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National policies for technical change: Where are the increasing returns to economic research?

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ABSTRACT Improvements over the past 30 years in statistical data, analysis, and related theory have strengthened the basis for science and technology policy by confirming the importance of technical change in national economic performance. But two important features of scientific and technological activities in the Organization for Economic Cooperation and Development countries are still not addressed adequately in mainstream economics: (*i*) the justification of public funding for basic research and (*ii*) persistent international differences in investment in research and development and related activities. In addition, one major gap is now emerging in our systems of empirical measurement—the development of software technology, especially in the service sector. There are therefore dangers of diminishing returns to the usefulness of economic research, which continues to rely completely on established theory and established statistical sources. Alternative propositions that deserve serious consideration are: (*i*) the economic usefulness of basic research is in the provision of (mainly tacit) skills rather than codified and applicable information; (*ii*) in developing and exploiting technological opportunities, institutional competencies are just as important as the incentive structures that they face; and (*iii*) software technology developed in traditional service sectors may now be a more important locus of technical change than software technology developed in "high-tech" manufacturing.

From the classical writers of the 18th and 19th centuries to the growth accounting exercises of the 1950s and 1960s, the central importance of technical change to economic growth and welfare has been widely recognized. Since then, our understanding—and consequent usefulness to policy makers—have been strengthened by systematic improvements in comprehensive statistics on the research and development (R&D) and other activities that generate knowledge for technical change and by related econometric and theoretical analysis.

Of particular interest to national policy makers have been the growing number of studies showing that international differences in export and growth performance countries can be explained (among other things) by differences in investment in "intangible capital," whether measured in terms of education and skills (mainly for developing countries) or R&D activities (mainly for advanced countries). These studies have recently been reviewed by Fagerberg (1) and Krugman (2). Behind the broad agreement on the economic importance of technical change, both reveal fundamental disagreements in theory and method. In particular, they contrast the formalism and analytical tractability of mainstream neoclassical analysis with the realism and analytical complexity of the more dynamic evolutionary approach. Thus, Krugman concludes:

> Today it is normal for trade theorists to think of world trade as largely driven by technological differences between countries; to think of technology as largely driven by cumulative processes of innovation and the diffusion of knowledge; to see a possible source of concern in the self-reinforcing character of technological advantage; and to argue that dynamic effects of technology on growth represent both the main gains from trade and the main costs of protection. . . the theory has become more exciting, more dynamic and much closer to the world view long held by insightful observers who were skeptical of the old conventional wisdom.
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> Yet. . . the current mood in the field is one of at least mild discouragement. The reason is that the new approaches, even though they depend on very special models, are *too* flexible. Too many things can happen. . . a clever graduate student can produce a model to justify any policy. [ref. 2, p. 360.]

Fagerberg finds similar tensions among the new growth theorists:

> . . . technological progress in conceived either as a "free good" ("manna from heaven"), as a by-product (externality), or as a result of intentional R&D activities in private firms. All three perspectives have some merits. Basic research in universities and other public R&D institutions provides substantial inputs into the innovation process. Learning by doing, using interacting, etc., are important for technological progress. However. . . models that do not include the third source of technological progress (innovation. . . by intentional activities in private firms) overlook one of the most important sources of technological progress. . .
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> . . . important differences remain. . . while formal theory still adopts the traditional neo-classical perspective as profit maximizers, endowed with perfect information and foresight, appreciative theorizing increasingly portrays firms as organizations characterized by different capabilities (including technology) and strategies, and operating under considerable uncertainty with respect to future technological trends. . . Although some formal theories now acknowledge the importance of firms for technological progress, these theories essentially treat technology as "blueprints" and "designs" that can be traded on markets. In contrast, appreciative theorizing often describes technology as organizationally embedded, tacit, cumulative in character, influenced by interaction between these firms and their environments, and geographically localized. [ref. 1, p. 1170.]

