs.

These issues are mitigated somewhat for quasi-public goods such as infratechnologies. In many (but not all) cases, infratechnologies and associated industry standards are introduced at points in the technology life cycle where markets already exist. In such cases, the existing product structure is not replaced; rather, measurement of the performance of some attribute of the product or an attribute that provides an interface with other products is standardized. The resulting productivity increase can be measured as an incremental gain in an existing production process, which is, in effect, equivalent to Mansfield *et al*'s requirement to net out the residual value of obsolete technology.[19]

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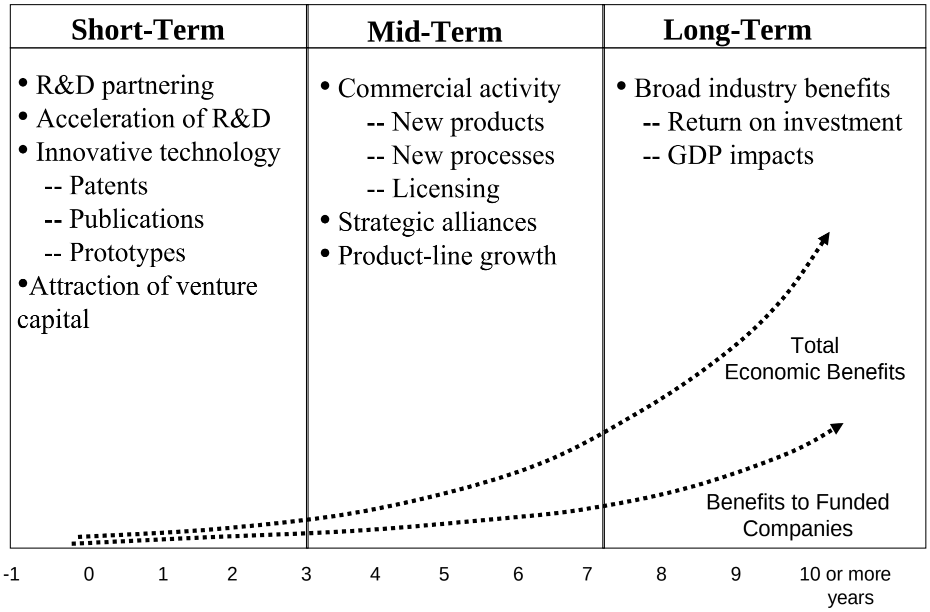
[19] If assimilating the new infratechnology results in the purchase of new equipment, for example, writing off the old equipment could be viewed as constituting a "cost".

For new generic technologies, which replace older generations as technology platforms for innovation efforts, the issue of subtracting benefits lost requires more attention. Even here, for prospective studies, at least, a capital budgeting approach would only require estimating rates of return over the study period for both the new and defender technologies from the point in time of the analysis and making an investment decision accordingly (that is, R&D and other initial investments associated with the defender technology are regarded as sunk costs and ignored in the calculation). For retrospective studies, one also can rationalize ignoring the defender technology. What really counts is the rate of return realized by the technology under study relative to an appropriate hurdle rate.



Source: Adapted from Ruegg (1999)

FIGURE 3 *Organization of Metrics by Technology Life Cycle: NIST's Advanced Technology Program*

Finally, the selection of metrics depends on the phase of the R&D program and hence the phase of the target industry's technology life cycle, as indicated in Figure 3. Conducting impact assessments with the correct metrics at various phases in the R&D program's and technology's life cycles is important to enable mid-course adjustments in management of the program. Such periodic assessments are also necessary because R&D support can take many years to reach ultimate objectives and policy officials need assurances that the program is on track.

5.1 Input (cost) metrics

All costs, private and public, should be included. Some cost data may have to be disaggregated and a portion assigned to the project under study. Specific cost categories are

- direct and indirect government research program costs: research labor, production labor (for prototypes and other transfer artifacts such as standard reference materials), overhead, equipment, and technology transfer/outreach
- industry research program costs: research labor, equipment and overhead (for independent or joint research projects), "pull" (technology assimilation) costs, including fees paid to government or universities for technology transfer and related services
- industry commercialization costs: applied R&D investment, intellectual property assignment, production scale-up, market research and workforce training costs

5.2 Output (technical knowledge) metrics

Conducting economic impact studies of government research requires the selection of performance variables that can be directly attributed to the government funded or conducted research project and that can be related to subsequent economic impacts (outcomes). Examples of output measures frequently identified are

