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The disaggregated technology production function: A new model of university and corporate research

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Abstract

Technology and the process that produces it, research and development (R&D), are typically characterized as homogeneous entities. In reality, the typical industrial technology is composed of three elements: a generic technology base, supporting infratechnologies, and proprietary market applications (innovations). The first two have public good characteristics, and therefore, explicitly modeling them is essential for public policy purposes. The fundamental relationships among these elements require a technology production function that captures the supporting roles of the public good elements in creating proprietary applied technology. These critical quasi-public technology goods are supplied to a significant extent by exogenous (external) sources: central corporate research labs, government labs, and increasingly, universities. The expanding university role beyond basic research complicates the structure and functioning of the national R&D establishment and increases the need for a more accurate model of technological change to better inform R&D policy.

Moreover, in assessing the resulting applied technology's impact on economic growth, both the general and partial equilibrium literatures enter the technology variable into a production function with the common "production" assets (physical capital and labor). Such models obscure an important distinction between technology and these production assets—namely, the fact that technology is primarily a "demand-shifting" asset. As such, its role is correctly specified only when combined with the other major demand-shifting asset, marketing. Allocations to these two assets vary across competing firms implying a spatial model of competition, while still providing traceability to the exogenous sources of public good technology elements, such as universities.
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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, research and development (R&D), as homogeneous entities. Only a few efforts have attempted even a partial disaggregation, which have consisted of separating scientific research from technology research.

In reality, the typical industrial technology consists of several private and quasi-public elements. The failure to disaggregate the technology variable based on

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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. These limitations significantly reduce the effectiveness of R&D policy.

The policy analysis problem has become more demanding in recent years 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) government spending on such research has been erratic and highly skewed toward a few technologies tied to specific social objectives; (3) universities have assumed a larger role in such early-phase technology research, with implications for intellectual property (IP) and research portfolio management.

University conduct of early-phase technology research has become increasingly important, as it has gown substantially over the past several decades in response to a declining corporate role and the 1980 Bayh-Dole Act. This legislation enabled the assignment of IP rights to universities who conduct federally funded research, and such ownership has created large revenue opportunities. However, it has also led to disputes with industry over control of and access to the IP and relationships with spin-offs/start-up firms.[1]

At the same time, the shortening of technology life cycles due to rapidly expanding research capabilities and R&D investment in Asia and Europe have created an imperative to better understand the R&D investment process, so that public policy can better match incentives and research capabilities for the participants in each phase of the R&D cycle. The ascending role of the university in the early phases of technology research complicates the R&D establishment structure and hence the management of government funding policies.

To better understand the R&D policy requirements for dealing with such complexity, industrial technology and the degree to which existing R&D growth models are inadequate are assessed in the next three sections. A model is then developed in Section 4 for representing both public and private elements of an industrial technology in the same technology output function. Section 5 presents a framework for using such a model to describe the risk profile of the typical R&D cycle and thereby focus policy analysis. Finally, Section 6 develops a performance function in which the economic impact of technology output can be assessed in a spatial model of competition.

1. The complexity of industrial technology

Technology is far from a homogeneous "black box", as implicitly characterized in much of the economics literature. In contrast, each industrial technology should be described in terms of three major elements: a fundamental or "generic" technology base, proprietary technologies (market applications) derived from the generic technology, and a set of "infratechnologies" that facilitate the development and utilization of the other two elements.

1.1. Public good technology elements

The enabling role of generic technologies for the development of market applications (innovations) has been discussed qualitatively (Link and Tassey, 1987; Tassey, 1991, 1997, 2005; Nelson, 1992).[2] Similarly, Dosi (1982, 1988) defines a "technology paradigm", which is portrayed as a "pattern" of solutions of 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 risk sufficiently to enable applied R&D investments to be rationalized.[3]

[1] See, for example, Lerner (2005) and Mowery and Sampat (2005).

[2] A generic technology is not the same thing as a "general purpose technology" (Bresnahan and Trajtenberg, 1995). The latter refers to a (homogeneous) technology with multiple market applications (i.e., economies of scope), a distinctly different concept from the generic base upon which a particular technology 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 could be used to construct a semiconductor switch or amplifier, resulting in the creation of the transistor (Nelson, 1962). The best known example 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 rout-

Infratechnologies are the other quasi-public technology good. They have a strong infrastructure and hence public good character. Infratechnologies include research tools (measurement and test methods), scientific and engineering data, the technical bases for interface standards, quality control techniques, etc. Collectively, they constitute the technical infrastructure of an industry and are ubiquitous across technology-based economic activity. Infratechnologies often are implemented as industry standards (Tassey, 1982, 1997).[4]

Both generic technology and infratechnology elements are drawn upon by competing firms. However, although attainment of partial property rights is possible, spillovers and other sources of market failure are prominent. The resulting underinvestment varies across technologies and over each technology's life cycle, which complicates public policy responses. Nevertheless, every industrialized nation provides funds to leverage generic technology and infratechnology research and assimilation, thereby underscoring recognition of the public good content, even though identifying and measuring this content remains difficult (Tassey, 2005).[5]

Several decades of economic studies have attempted to provide the needed explanatory models. At the national economy level, theories of endogenous technological change (Romer, 1990) have acknowledged the existence of excludable and non-excludable (public good) elements of the typical stock of technology. Microeconomic models have partially revealed the heterogeneous nature of the typical industrial technology and related them to various output measures (Griliches, 1995). However, the few efforts at disaggregation have focused exclusively on the distinction between scientific research and applied R&D.

1.2. Technology trajectories and life cycles

In addition to assessments of static representations of industrial technology, the analyst must also be concerned with the dynamics of technology-based growth (i.e., the process of creative destruction). Here, the literature has characterized technological change by "trajectories" or directions of market applications (Nelson and Winter, 1982; Dosi, 1982, 1988; Achilladelis and Antonakis, 2001). The implication is that the nature of the underlying generic technology and the subsequent evolution of a supporting infrastructure (infratechnologies) combine to determine the direction of subsequent market applications, which is often assumed to be linear for some time into the future.