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Abbreviations: R&D, research and development; OECD, Organization for Economic Cooperation and Development.

As a student of science and technology policy—and therefore unencumbered by any externally imposed need to relate my analyses to the assumptions and methods of mainstream neoclassical theory—I find what Krugman calls "more exciting, more dynamic" theorizing and what Fagerberg calls "appreciative" theorizing, far more useful in doing my job. More to the point of this paper, while the above differences have been largely irrelevant to past analyses of technology's economic importance, they are turning out to be critical in two important areas of policy for the future: the justification of public support for basic research and the determinants of the level of private support of R&D. They will therefore need to be addressed more explicitly in future. So, too, will the largely uncharted and unmeasured world of software technology.

The Usefulness of Basic Research

The Production of Useful Information? In the past, the case for public policy for basic research has been strongly supported by economic analysis. Governments provide by far the largest proportion of the funding for such research in the Organization for Economic Cooperation and Development (OECD) countries. The well-known justification for such subsidy was provided by Nelson (3) and Arrow (4): the economically useful output of basic research is codified information, which has the property of a "public good" in being costly to produce and virtually costless to transfer, use, and reuse. It is therefore economically efficient to make the results of basic research freely available to all potential users. But this reduces the incentive of private agents to fund it, since they cannot appropriate the economic benefits of its results; hence the need for public subsidy for basic research, the results of which are made public.

This formulation was very influential in the 1960s and 1970s, but began to fray at the edges in the 1980s. The analyses of Nelson and Arrow implicitly assumed a closed economy. In an increasingly open and interdependent world, the very public good characteristics that justify public subsidy to basic research also make its results available for use in any country, thereby creating a "free rider" problem. In this context, Japanese firms in particular have been accused of dipping into the world's stock of freely available scientific knowledge, without adding much to it themselves.

But the main problem has been in the difficulty of measuring the national economics benefits (or "spillovers") of national investments in basic research. Countries with the best record in basic research (United States and United Kingdom) have performed less well technologically and economically than Germany and Japan. This should be perplexing—even discouraging—to the new growth theorists who give central importance to policies to stimulate technological spillovers, where public support to basic research should therefore be one of the main policy instruments to promote technical change. Yet the experiences of Germany and Japan, especially when compared with the opposite experience of the United Kingdom, suggest that the causal linkages run the other way—not from basic research to technical change, but from technical change to basic research. In all three countries, trends in relative performance in basic research since World War II have lagged relative performance in technical change. This is not an original observation. More than one hundred years ago, de Tocqueville (5) and then Marx (6) saw that the technological dynamism of early capitalism would stimulate demand for basic research knowledge, as well as resources, techniques, and data for its execution.

At a more detailed level, it has also proved difficult to find convincing and comprehensive evidence of the direct technological benefit of the information provided by basic research. This is reflected in Table 1, which shows the frequency with which U.S. patents granted in 1994 cite (i.e., are related to) other patents, and the frequency with which they cite science-refereed journals and other sources. In total, information from refereed journals provide only 7.2% [= 0.9/(10.9 + 0.9 + 0.7), from last row of Table 1] of the information inputs into patented inventions, whereas academic research accounts for ≈17% of all R&D in the United States and in the OECD as a whole. Since universities in the USA provide ≈70% of refereed journal papers, academic research probably supplies less than a third of the information inputs into patented inventions than its share of total R&D would lead us to expect.