- contributions to underlying science
- generic technology or infratechnologies developed
- intellectual property produced and its dissemination resulting from the research project, including patents or licenses in the case of generic technology and adoption of standards in the case of infratechnologies

5.3 Outcome (economic impact) metrics

Selection of specific outcome metrics depends on a number of factors, including the type of R&D targeted by the project being studied (in particular, generic technology vs. infratechnology) and the objectives of the broader research program of which the project is a part (which may include industry structure and industry growth objectives). Categories of outcome metrics frequently estimated include impacts on

- post-project assimilation/use of generic technology or infratechnology
- post-project applied R&D investment
- post-project increase in venture capital
- market access created and subsequent market entry decisions
- reductions in industry R&D cycle times (time to commercialization)
- productivity increases (R&D or production process)
- market penetration of new technology (sales and/or profits generated)
- product quality
- increase in product and system reliability
- reduction in transaction costs (equity in trade, performance verification)

Effective use of these metrics in assessments of the economic impact of technology infrastructure projects requires the selection of quantitative measures. Because of the demanding data requirements for estimating equations [3] and [4], the analyst will have to rely on corporate finance measures: net present value (NPV), benefit-cost ratio (BCR), and internal (social) rate of return (SRR). Adequate data typically can be collected from government project records (costs) and industry surveys (benefits) to enable estimation of these measures, but each has a unique set of strengths and weaknesses. The analyst should therefore estimate all three measures.[20]

6 SUMMARY

Technology infrastructure is a multifaceted and complex part of every industrial technology. Its two basic elements, generic technologies and infratechnologies, have different but profound impacts on the technology life cycle and therefore on innovation and technology-based economic growth. The model presented disaggregates the traditional knowledge production function, thereby allowing analysis of each category of technology infrastructure and their combined effect on private-sector investments in applied R&D.

The quasi-public good character of generic technologies and infratechnologies means that both industry and government will fund portions these technology elements. The assessment of private-sector investment behavior is complex. For policy analysis purposes, data and impact assessment methods must be adapted to both the appropriate economic models and the feasibility of data collection. Unfortunately, both prospective studies for strategic planning and retrospective studies for program impact evaluation must make compromises with respect to the metrics selected because of data quality issues. Nevertheless, empirical analyses to date indicate that technology infrastructure has a substantial enabling effect on private-sector R&D investment decisions and performance.

7 REFERENCES

Atkins, Peter (1994) *Physical Chemistry*. New York: W.H. Freeman and Company.

Bresnahan, T. and M. Trajtenberg (1995) General purpose technologies: ‘engines of growth’? *Journal of Econometrics*, **65**(1), 83–108.

Darby, M. and L. Zucker (2003) Grilichesian Breakthroughs: Inventions of Methods of Inventing and Firm Entry in Nanotechnology (NBER Working Paper 9825). Cambridge, MA: National Bureau of Economic Research (July).

Dosi, Giovanni (1982) Technological Paradigms and Technological Trajectories *Research Policy*, **11**, 147–62.

Dosi, Giovanni (1988) Source, Procedures, and Microeconomic Effects of Innovation *Journal of Economic Literature*, **26**(3), 1120–71.

Fogel, Robert William (1962) “A Quantitative Approach to the Study of Railroads in American Ecnomic Growth: A Report of Some Preliminary Findings” *Journal of Economic History*, **22**(2), 163–97.

Frederick, S., G. Loewenstein and T. O’Donoghue (2002) “Time Discounting and Time Preference: A Critical Review”, Journal of Economic Literature, **40**(2), 351–401.

Griliches, Zvi (1977) “Economic Problems of Measuring Returns on Research” in *Towards A Metric of Science: The Advent of Science Indicators*, Vehuda Elkana (ed.) New York: John Wiley & Sons.

Griliches, Zvi (1986) Productivity, R&D, and Basic Research at the Firm Level in the 1970’s. *American Economic Review*, **77**(1), 141–54.

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[20] See Tassey (2003) for a detailed discussion of the use of each measure and their collective utility for economic impact assessment.

Griliches, Zvi (1995) “R&D and Productivity: Econometric Results and Measurement Issues” in Paul Stoneman (ed) Handbook of the Economics of Innovation and Technological Change. Cambridge, MA, Blackwell.

Jaffe, Adam (1989) Real Effects of Academic Research. *American Economic Review*, **79**(5), 957–70.