However, portraying these trajectories as linear, steady-state expansion paths of a homogeneous technology is incomplete. Rather than linear, such trajectories display cyclical patterns, which are reflected in shifts in the composition of R&D over time in response to the evolving generic technology and its eventual obsolescence. Technological opportunity therefore also changes. Disruptive technologies, based on radically new generic technologies, spawn cascades of more incremental advances as firms enter the nascent industries to apply the generic technology and achieve economies of scale and scope. The early part of a technology's life cycle is correctly portrayed as being characterized by high risk but also increasing returns (at least at the industry level), as the proof-of-concept effect (i.e., the generic technology) unleashes market applications.[6]

ing. 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, p. 169). 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).

[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 (electricity, transportation, and communications) whose primary role is to provide services to other industries.

[5] The National Science Foundation disaggregates R&D data into "basic research", "applied research", and "development". Unfortunately, this taxonomy only partially captures the quasi-public good character of the several targeted elements of R&D. The reason seems to be that the U.S. and other national classification systems somewhat arbitrarily define the phases of R&D, instead of first defining the intrinsic targeted elements of industrial technology based on unique investment incentives and then defining the process phases that produce these targeted elements.

[6] The technology life cycle based on a generic technology, which is the focus here, is typically one cycle within a longer "technology wave" driven by periodic major advances in science (Kondratiev, 1925; Kuhn, 1962; Freeman, 1973; Graham and Senge, 1980). For example, advances in solid state physics led to a wave of generic digital electronic technologies. In the other direction, a technology trajectory or life cycle of a generic technology is characterized by successive product cycles (Utterback, 1979). For example, a PC is a product cycle within a generic digital computing trajectory.

Within the generic technology's life cycle, major technological opportunities decline over time as the set of potential applications of the underlying knowledge base is exhausted. Competition then shifts to incremental product improvements tied to shorter times to commercialization and to process innovations that focus on reducing cost as the basis of competition. However, while such an evolutionary pattern might imply decreasing returns to the original stock of generic technology after the initial market penetration, a successful technology achieves substantial efficiencies, such as economies of scale in production and distribution, economies of scope in markets penetrated, evolution of efficiency-enhancing infratechnologies and associated standards, and general learning economies. These factors leverage returns to incremental improvements and thereby delay the onset of decreasing returns.

1.3. Implications for a new model

Several concepts relevant for model development emerge from this discussion: (1) the typical technology consists of several discrete elements that respond to distinctly different investment incentives; (2) the elements interact over a technology's life cycle to influence individual firms' and entire industries' growth paths; (3) the technology elements exhibit different degrees of public good content, which has significance for investment behavior and hence for the sources of funding and conduct of various types of R&D. Therefore, to better understand how technology drives growth within this life cycle context and the complementary roles of industry, universities, and government, a more disaggregated view of technology and its evolutionary impact on economic growth is necessary. The next section assesses the characterization of technology in several alternative technology-based growth models.

2. Defining the technology variable

At the macroeconomic level, Solow's (1956) model defined a steady-state growth path for an economy in terms of an optimal capital–labor ratio determined by an exogenous stock of technology. For more than three decades, this model governed economic growth analysis, until important articles by Romer (1990) and Jones (1995, 2002) turned the role of technology completely around by making the stock of technology endogenous to an economy's production function.

If the supply of technology is completely exogenous to an economic system, as in Solow-type growth models, its source is presumably government, with the implication that technology is a pure (and homogeneous) public good. Such models show how an equilibrium capital–labor ratio is attained and how a steady-state growth path based on an implied level of technology is determined. The introduction of additional technology (embodied in capital) will increase the equilibrium capital–labor ratio over time.

However, the source of the technology and the process by which it increases productivity are not specified. Hence, R&D investment incentives cannot be considered. Conversely, endogenous growth theory treats technology as completely determined within the private economy, implying a purely endogenous research and development decision process. While the latter theory allows for spillovers among private economic agents, no interaction among donors and recipients of technology capital is specified.

Reality is a combination of the two models. That is, in the modern "mixed" economy, investments are made by both the public and private sectors, resulting in a stock of technology that has a "quasi-public" good character. The problem is to separate the private and quasi-public technology elements according to unique sets of investment incentives and define their economic functions.

The investment incentives dimension is becoming increasingly important for public policy. Companies obviously invest in applied technology from which they can sufficiently exclude others by using patents, secrecy, and other appropriation mechanisms. Many firms and increasingly universities invest in partially excludable generic technology, which they expect will diffuse or spillover to some degree and at some rate but yet still allow some degree of property rights to be maintained.[7]

[7] A rationale for this strategy is the fact that the rate of spillover is neither instantaneous nor costless. For example, Mansfield et al. (1981) estimate from survey data that imitating an innovation by another firm could cost as much as 50–75% of the cost of that innovation. Nelson (1992) observes, based on empirical studies of strategies for appropriating the results of R&D in Levin et al. (1987),

However, such next generation and especially radical technology research has become increasingly difficult for individual companies to rationalize. The main impact of spillovers is a lower expected return on investment (ROI), including reduced potential for the increasing returns benefit for first movers put forth by Arrow (1962) and others. In companies, generic technology research usually takes place in a central corporate research lab, which provides proof-of-concepts (generic technologies) to the firm's line-of-business units, which then conduct applied R&D leading to market innovations. Central research budgets have been reduced relative to line-of-business budgets in recent years. Even this trend probably understates the reduction in private sector investment in generic technologies, as many firms now use researchers in their central labs to assimilate generic technologies from external sources; i.e., they create inward spillovers from other company, government, or university sources, as opposed to actually conducting breakthrough research.

As a partial substitute, universities are increasingly conducting generic technology research as they receive more funding from both industry and government sources. This funding is designed to compensate for the relatively high risk of early-phase technology research and the substantial spillovers that characterize the research results. As universities can now own the IP from government-funded research, patents from new generic technologies can provide a significant source of income. Moreover, many state universities have been pushed in the direction of generic technology research by state governments as part of economic development strategies.