Furthermore, the direct economic benefits of the information provided by basic research are very unevenly spread amongst sectors, including among relatively R&D-intensive sectors. Table 1 shows that the intensity of use of published knowledge is particularly high in drugs, followed by other chemicals, while being virtually nonexistent in aircraft, motor vehicles, and nonelectrical machinery. Nearly half the citations journals are from chemicals, ≈37.5% from electronic-related products and only just over 5% from nonelectrical machinery and transportation. And in spite of this apparent lack of direct

Table 1. Citing patterns in U.S. patents, 1994

Manufacturing sector	No. of patents	No. of citations per patent to: Other patents	Science journals	Other	Share of all citations to journals
Chemicals (less drugs)	10,592	9.8	2.5	1.2	29.1
Drugs	2,568	7.8	7.3	1.8	20.6
Instruments	14,950	11.8	1.0	0.7	16.3
Electronic equipment	16,108	8.8	0.7	0.6	12.2
Electrical equipment	6,631	10.0	0.6	0.6	4.4
Office and computing	5,501	10.0	0.7	1.0	4.3
Nonelectrical machinery	15,001	12.2	0.2	0.5	3.3
Rubber and miscellaneous plastic	4,344	12.4	0.4	0.6	1.9
Other	8,477	12.2	0.2	0.4	1.9
Metal products	6,645	11.6	0.2	0.4	1.5
Primary metals	918	10.5	0.8	0.7	1.0
Building materials	1,856	12.6	0.5	0.7	1.0
Food	596	15.1	1.3	1.6	0.9
Oil and gas	998	15.0	0.6	0.9	0.7
Motor vehicles and transportation	3,223	11.3	0.1	0.3	0.4
Textiles	567	12.4	0.3	0.8	0.2
Aircraft	905	11.6	0.1	0.3	0.1
Total	99,898	10.9	0.9	0.7	100.0

Data taken from D. Olivastro (CHI Research, Haddon Heights, NJ; personal communication).

usefulness, many successful British firms recently advised the Government to continue to allow universities to concentrate on long-term academic research and training and to caution against diverting them to more immediately and obviously useful goals (7).

We also find that, in spite of the small direct impact on invention of published knowledge and contrary to the expectations of the mainstream theory, large firms in some sectors both undertake extensive amounts of basic research and then publish the results. About 9% of U.S. journal publications come from firms. And Hicks *et al.* (8) have shown that large European and Japanese firms in the chemicals and electrical/electronic industries each publish >200 and sometimes up to 500 papers a year, which is as much as a medium-sized European or Japanese university.

The Capacity to Solve Complex Problems. Thus business practitioners persist in supporting both privately and publicly funded basic research, despite its apparently small direct contribution to inventive and innovative activities. The reason is that the benefits that they identify from public and corporate support for basic research are much broader than the "information," "discoveries," and "ideas" that tend to be stressed by economists, sociologists, and academic scientists. Practitioners attach smaller importance to these contributions than to the provision of trained researchers, improved research techniques and instrumentation, background (i.e., tacit) knowledge, and membership of professional networks (see, in particular, refs. 9–14)

In general terms, basic research and related training improve corporate (and other) capacities to solve complex problems. According to one eminent engineer:

> . . . we construct and operate. . . systems based on prior experiences, and we innovate in them by the human design feedback mode. . . first, we look at the system and ask ourselves "How can we do it better?"; second, we make some change, and observe the system to see if our expectation of "better" is fulfilled; third, we repeat this cycle of improvements over and over. This cyclic, human design feed back mode has also been called "learning-by-doing," "learning by using," "trial and error," and even "muddling through" or "barefoot empiricism". . . Human design processes can be quite rational or largely intuitive, but by whatever name, and however rational or intuitive. . . it is an important process not only in design but also in research, development, and technical and social innovations because it is often the only method available. [ref. 15, p. 63.]

Most of the contributions are person-embodied and institution-embodied tacit knowledge, rather than information-based codified knowledge. This explains why the benefits of basic research turn out to be localized rather than available indifferently to the whole world (8, 16, 17). For corporations, scientific publications are signals to academic researchers about fields of corporate interest in their (the academic researchers') tacit knowledge (18). And Japan has certainly not been a free rider on the world's basic research, since nearly all the R&D practitioners in their corporations were trained with Japanese resources in Japanese universities (19).