Leech, David (2000) *The Economic Impacts of NIST Cholesterol Standards Program* (NIST Planning Report 00–4). Gaithersburg, MD: National Institute of Standards and Technology.

Leech, D. and M. Chinworth (2001), *The Economic Impacts of NIST’s Data Encryption Standard (DES) Program* (NIST Planning Report 01–2). Gaithersburg, MD: National Institute of Standards and Technology.

Leyden, D. and A. Link (1991) Why Are government and Private R&D Complements? *Applied Economics*, **23**(4), 1673–81.

Link, Albert (1981) Basic Research and Productivity Increase in Manufacturing: Additional Evidence. *American Economic Review*, **71**(4), 1111–12.

Link, A. and J. Scott (1998) *Public Accountability: Evaluating Technology-Based Institutions*. Norwell: Kluwer.

Link, A, and G. Tassey (1987) Strategies for Technology-based Competition. Lexington, MA: Lexington Books.

Link, A. and G. Tassey (1993) The Technology Infrastructure of Firms: Investments in Infratechnology *IEEE Transactions on Engineering Management*, **40**(3), 312-315

Mansfield, E., J. Rapport, A. Romeo, S. Wagner, and G. Beardsley (1977) Social and Private Rates of Return from Industrial Innovations. *Quarterly Journal of Economics*, **91**(2), 221–240.

Mansfield, Edwin (1980) Basic Research and Productivity Increase in Manufacturing. *American Economic Review*, **70**(3), 863–873.

Mansfield, Edwin (1991) Academic Research and Industrial Innovation. *Research Policy*, **20**(1), 1–12.

Nadiri, Ishaq (1993) Innovations and Technological Spillovers (NBER Working Paper No. 4423). New York: National Bureau of Economic Research (August).

National Research Council (1999) *Funding a Revolution: Government Support for Computing Research*. Washington, DC: National Academy Press.

Nelson, Richard (1959) The Simple Economics of Basic Scientific Research. *Journal of Political Economy*, **49** (2), 297–306.

Nelson, Richard (1962) The Link Between Science and Invention: The Case of the Transistor in National Bureau of Economic Research in *The Rate and Direction of Inventive Activity*. Princeton: Princeton University Press, 549–583.

Nelson, Richard (1992) What is ‘Commercial’ and What Is ‘Public’ about Technology, and What Should Be? in N. Rosenberg, R. Landau, and D. Mowery (eds.) *Technology and the Wealth of Nations*. Stanford, CA: Stanford University Press, 57–71.

Ruegg, Rosalie (1999) *Advanced Technology Program’s Approach to Technology Diffusion* (NISTR 6385). Gaithersburg, MD: National Institute of Standards and Technology (September).

Stokes, Donald (1997) *Pasteur’s Quadrant: Basic Science and Technological Innovation*, Washington, DC: Brookings Institution.

Tassey, Gregory (1997) *The Economics of R&D Policy*. Westport, CT: Greenwood Publishing Group (Quorum Books).

Tassey, Gregory (2000) Standardization in Technology-Based Markets’ in A. Link and D. Roessner (eds.) *The Economics of Technology Policy*, special issue of *Research Policy* **20**, 587–602.

Tassey, Gregory (2003) *Methods for Assessing the Economic Impacts of Government R&D* (NIST Planning Report 03-1). Gaithersburg, MD, National Institute of Standards and Technology (September) (http://www.nist.gov/director/prog-ofc/report03-1.pdf).

Tassey, Gregory (2005a) Underinvestment in Public Good Technologies *Journal of Technology Transfer*, **30**(1), special issue in honor of Edwin Mansfield, 89–113.

Tassey, Gregory (2005b) The Disaggregated Technology Production Function: A New Model of University and Corporate Research in A. N. Link and D. Siegel (eds.) *University-Based Technology Initiatives*, special issue of *Research Policy*, **34**, 287–303.

Tassey, Gregory (2007) *The Technology Imperative*. Cheltenham, UK and Northhampton, MA USA: Edward Elgar.

Tewksbury, J., M. Crandall, W. Crane (1980) Measuring the Societal Benefits of Innovation, *Science*, **209**(8), 658–662.

Toole, A.A. 1999 Public Research, Public Regulation, and Expected Profitability: The Determinants of Pharmaceutical Research and Development Investment. Stanford Institute for Economic Policy Research Working Paper, Stanford University.