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 exogenous sources of supply acknowledged. However, technological knowledge is assumed to be a purely private good, even taking spillovers into account.[8]

that letting generic technology spillover does not provide a disincentive to conduct the research because "first mover" strategies allow market applications to gain market share and thereby provide an above-hurdle-rate return.

3. Alternative technology production functions

3.1. Endogenous growth models

In all endogenous growth models, private investments in R&D are undertaken to create technology and thereby improve or maintain competitive position. In the macroeconomic arena, Romer (1990) distinguishes between "rival" and "non-rival" elements of technology in his general equilibrium growth model. The rival (excludable) component of technology is that portion embodied in human production capital H_Q. The non-rival component K (presumably disembodied with respect to any specific factor of economic activity) is viewed as partially excludable.[9]

In such a model, the traditional output function, based on the interaction between physical capital C_Q and human production capital H_Q, is modified to reflect the fact that the stock of rival technical knowledge embodied in H_Q "interacts" with the stock of non-rival technology K and then with C_Q to determine an output Q, as shown in Eq. (1):

$$Q = C_Q^{1-\alpha}(KH_Q)^{\alpha} \quad (1)$$

This specification requires a technology output function:

$$\dot{K} = \bar{\delta}H_K \quad (2)$$

[8] 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; Toole, 1999).

[9] Romer uses the public finance literature's two main attributes of any economic good: the degree to which it is rivalrous and the degree to which it is excludable (Cornes and Sandler, 1986). The rivalrous nature of a good is the degree to which use by one economic agent (individual or firm) limits its use by another. Excludability is the degree to which one agent can prevent another from using a good. Microeconomists characterize the inability to exclude use of technology by others as resulting in "spillovers" (Griliches, 1991; Jaffe, 1998).

where H_K is the human research capital and $\bar{\delta}$ is the research productivity.[10] The technology creation process is characterized as the application of rival human research capital to create non-rival, partially excludable technology goods (new "designs").

Jones (1995) modified Romer's functional form to allow variation in scale effects due to differences in the productivity of the existing stock of technical knowledge and R&D. This is accomplished by first representing the productivity parameter as

$$\bar{\delta} = \delta K^{\phi} \tag{3}$$

where $\phi < 0$ is diminishing returns, $\phi > 0$ is increasing returns, and $\phi = 0$ is the constant returns case, and then substituting in Eq. (2) to get

$$\dot{K} = \delta H_K^{\gamma} K^{\phi} \tag{4}$$

where γ allows for inefficiencies in the use of human research capital, namely duplication of effort, and has values in the range $0 < \gamma \leq 1$. For $\gamma = 1$ and $\phi = 0$, this equation reduces to the Romer growth model (fixed efficiency of human research capital and constant returns to the scale for the stock of available technical knowledge).[11]

Although such models catch up to several decades of microeconomic research in which technology is endogenous to company or industry growth models, they also specify a separate technology production function with several distinct inputs and at least imply a relationship among these inputs. However, while these models also characterize elements of technical knowledge as rival and non-rival and, more importantly, as excludable and non-excludable (or, partially excludable), they fail to relate these characteristics to the inputs in the technology production function.

Specifically, such models do not address the long-standing need to disaggregate technical knowledge into public and private elements according to the existence of different investment incentives. Thus, while the output of the technology production function is characterized by Romer as "new designs", implying proprietary (excludable) technology, this output is also characterized as "partially excludable", implying that generic technical knowledge is simultaneously produced and is a byproduct of the technology production process.

This approach contradicts the well-documented ordering of the R&D process in which early-phase "proof-of-concept" research, exhibiting low excludability, nevertheless precedes the development of proprietary "designs" (i.e., innovations). The latter are the output of later-phase applied R&D and can legitimately be thought of as entering directly into a production function.

Thus, the distinct phases of R&D, which respond to different investment incentives and thereby require different sources of funding (government, industry) and different performers (government, industry, universities), are not addressed by such models. That is, although scale effects imply the possibility of a life cycle character to knowledge creation and partial excludability implies the possibility of public and private good elements, neither characteristic can be represented without some further disaggregation of the technology production function and a realignment of the interactions among technology elements.

3.2. Microeconomic approaches

Research on the economics of technological change has been conducted by microeconomists for decades, but technical knowledge production has remained characterized for the most part as resulting simply from a set of lagged R&D expenditures (Griliches (1986):

$$K_t = \sum_i w_i R_{t-i} \tag{5}$$

Obviously, the specification of the desired function becomes complex when several elements with different degrees of excludability are taken into account. Multiple categories of knowledge need to be identified and interrelationships (directions of knowledge flows) specified. Within an industry, spillovers occur from one firm to another, among a consortium of firms acting collectively, or to all firms from a source exogenous to the industry (government or universities). Non-excludable

[10] Of course, additions to the stock of knowledge result from investments in both human research capital, H_K, and physical research capital, C_K. Including both major factors of knowledge production would change Eq. (2) to $\dot{K} = \bar{\delta}(C_K H_K)$. In microeconomic models, technology is assumed to be produced by an R&D investment involving both research labor and research capital in fixed proportion.

[11] Note that in the constant returns-to-scale case, the growth rate of knowledge is independent of the stock of knowledge, depending solely on the growth rate of the R&D labor force.

technology thus moves into and out of firms and into the industry as a whole from external sources.