Why Public Subsidy? These conclusions suggest that the justification for public subsidy for basic research, in terms of complete codification and nonappropriable nature of immediately applicable knowledge, is a weak one. The results of basic research are rarely immediately applicable, and making them so also increases their appropriable nature, since, in seeking potential applications, firms learn how to combine the results of basic research with other firm-specific assets, and this can rarely be imitated overnight, if only because of large components of tacit knowledge (20–22). In three other dimensions, the case for public subsidy is stronger.

The first was originally stressed strongly by Nelson (3); namely, the considerable uncertainties before the event in knowing if, when, and where the results of basic research might be applied. The probabilities of application will be greater with an open and flexible interface between basic research and application, which implies public subsidy for the former.

A second, and potentially new, justification grows out of the internationalization of the technological activities of large firms. Facilities for basic research and training can be considered as an increasingly important part of the infrastructure for downstream technological and production activities. Countries may therefore decide to subsidize them, to attract foreign firms or even to retain national ones.

The final and most important justification for public subsidy is training in research skills, since private firms cannot fully benefit from providing it when researchers, once trained, can and do move elsewhere. There is, in addition, the important insight of Dasgupta and David (23) that, since the results of basic research are public and those of applied research and development often are not, training through basic research enables more informed choices and recruitment into the technological research community.

Uneven Technological Development Amongst Countries

Evidence. Empirical studies have shown that technological activities financed by business firms largely determine the capacity of firms and countries both to exploit the benefits of local basic research and to imitate technological applications originally developed elsewhere (11, 24). Thus, although the output of R&D activities have some characteristic of a public good, they are certainly not a free good, since their application often require further investments in technological application (to transform the results of basic research into innovations) or reverse engineering (to imitate a product already developed elsewhere). This helps explain why international differences in economic performance are partially explained by differences in proxy measures of investments in technological application, such as R&D expenditures, patenting, and skill levels.

Another important gap in our understanding is the persistent international differences in intangible investments in technological application. Even amongst the OECD countries, they are quite marked. Using census data, Table 2 shows that within Western Europe there are considerable difference in the level of training of the non-university-trained workforce.

Table 2. Qualifications of the workforce in five European countries

Level of qualification	Percentage of workforce				
	Britain*	Netherlands†	Germany‡	France*	Switzerland§
University degrees	10	8	11	7	11
Higher technician diplomas	7	19	7	7	9
Craft/lower technical diplomas	20	38	56	33	57
No vocational qualifications	63	35	26	53	23
Total	100	100	100	100	100

Data taken from ref. 25. Data shown are from the following years: *, 1988; †, 1989; ‡, 1987; and §, 1991.

These broad statistical difference are confirmed by more detailed comparisons of educational attainment in specific subjects, and their economic importance is confirmed by marked international differences in productivity and product quality (25). There is also partial evidence that the United States resembles the United Kingdom, with a largely unqualified workforce, while Japan and the East Asian tigers resemble Germany and Switzerland (26).

In addition, OECD data show no signs of convergence among the member countries in the proportion of gross domestic produce spent on business-funded R&D activities. Japan, Germany, and some of its neighbors had already caught up with the U.S. level in the early to mid-1970s (19). At least until 1989, they were forging ahead, which could have disquieting implications for future international patterns of economic growth, especially since there are also signs of the end of productivity convergence amongst the OECD countries (see, for example, ref. 27).

In spite of their major implications for both science and economic policies, relatively little attention has been paid to explaining these international differences, particularly when they are supported. The conventional explanations are in terms of either macroeconomic conditions (e.g., Japan has an advantage over the United States in investment and R&D because of differences in the cost of capital) or in terms of market failure (e.g., given lack of labor mobility, Japanese firms have greater incentives to invest in workforce training; see ref. 28).

Institutional Failure. But while these factors may have some importance, they may not be the whole story. Some of the international differences have been long and persistent, and none more so (and none more studied) than the differences between the United Kingdom and Germany, which date back to at least the beginning of this century, and which have persisted through the various economic conditions associated with imperialism, Labour Party corporatism, and Thatcherite liberalism in the United Kingdom, and imperialism, republicanism (including the great inflation of 1924), nazism, and federalism in Germany (29). The differences in performance can be traced to persistent differences in institutions (30, 31), their incentive structures, and their associated competencies (i.e., tacit skills and routines) that change only slowly (if at all) in response to international differences in economic incentives.

One of the most persistent differences has been in the proportion of corporate resources spent on R&D and related activities. New light is now being thrown on this subject by improved international data on corporate R&D performance. Table 3 shows that, in spite of relatively high profit rates and low "cost of funds," the major U.K. and U.S. firms spend relatively low proportions of their sales on R&D. Similarly, despite higher cost of funds, Japanese firms spend higher shares of profits and sales on R&D than U.S. firms. Preliminary results of regression analysis suggest that each firm's R&D/sales ratio is influenced significantly by its profits/sales ratio and by country-specific (i.e., institutional) effects. However, each firm's cost of funds/profits ratio turns out not to be a significant influence, except for the subpopulation of U.S. firms.

These differences cannot be explained away very easily. In a matched sample of firms of similar size in the United Kingdom and Germany, Mayer (33) and his colleagues found that, in the period from 1982 to 1988, the proportion of earnings paid out as dividends were 2 to 3 times as high in the U.K. firms. Tax differences could not explain the difference; indeed, retentions are particularly heavily discouraged in Germany. Nor could differences in inflation or in investments requirements explain it. Mayer attributes the differences to the structures of ownership and control. Ownership in the United Kingdom is dispersed, and control exerted through corporate takeovers. In Germany, ownership is concentrated in large corporate groupings, including the banks, and systems of control involve suppliers, purchasers, banks, and employees, as well as shareholders. On this basis, he concludes that the U.K. system has two drawbacks:

> [F]irst. . . the separation of ownership and control. . . makes equity finance expensive, which causes the level of dividends in the UK to be high and inflexible in relation to that in countries where investors are more closely involved. Second, the interests of other stakeholders are not included. This discourages their participation in corporate investment.
>
> UK-style corporate ownership is therefore likely to be least well suited to co-operative activities that involve several different stakeholders, e.g. product development, the development of new markets, and specialised products that require skilled labour forces. [ref. 33, p. 191.]

I would only add that the U.K. financial system is likely to be more effective in the arms-length evaluation of corporate R&D investments that are focused on visible, discrete projects that can be evaluated individually—for example, aircraft, oil fields, and pharmaceuticals. It will be less effective when corporate R&D consists of a continuous stream of projects and products, with strong learning linkages amongst them—for example, civilian electronics.

Similar (and independently derived) analyses have emerged in the USA, especially from a number of analysts of corporate

Table 3. Own R&D expenditures by world's 200 largest R&D spenders in 1994

Country (*n*)	R&D as percentage of: Sales	Profits*	Costs of funds†	Profits/sales, %	Cost of funds/profits, %
Sweden (7)	9.2	73.4	194.3	12.5	37.8
Switzerland (7)	6.9	69.0	140.4	10.0	49.1
Netherlands (3)	5.6	103.8	201.0	5.4	51.6
Japan (60)	5.5	204.0	185.6	2.7	109.9
Germany (16)	4.9	149.0	202.9	3.2	73.4
France (18)	4.6	256.5	111.9	1.8	229.2
United States (67)	4.2	43.8	96.6	9.6	45.3
United Kingdom (12)	2.6	23.7	52.3	11.0	45.3
Italy (4)	2.3	N/A	34.0	N/A	N/A
Total (200)	4.7	72.1	119.1	6.5	63.1

Data taken from ref. 32. *n*, No. of firms; N/A, not applicable.

*Profits represent profits before tax, as disclosed in the accounts.