A few examples can be found of partial disaggregation of the technology variable. Mansfield (1980) and Griliches (1986) hint at a distinction between endogenous and exogenous sources of knowledge by including a variable e^{λ} in their production functions, which Griliches calls "disembodied external technical change":

$$Q_t = Ae^{\lambda t} K_t^{\alpha} C_t^{\beta} L_t^{1-\beta} \quad (6)$$

Griliches (1979) also briefly mentions a generalized production function of the form $F(K_N, K_E, X)$, where excludable technology, K_E, is accumulated intentionally and non-excludable technology, K_N, is created as "a side effect" of producing K_E.[12]

3.3. Specifying the public and private good technology elements

Given this limited treatment of the public good content of industrial technology and associated investment incentives and the incorrect characterization of K_N as a side effect of producing K_E, existing definitions of excludable and non-excludable technology and the relationships with their respective exogenous or endogenous sources need to be specified based on four themes:

(1) Market applications (innovations) are derived from a largely excludable stock of knowledge K_E. This stock, in turn, derives from a generic technology base or "technology platform" K_N, which is only partially excludable.
(2) Firms use both K_N and K_E to compete. However, whereas K_E is endogenous to the firm, K_N is at least partly exogenous to the firm and frequently the entire industry, often originating in universities or government laboratories. Thus, if anything, inward spillovers of K_N may dominate, a phenomenon not considered in the microeconomics literature, but one that is increasingly important in global technology-based markets and underscores the increasing role of universities.
(3) While the non-excludable portion of technology has been regarded by economists as a spillover from investment in K_E, K_N is generally a necessary precursor for the majority of investments in K_E.
(4) Technology-based growth cannot take place rapidly or over sustained periods of time without investment in an elaborate technical infrastructure, η, composed of a set of infratechnologies that leverage the productivity of both developing and using K_E and K_N.

3.4. Investment incentives and risks

The above themes imply a model in which the interactions among K_E, K_N, and η are not simply one of complementarity among endogenous variables. Further, the dependency of K_E on K_N implies linearity with respect to the R&D process, a concept that may appear to contradict a portion of the innovation literature.[13] Specifically, in contrast to Griliches' characterization of K_N as a side effect of producing K_E, companies need access to K_N early in a technology's life cycle as a means of entry or life cycle transition.

The more free riding that takes place, the less incentive individual firms have to invest in the quasi-public good technology elements (generic technologies and infratechnologies). At some level of spillovers, all or most private investment in K_N is suppressed. Expanding global competition in R&D-intensive industries tends to increase spillovers, simply because the existence of more scientists and engineers and global R&D funding increases the aggregate capacity to absorb new technical knowledge. Complex partnerships of public and private institutions are evolving to emphasize inward spillovers (i.e., absorption of somebody else's K_N). This fact supports the proposition that K_N is not a "side effect" of firm-level R&D, but a critical

[12] Nelson (1992) mentions the same relationship.

[13] For example, Klein and Rosenberg (1986) argue that the innovation process is not a simple linear phenomenon. Rather, it involves syntheses across technologies ("chain-link" model) and feedback loops during a typical technology life cycle. Moreover, examples can be found of important technologies that evolved ahead of the discovery of the fundamental or generic technology base. However, the vast majority of modern technologies display a linear evolutionary life cycle, albeit as a series of repeated or "nested" cycles (Tassey, 2004, 2005). Similarly, Freeman et al. (1982) provide case studies, which show that successive waves of product innovations depend on prior development of an underlying science base.

technology asset that must be available to enable the remainder of the R&D cycle.

Furthermore, the shortening of technology life cycles in recent decades raises the risk adjustment firms make to ROI estimates for R&D, especially long-term, high-risk research. The higher time and risk discount factors lead to greater underinvestment at the corporate level in generic technology research and increases the need for external sources of K_N.[14]

In summary, investments in R&D take place at the firm level for K_E and at several levels (firm, industry, and government) for K_N. This is the case because of the quasi-public good nature of K_N. That is, it is partially excludable and hence subject to free riding. Moreover, the generic character of K_N implies scope economies as well as non-excludability, both of which are attributes of public goods. This fact, in turn, implies the need for exogenous sources such as universities in an efficient national innovation structure. Correctly modeling the process of technological change therefore requires the inclusion of both private and public good elements in the technology production function.

4. A disaggregated technology production function

4.1. The technology production function

The preceding conceptual framework argues that much of the investment in K_N occurs prior to investment in K_E. Specifically, the results of investment in K_N accumulate as a generic technology or technology platform, which drives applied R&D for specific market applications. A significant portion of K_N must be available in the early part of a technology's life cycle to provide the basis for the applied R&D, which creates K_E. The more robust is K_N and the more easily it is accessed, the greater is the productivity of a firm's applied R&D in producing K_E.[15]

Another important attribute of the disaggregated model is the fact that a firm's R&D productivity is leveraged by the availability of an infrastructure consisting of a set of technical tools, databases, and specifications, which frequently become industry standards. These infratechnologies often do not arise from K_N and may have applicability across a number of related industries. The R&D, process, and marketing productivities of the typical technology-based industry depend on hundreds of infratechnologies and associated standards.

Thus, an investment-based model of innovation and its impact on economic growth must represent the productivity of private sector applied R&D in terms of both private and public sector expenditures that precede it and also the contributions of the supporting innovation infrastructure. The generalized form of such a model is

$$Q = S_N F(K_N, K_E, X) \tag{7}$$

where S_N is the science base from which generic technology is derived and is assumed to be fixed, based on the concept of long-term technology life cycles or "waves" spawned by periodic bursts of scientific discovery. X is a set of factors that affect output/performance in addition to the non-proprietary and proprietary technology elements.[16]

At any point in time, technical output is equivalent to the growth in the stock of proprietary (excludable) technology, K_E, represented by

$$\dot{K}_E = \delta R_E^{\lambda} \tag{8}$$

where R_E is applied R&D expenditures targeted at developing excludable technology (innovations) and δ is an R&D productivity factor.[17] In production functions, scale parameters are assumed constant. Here, the scale parameter λ is affected by the internal organization and management of the firm and by the overall productivity of an economy's education and technical infrastructures. These factors change very slowly, so assuming λ to be constant is reasonable.

[14] This leads to risk pooling strategies, such as participation in research consortia with universities and government research institutes who subsidize and/or perform this type of research. All industrialized nations support research consortia, implicitly recognizing the quasi-public good character of technology development.