†Cost of funds represents (equity and preference dividends appropriated against current year profits) + (interest servicing costs on debt) + (other financing contracts, such as finance leases).

behavior at Harvard Business School (34, 35). In addition to deficiencies in the financial system, they stress the importance of command and control systems installed by corporate managers. In particular, they point to the growing power of business school graduates, who are well trained to apply financial and organizational techniques, but have no knowledge of technology. They maximize their own advantage by installing decentralized systems of development, production, and marketing, with resource allocations and monitoring determined centrally by short-term financial criteria. These systems are intrinsically incapable of exploiting all the benefits of investments in technological activities, given their short-term performance horizons, their neglect of the intangible benefits in opening new technological options, and their inability to exploit opportunities that cut across established divisional boundaries. Managers with this type of competence therefore tend to underinvest in technological activities.

Institutions and Changing Technologies. But given above deficiencies, how did the United States maintain its productivity advance over the other OECD countries from 1870 to 1950? According to a recent paper by Abramovitz and David [ref. 36; similar arguments have been made by Freeman *et al.* (37), Nelson and Wright (38), and von Tunzelmann (39)], the nature of technical progress in this period was resource-intensive, capital-using, and scale-dependent—symbolized by the large-scale production of steel, oil, and the automobile. Unlike all other countries, the United States had a unique combination of the abundant natural resources, a large market, scarce labor, and financial resources best able to exploit this technological trajectory. These advantages began to be eroded after World War II, with new resource discoveries, the integration of national markets, and the improvements in transportation technologies. Furthermore, the nature and source of technology has been changing, with greater emphasis on intangible assets like training and R&D and lesser emphasis on economies of scale. Given these tendencies, Abramovitz and David foresee convergence amongst the OECD countries in future. The data in Tables 2 and 3 cast some doubt on this.

Is Uneven Technological Development Self-Correcting? But can we expect uneven international patterns of technological development to be self-correcting in future? In an increasingly integrated world market, there are powerful pressures for the international diffusion of the best technological and related business practices through the international expansion of best practice firms, and also for imitation through learning and investment by laggard firms. But diffusion and imitation are not easy or automatic, for at least three sets of reasons.

First, technological (and related managerial) competencies, including imitative ones, take a long time to learn, and are specific to particular fields and to particular inducement mechanisms. For example, U.S. strength in chemical engineering was strongly influenced initially by the opportunities for (and problems of) exploiting local petroleum resources (40). More generally, sectoral patterns of technological strength (and weakness) persist over periods of at least 20–30 years (19, 41).

Second, the location and rate of international diffusion and imitation of best practice depend on the cost and quality of the local labor force (among other things). With the growing internationalization of production, firms depend less on any specific labor market and are therefore less likely to commit resources in investment in local human capital. In other words, firms can adjust to local skill (or unskilled) endowments, rather than attempt to change them. National policies to develop human capital (including policies to encourage local firms to do so) therefore become of central importance.

Third, education and training systems change only slowly, and are subject to demands in addition to those of economic utility. In addition there may be self-reinforcing tendencies intrinsic in national systems of education, management, and finance. For example:

- The British and U.S. structure of human capital, with well-qualified graduates and a poorly educated workforce, allows comparative advantage in sectors requiring this mix of competencies, like software, pharmaceuticals, and financial services. The dynamic success of these sectors in international markets reinforces demand for the same mix of competencies. In Germany, Japan and their neighboring countries, the dynamics will, on the contrary, reinforce demands in sectors using a skilled workforce.
- Decentralized corporate management systems based on financial controls breed managers in the same mold, whose competencies and systems of command and control are not adequate for the funding of continuous and complex technical change. Firms managed by these systems therefore tend to move out (or are forced out) of sectors requiring such technical change. See, for example, Geenen's ITT in the United States, and Weinstock's General Electric Company in the United Kingdom (35, 42).
- The British financial system develops and rewards short-term trading competencies in buying and selling corporate shares on the basis of expectations about yields, while the German system develops longer-term investment competencies in dealing with shares on the basis of expected growth. These competencies emerge from different systems of training and experience and are largely tacit. It is therefore difficult, costly, and time-consuming to change from one to the other. And there may be no incentive to do so, when satisfactory rates of return can be found in both activities.