[15] Although not explicitly addressed in this model, feedback loops exist. In concert with the learning-by-doing literature, advancing K_E and subsequent production and marketing experiences feed back to stimulate directions in applied R&D that produces additional K_E.

[16] The contents of X are largely ignored by the economics of technological change literature. However, the fact that technology affects both the composition and the rate of the output of an industry in a cyclical manner suggests that other factors are important in managing the technology life cycle (see Section 6).

[17] Technical output is assumed to be identical to or at least perfectly correlated with innovative output.

δ is a key distinguishing element of this model. In technology production functions, where K is treated as a homogeneous entity, the rate of growth in K is a function of the current stock of knowledge (Eq. (4)). In the disaggregated model, however, K_E is a function of available K_N and this relationship is expressed through the productivity parameter.[18] For an individual technology, δ is determined by the available stock of K_N relative to a target rate of investment in innovation enabled by K_N:

$$\delta = \eta e^{-K_N/R_E} \tag{9}$$

where η represents the set of infratechnologies that leverage the efficiency of R&D. Change in this infrastructure occurs more slowly than does K_E and such change tends to occur early in the innovation process.[19] Thus, a reasonable approximation is to assume η is a process constant over the R&D cycle.[20]

Substituting Eq. (9) into (8) gives the technology production function:

$$\dot{K}_E = \eta e^{-K_N/R_E} R_E^{\lambda} \tag{10}$$

K_N is assumed to be available to all firms in an industry, although in reality it will not be accessible in equal amounts across firms. K_N thus serves as a measure of innovation opportunity for individual firms, which they draw upon in producing stocks of proprietary (excludable) technology, K_E. The negative sign on K_N may be counterintuitive, but a generic or platform technology is of value to the firm only as a facilitator of the applied R&D that produces K_E. K_N is essential to reduce technical and market risk to levels that allow conventional corporate R&D investment criteria to be applied. The less developed is K_N, the more inefficient are attempts at market applications through applied R&D (i.e., the productivity of applied R&D is reduced and the risk associated with a given R&D expenditure is increased).[21]

Empirical testing of Eq. (10) will require confronting the typically difficult problem of estimating stocks. Quantifying K_N for purposes of empirical analysis is a particularly difficult challenge due to the substantial spillovers. However, approximations are possible. For a larger firm with an annual budget for its central research laboratory, as well as for applied R&D conducted by its lines of business, the ratio of the two budgets can be a surrogate for that firm's overall technology strategy. Eq. (9) can then be thought of as an average productivity for the firm's overall R&D investment.[22] This approach implies a constant adjustment to K_N from generic technology research, R_N, for the firm's portfolio of research projects.[23] Under these assumptions, (9) can be modified to give

$$\delta = \eta e^{-R_N/R_E} \tag{11}$$

Not only will this assumption facilitate empirical work, but it may be better than attempting to correct flows by some arbitrary percentage asserted to represent obsolescence of technology in an economic sense.

18 Thus, the rate of growth of K_E is not directly dependent on the existing stock of excludable technology, as in some other knowledge production functions (for example, Jones, 1995). This is because K_E is more directly a function of K_N.

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

20 This representation has an analog in physical chemistry. Combining reactants to produce a new chemical entity requires an "activation energy" to initiate the reaction process (in this model, the activation energy is the enabling generic technology research expenditures, K_N). The chemical reaction itself proceeds at a specific (target) thermal energy (applied R&D expenditures, R_E). See, for example, Atkins (1994).

21 This proposition is complicated by the fact that some (mostly large) firms conduct generic technology research in "central" or "corporate" research labs. The results of this research are transferred to the applied R&D operations in the company's lines of business. The research objectives and the R&D project selection criteria are distinctly different for the central lab and the line-of-business labs, and management of the two types of research are organizationally separate (Buderi, 2000). Thus, the generic technology produced by the central lab is in effect exogenous to the operations of the lines of business. Of course, such generic technology leaks more slowly to other firms than if it were produced by a source outside a single firm (industry consortium, university, government laboratory, etc.). Hence, the excludability of specific additions to an industry's K_N will vary over time and across firms. In any case, the spillover rate will be higher than for K_E.

22 This assumption of continuous R_N is even more justified for interindustry analyses.

23 A number of large companies set the budgets of their central research labs as a percentage of total R&D expenditures. However, the content of "corporate research" varies from one firm to another, thereby weakening comparisons across firms. See Buderi (2000).

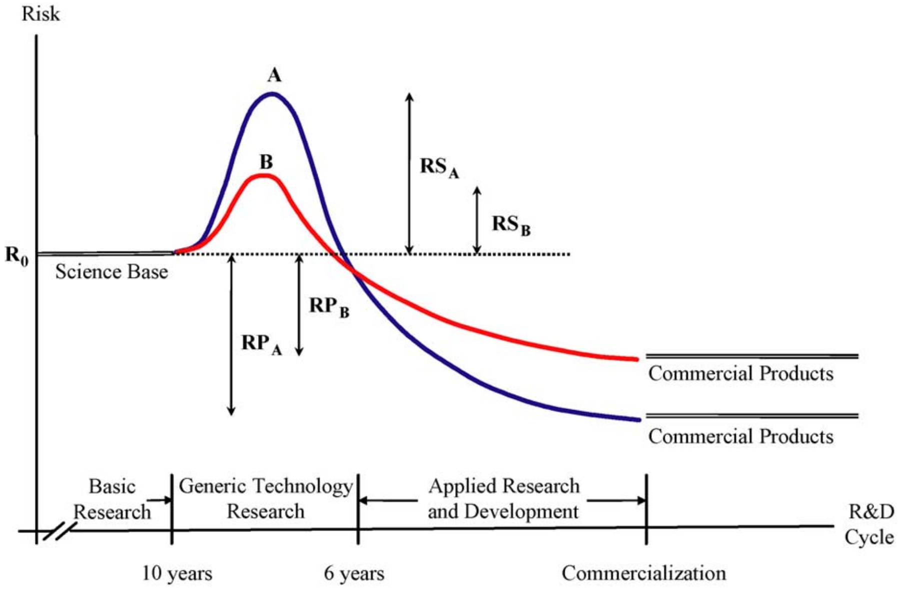

Fig. 1. Risk reduction in the R&D process.

5. Risk reduction over the R&D cycle

5.1. Types of risk

For corporate R&D decision making, the amount of generic technology available directly affects the risk associated with R&D project selection; i.e., the targeted rate of change in K_E. The relationship between K_N and K_E from an investment incentive perspective is depicted in Fig. 1. At an early point in the R&D cycle, the decision making process faces a pure "technical" risk, R_0, that summarizes estimates of the probability that a technology can be developed from the body of scientific knowledge (i.e., can be shown to work in some generic sense). In addition, the characteristic that distinguishes technology research from scientific research is the fact that the ultimate intent is commercialization. Thus, an additional amount of technical risk must be estimated and added to R_0 because the scientific principles presented now have to be proven capable of conversion into specific technological forms with specific performance attributes that meet specific market needs.

A "market" risk also must be estimated to allow for the significant probability that, even with technical success, demand for the new technology will be overestimated or that market penetration will be slower than projected due to a number of possible barriers (Tassey, 2005). Either of these potential occurrences will lower estimated ROI, so a market risk estimate must be added to the projected technical risk.

5.2. The "risk spike"

The hump in the investment risk curve therefore represents the fact that technology research, with its ultimate objective of market applications, encounters an initial major increase in risk associated with the target ROI from commercialization. This additional risk, RS, occurs in the early phases of technology research and acts as a substantial barrier to private investment in later-phase applied R&D.

Fig. 1 shows this pattern of risk over the R&D cycle for two hypothetical technology risk profiles, A and B. The combined increases in technical risk and market risk are represented by RS_A or RS_B, respectively. Such "risk spikes" might be thought of as the "public (or social) component" of total risk because they occur in the early generic technology research phase, which has the public good dimension described earlier. Technology A is the more radical innovation and thus presents a greater initial risk spike, RS_A. Eliminating the risk spike requires K_N.

Without the risk spike, firms would be faced only with a reduction in the "private risk" component, RP. In this situation, conventional R&D investment criteria would target K_E and deal with RP because it falls within acceptable reward–risk ratios. Thus, if at the level of pure technical risk, R_0, application of conventional corporate R&D criteria would result in private investment based on risk-adjusted ROI estimates for K_E, the policy problem is to overcome the risk spike so that corporate investment criteria can be applied at R_0.

The importance of overcoming the risk spike for the more radical Technology A is underscored by the fact that overall risk can actually decline to a lower level than that for Technology B. This occurs because, if Technology A is successfully developed, the resulting set of market applications will likely have a larger collective value than B (reduces market risk to a greater degree). This is depicted in Fig. 1 by a greater decline in private risk for Technology A, RP_A.

Understanding the evolution of and the interaction between technical and market risk and the consequent impacts on private sector investment must be a key element of R&D policy analysis. However, neither economic models nor current R&D policy completely recognizes the large discontinuity in the total risk reduction process. If it did not occur, the gradual slope of the curve in Fig. 1 would support proponents of no government support for R&D beyond basic science.[24]

Consideration of the risk discontinuity aside, the slope of the risk reduction curve varies depending on a number of R&D efficiency factors. An important one is the availability of a range of infratechnologies. Such technical infrastructure has a strong public good character resulting in underinvestment by industry. Infratechnologies and associated standards are ubiquitous across technology-based economic activity. This characteristic decreases their visibility and increases difficulties in impact assessment, leading to substantial underinvestment.

[24] The fact that all industrialized nations have government programs that fund generic technology research in industry and universities indicates a general recognition of the existence of the risk spike. However, the lack of a consensus model of R&D investment and subsequent empirical analysis to support decision making leads to uncertainty on the part of policy makers and thus underfunding of generic technology research, as exemplified by the history of NIST's Advanced Technology Program.

5.3. Policy implications

Analysis of investment in K_N is complicated by this technology element's quasi-public good content and the high technical and market risk associated with more radical and longer term technology research. Because this research has an ultimate market objective (in contrast to basic research), several risk factors must be added to the investment criteria. The higher the risk spike associated with the initiation of technology research, the lower is the projected R&D productivity δ and the subsequent rate of growth in technology K_E. Thus, the unavailability of K_N is a barrier to the conduct of proprietary (private) research and should be thought of in terms of the risk its absence imposes on subsequent applied R&D decision making.

From a public policy perspective, a decline in K_N investment increases the risk of failure to be competitive in the next generation or radically new technology. Thus, one major policy concern is technological opportunity, as represented by an industry's stock of generic technology. As indicated by the negative sign on K_N in Eq. (9), the technology platform upon which an industry's existence is based represents a threshold level of generic technical knowledge that must be available and accessed to enable positive investment decisions with respect to applied R&D.

The second policy concern is the adequacy of the supporting technology infrastructure, η, which drives the efficiency of the overall R&D process. Infratechnologies are individually small but ubiquitous in most high-tech industries. Thus, their aggregate economic impact is substantial.[25] However, their small individual size, public good character (most are eventually adopted as standards), and the fact that they derive from different generic technologies than do the core industry technologies combine to create substantial underinvestment.

A third concern is the shifting nature of the policy response mechanisms. Ideological conflicts and inadequate R&D investment models based on market failure analysis contribute to poor research portfolio management by both government and industry (Tassey, 2005).

[25] The semiconductor industry, for example, spends billions of dollars per year on measurement. Individual measurement infratechnologies are used in the R&D, production, and market transaction stages of economic activity. See, for example, Finan (1998).