Needless the say, these trends will be reinforced by explicit or implicit policy models that advocate "sticking to existing comparative advantage," or "reinforcing existing competencies."

Table 4. The growth of U.S. science and engineering employment in life science, computing, and services

Field	Ratio, no. of employees in 1992/no. of employees in 1980
All fields	1.44
Life sciences	3.12
Computer specialists	2.03
Manufacturing sectors	1.30
Nonmanufacturing sectors	1.69
Financial services	2.37
Computer services	4.10

Data taken from ref. 45.

The Measurement of Software Technology

The institutional and national characteristics required to exploit emerging technological opportunities depend on the nature and locus of these opportunities. Our apparatus for measuring and analyzing technological activities is becoming

Table 5. Industries' percentages of business employment of scientists and engineers, 1992

Field	Employment of scientists and engineers, % (computer specialists, %)
Manufacturing	48.1 (10.9)
Nonmanufacturing	51.9 (23.7)
Engineering services	9.1 (3.2)
Computer services	8.3 (51.8)
Financial services	6.1 (58.5)
Trade	5.2 (25.5)

Data taken from ref. 45.

Table 6. Differing policies for basic research

Subject	Assumptions on the nature of useful knowledge: Codified information	Assumptions on the nature of useful knowledge: Tacit know-how
International Free riders	Strengthen intellectual property rights; restrict international diffusion	Strengthen local and international networks
Japan's and Germany's better technological performance than United States and United Kingdom with less basic research	More spillovers by linking basic research to application	Increase business investment in technological activities
Small impact of basic research on patenting	Reduce public funding of basic research	Stress unmeasured benefits of basic research
Large business investment in published basic research	Public relations and conspicuous intellectual consumption	A necessary investment in signals to the academic research community

obsolete, since the conventional R&D statistics do not deal adequately with software technology, to which we now turn.

There is no single satisfactory proxy measure for the activities generating technical change. The official R&D statistics are certainly a useful beginning, but systematic data on other measures show that they considerably underestimate both the innovations generated in firms with <1000 employees (where most firms do not have separately accountable R&D departments) and in mechanical technologies (the generation of which is dispersed a wide variety of product groups; refs. 43 and 44).

A further source of inaccuracy is now emerging with the growth in importance of software technology, for the following reasons:

- One revolutionary feature of software technology is that it increases the potential applications of technology, not only in the sphere of production, but also in the spheres of design, distribution, coordination, and control. As a consequence, the locus of technological change is no longer almost completely in the manufacturing sector, but also in services. In all OECD countries, a high share of installed computing capacity in the United States is in services, which have recently overtaken manufacturing as the main employers of scientists and engineers (see Tables 4 and 5).
- Established R&D surveys tend to neglect firms in the service sector. According to the official U.S. survey, computer and engineering services accounted in 1991 for only 4.2% of total company funded R&D compared with >8% of science and engineering employment. The Canadian statistical survey has done better: in 1995, ≈30% of all measured business R&D was in services, of which ≈12% was in trade and finance (46).
- This small presence of software in present surveys may also reflect the structural characteristics of software development. Like mechanical machinery, software can be considered as a capital good, in that the former processes materials into products, and the latter processes information into services. Both are developed by user firms as part of complex products or production systems, as well as by small and specialized suppliers of machinery and applications software (for machinery, see ref. 47). As such, a high proportion of software development will be hidden in the R&D activities of firms making other products and in firms too small for the establishment of a conventional R&D department.

Conclusions

The unifying theme of this paper is that differences among economists about the nature, sources, and measurement of technical change will be of much greater relevance to policy formation in the future than they were in the past. These differences are at their most fundamental over the nature of useful technological knowledge, the functions of the business firm, and the location of the activities generating technological change. They are summarized, and their analytical and policy conclusions are contrasted, in Tables 6, 7, and 8. On the whole, the empirical evidence supports the assumptions underlying the right columns, rather than those on the left.

Basic Research. The main economic value of basic research is not in the provision of codified information, but in the capacity to solve complex technological problems, involving tacit research skills, techniques, and instrumentation and membership in national and international research networks. Again, there is nothing original in this:

> [t]he responsibility for the creation of new scientific knowledge—and for most of its application—rests on that small body of men and women who understand the fundamental laws of nature and are skilled in the techniques of scientific research. [ref. 48, p. 7.]

Exclusive emphasis on the economic importance of codified-information:

- exaggerates the importance of the international free rider problem and encourages (ultimately self-defeating) techno-nationalism;
- reinforces a constricted view of the practical relevance of basic research by concentrating on direct (and more easily measurable) contributions, to the neglect of indirect ones;
- concentrates excessively on policies to promote externalities, to the neglect of policies to promote the demand for skills to solve complex technological problems (49, 50).

Uneven Technological Development. In this context, too little attention has been to the persistent international differences, even among the advanced OECD countries, in investments in R&D, skills, and other intangible capital to solve complex problems. Explanations in terms of macroeconomic policies and market failure are incomplete, since they concentrate entirely on incentives and ignore the competencies to respond to them. Observed "inertia" in responding to incentives is not just a consequence of stupidity or self-interest, but also of cognitive limits on how quickly individuals and institutions can learn to new competencies. Those adults who have tried to learn a foreign language from scratch will well understand the problem. Otherwise, the standard demonstration is to offer economists $2 million to qualify as a surgeon

Table 7. Differing policies for corporate technological activities

Subject	Assumptions on the functions of business firms: Optimizing resource allocations based on market signals	Assumptions on the functions of business firms: Learning to do better and new things
Inadequate business investment in technology compared to foreign competition	R&D subsidies and tax incentives; reduce cost of capital; increase profits	Improve worker and manager skills; improve (through corporate governance) the evaluation of intangible competencies

Table 8. Differences in the measurement of technological activities

	Assumptions on the nature of technological activities	
Subject	Formal R&D	Formal and informal R&D including software technology
The distribution of technological activities	Mainly in large firms, manufacturing, and electronics/chemicals/transportation	Also in smaller firms in nonelectrical machinery and large and small firms in services

within 1 year. (Some observers have been reluctant to make the reverse offer.)

These competencies are located not only in firms, but also in financial, educational, and management institutions. Institutional practices that lead to under- or misinvestment in technological and related competencies are not improved automatically through the workings of the market. Indeed, they may well be self-reinforcing (Table 7).

Software Technology. Although R&D statistics have been an invaluable source of information for policy debate, implementation, and analysis, they have always had a bias toward the technological activities of large firms compared with small ones and toward electrical and chemical technologies compared with mechanical engineering. The bias is now becoming even greater with the increasing development of software technology in the service sector, while R&D surveys concentrate on manufacturing (Table 8).

As a consequence, statistical and econometric analysis will increasingly be based on incomplete and potentially misleading data. Perhaps more worrying, some important locations of rapid technological change will be missed or ignored. While we are bedazzled by the "high-tech" activities of Seattle and Silicon Valley, the major technological revolution may well be happening among the distribution systems of the oldest and most venal of the capitalists: the money lenders (banks and other financial services), the grocers (supermarket chains), and the traders (textiles, clothing, and other consumer goods).

To conclude, if economic analysis is to continue to inform science and technology policy making, it must play greater attention to the empirical evidence on the nature and locus of technology and the activities that generate it and spend more time collecting new and necessary statistics in addition to exploiting those that are already available. That the prevailing norms and incentive structures in the economics profession do not lend themselves easily to these requirements is a pity, just as much for the economists as for the policy makers, who will seek their advice and insights elsewhere.

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