The university role has been shifting for several decades as a partial response to these problems. Two traditional roles of the university have been to produce scientific knowledge and human research capital (H_K). The portion of this human research capital that stays within the university sector of the R&D establishment is increasingly focusing on the conduct of R_N. This shift in research composition is evidenced by the explosion in university patents since Bayh-Dole and has led to conflicts with industry over access to this generic technology.[26]

6. A technology-based performance function

6.1. Production versus performance functions

A critical issue for the economics of technological change is the selection of an appropriate performance model in which the impact of the output of the technology production function can be analyzed. The correct performance function should both accurately represent the strategic role of technology; in particular, distinguish between the proprietary and public good technology elements.

However, the vast majority of the innovation literature treats technology as an independent and largely self-sufficient demand-shifting asset. That is, an implied assumption is that the life cycle resulting from the emergence of a new technology paradigm and the subsequent succession of market applications (innovations and subsequent product life cycles) is accurately represented by a single-strategy framework based on overcoming technical risk (i.e., through the conduct of R&D). This assumption is implicit in the many models of technology-based growth that combine technology with the major production assets, capital, and labor.[27]

Within this framework, endogenous growth theory, both macroeconomic and microeconomic, attempts to explain technology-based growth by modifying the traditional production function. Both a "state of technology" represented by a shift parameter[28] and an explicit technology variable can be added to capital and labor inputs in the traditional production function to represent the impact of technological change.

However, a production function, which explains output based on complementary technical relationships among physical, human, and technological inputs, can at best only partially reflects the strategic role of technology investment. In fact, a fundamental way, reliance on such a vague set of complementary relationships confuses analysis of this role.

Resolution of these issues, especially to emphasize technology's creative destruction role may benefit from focusing more on technology's ultimate economic role, which is to shift demand through either (1) the introduction of new products and services—a product attribute strategy or (2) cost-reducing process innovations—a price reduction strategy.

Therefore, the output of the technology production function should become an input into a *performance* function, which emphasizes the fact that a firm's strategy is to shift demand in its favor through enhanced products and services or through process improvements that reduce cost and hence price. That is, if assessing the impact of technology in determining relative performance among firms in a given industry (or among industries) is the objective, then the performance function should emphasize the roles of demand-shifting investments.

6.2. The demand-shifting roles of technology and marketing

A major shortcoming of the production function approach is the fact that technology cannot shift demand by itself.[29] In his review of the microeconomics of innovation, Dosi (1988, p. 1152) observes that "after allowing for the effect of firm size, one still generally observes a substantial unexplained interfirm, intrasectoral variance, in terms of both R&D investments and, even more so, innovative output". This observation results from the fact that, unlike the business literature,

26 The large increase in university patents since 1980 demonstrates that the results of R_N are sufficiently excludable to convey considerable IP to universities and that government funding of much of this research compensates for the loss of the remaining IP from spillovers. See Mowery and Sampat (2005).

27 Economists have identified different innovation strategies among firms in the same industry: innovator, fast follower, "wait and see" (Dosi, 1988).

28 See, for example, Grossman and Helpman (1994).

29 That is, the saying "build a better mousetrap and the world will beat a path to your door" is inaccurate.

only a small number of economic studies have recognized that the cyclical pattern of creative destruction depends on marketing strategies as well as technology strategies.

Freeman (1973) conducted an exhaustive study of numerous elements affecting the success and failure of industrial innovations. His results emphasized the role of marketing (including market research) as well as a firm's technical capabilities. Levin et al. (1987, p. 33) found that for most industries lead times and technological progress (learning curve effects) combined with marketing appear to be the "principle mechanisms of appropriating returns for product innovations". Particularly relevant for the model developed here is a longitudinal study of 12 R&D firms by O'Conner and Ayers (2005) that demonstrates the integration of technology and market planning by high-tech firms in the early phases of attempts at radical innovations.

The shortcomings of models that ignore complementary roles of technology and marketing are evidenced at all phases of the technology life cycle, but especially for small, innovative firms, including spin-offs from university research. The latter are frequently technology rich and marketing poor, resulting in the need to give up equity or even the entire company to acquire marketing expertise.

6.3. *A demand-shifting model of economic performance*

The process of creative destruction (i.e., the initiation of the technology life cycle) begins with initial endowments of generic technology and marketing assets. Each firm entering the young industry undertakes a process of asset accumulation and learning in response to its initial endowments plus industry dynamics, relative prices, and external institutional changes. Using the technology production function developed in Section 4, initial technology asset accumulation, K_N, can be linked to external sources such as universities and government laboratories. Firms then attempt to shift demand in their favor by investing in unique combinations of the demand-shifting assets, applied technologies (K_E) and marketing capabilities. Each firm attempts to maintain its unique strategic innovation/imitation and marketing approach within competition space.

This process is seen clearly in young technology-based industries such as biotechnology, where firms pursue strategies such as accessing K_N from a university and then attempt to apply it through arrangements with, say, university professors. At the same time, these firms evolve a marketing strategy commensurate with the perceived relative strength and unique features of the targeted technology.[30]

Even when a shift in strategy seems warranted, the ability of a firm to make adjustments is limited because mobility barriers exit. For example, Mansfield et al. (1971) found that the maximum adjustment to a firm's stock of technology capital in any year is 10–15%. Similarly, adjustments to marketing require changes in sales personnel, advertising programs, and organizational structures.

Tassey (1983) showed that, because both technology and marketing assets take time and resources to accumulate and because organizational structures evolve to maximize returns on these capabilities, strategies based on particular combinations of the two assets tend to remain stable over time and are distinguishable from other strategies by competing firms within the same industry.

The stability over time of asset-based demand-shifting strategies implies a spatial model of competition. In such as model, competitive strategies are based on unique combinations of demand-shifting assets that determine firm-specific expansion paths. Each expansion path represents a strategy in demand-shifting space. Thus, assuming equal access by competing firms to stocks of capital and labor, relative performance can be explained using a spatial model of competition based on firm-specific allocations to R&D and marketing.

Such a relationship is best expressed by a homothetic function of the general form:

$$P = F[f(\bar{R}, M)] \tag{12}$$

where P is performance (sales or profits). $\bar{R}$ and M are the two demand-shifting assets possessed by a firm.[31]

[30] Darby and Zucker (2003) use empirical studies of technology diffusion in biotechnology to conclude that companies can retard spillovers of generic technologies by hiring and keeping star scientists whose tacit knowledge (a significant part of generic technologies) can only diffuse slowly, largely through person-to-person contact.

[31] See Tassey (1983) for the derivation of the specific functional form.

A homothetic function is hypothesized because the elasticity of substitution must be constant only at the points of intersection between isoquants and a particular ray from the origin, which represents the expansion path or "strategic trajectory" for a particular firm. In contrast to conventional production theory, allowing the elasticity of substitution to vary along an isoquant captures differences among competing firms with respect to demand-shifting strategies.

For empirical work, the above general form can be converted to

$$\log P_i = \phi \log x_i + \phi(a_0 + a_1 x_i + a_2 x_i^2 + a_3 x_i^3 + \cdots) + v_i \tag{13}$$

where $x = M/\bar{R}$ and the coefficient ϕ is a returns-to-scale parameter. $\bar{R}$ could be aggregate R&D spending or, preferably, the ratio R_E/R_N, and M is the marketing expenditures.

Using Compustat data for marketing (advertising) and aggregate R&D spending, Tassey (1983) calculated F-ratios for six technology-based industry groups (chemicals, drugs, machinery, computers, electronic components, and instruments). These ratios strongly supported the hypothesis of distinctly different and constant proportions of marketing and technology assets across firms. That is, the variation in annual ratios of marketing (advertising) to R&D expenditures for firms in an industry group was significantly less than the variation in the mean values of the firms' respective time series. Thus, a spatial model of competition in demand-shifting space is supported.

The performance function was tested using OLS regressions to select the polynomial (M/R) that best fitted the data. The model had high explanatory power for all industry groups using sales and net income as dependent variables. The net income model was particularly impressive, as the constant term was not a major explanatory factor. A consistent negative sign on the square of the demand-shifting strategy variable indicates a limit on the range of feasible strategies, as represented by investments in marketing relative to R&D. The sales model showed varying degrees of decreasing returns to scale for investment in a firm's demand-shifting strategy, with the more R&D-intensive industries approaching the constant returns case. The net income model showed the same distribution of returns-to-scale values across industry groups, but with all values closer to or actually at constant returns.[32]

Two important policy implications are inherent in a homothetic performance function. First, assuming that the ratios of R_E/R_N and M together represent unique product and process technology strategies across firms, then the conclusion is that significant competition exists in technology-based industries derived from a singular underlying generic technology base. This fact counters the long-held view of many U.S. R&D policymakers that government funding of early-phase technology research subverts the market mechanism by "picking winners and losers" (i.e., determining which innovations are developed and reach the marketplace and which do not).

The second implication is that a broader and deeper generic technology base will support more strategies and hence firms, thereby expanding aggregate output or at least the diversity of output for a particular industry. At any size, however, only a limited number of strategies can be supported in technology-marketing space. Thus, countries that invest in national innovative capacity (industrial structures, universities, and government research institutes) will likely not only develop the generic technology first, but will "fill" the technology-marketing strategic space ahead of competition in other countries and thereby gain a large share of the benefits from the particular technology.

7. Conclusion

A number of factors determine the rate and direction of technological advance: technological opportunity (the inherent performance capacity of the generic technology), the public and private good characteristics of the technology, industry structure and behavior, and demand conditions. Such technological progress

[32] In the decreasing returns case, the selected demand-shifting investment policy will determine the long-run equilibrium values of R&D and marketing inputs, so that an optimal size for demand-shifting assets exists. For the constant returns case, the rate of growth would be independent of the sizes of the R&D and marketing assets and the optimal investment policy would simply be determined by the ratio of demand-shifting assets commensurate with the firm's industry strategy and a rate of growth.

is also affected by the existence of relatively high risk, which is regularly used as the rationale for government support of R&D. However, the general approach taken oversimplifies the realities of technology-based competition and has therefore contributed significantly to the lack of consensus with respect to government roles in support of technology-based economic growth.

A disaggregated technology production function is needed to reflect the fact that private sector investment decisions are affected by the existence of and interaction among the three major elements of an industrial technology: generic technology, infratechnology, and proprietary technology. Each element exhibits a distinctly different risk profile and therefore responds differently to investment incentives.

These elements of the typical industrial technology have varying degrees of public good content and therefore must be funded from different combinations of public and private funds. Specifically, industry's problems with respect to acquiring and using technology are twofold. First, an adequate science base must be available and accessible at any point in time. Industry itself contributes relatively little to the evolution of this science base because of the almost pure "public good" character of scientific research. Thus, government provides the vast majority of the funds for this research, largely through universities. Second, industry's investments in the three technology elements suffer to different degrees from a number of partial market failures, and government's role is therefore more difficult to define and implement.

Once available, individual firms use applied technology in a logical effort to achieve competitive advantage. In developing this applied technology, these competing firms largely draw upon an industry-unique generic technology base and a set of infratechnologies that define that industry's infrastructure. The quasi-public good character of these shared technology elements implies the need for exogenous sources, such as universities and government laboratories.

Simply stating that R&D is risky or that industry's R&D cycle times are too long does not automatically lead to the need for an R&D support by government. The application of the models developed here allows a more disaggregated and hence presumably more efficient algorithm for market failure identification and characterization. However, while this framework should lead to more accurate policy analysis and development, it also underscores the potential for error due to the need for a more complicated analytical framework and corresponding data set.

Finally, the economics literature has largely focused on technology as a single demand-shifting asset. Yet, it cannot be delivered to the market without other assets, specifically marketing, that provide information to consumers about the attributes of the technology. A spatial model of technology-based competition captures the diversified strategies of individual firms with respect to investment in multiple demand-shifting assets. Equally important, in the modern global economy, the initiation of the respective competitive trajectories in demand-shifting space increasingly depends on the supply of public good technology elements from exogenous sources, namely universities and government.

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