Chapter 18

EMPIRICAL STUDIES OF INNOVATION AND MARKET STRUCTURE

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1. Introduction

A central question in the field of industrial organization is how firms and markets should be organized to produce optimal economic performance. Empirical estimates of the costs of static resource misallocation attributable to suboptimal market organization range from miniscule [0.07 percent of GNP, as estimated by Harberger (1954)] to substantial [4-13 percent of GNP, as estimated by Cowling and Mueller (1978)]. Even the largest of these estimated costs, however, might be worth incurring in return for modest improvements in the rate of technological progress. The potential tradeoff between static and dynamic efficiency is therefore central to evaluating the performance of alternative modes of firm and market organization.

The idea that technological progress facilitated economic growth and improved welfare was appreciated long before economists became concerned with quantifying its impact. In the classical political economy of Ricardo, Mill, and Marx, technological progress was the principal force offsetting the tendency of capital accumulation to depress the rate of profit. For Ricardo and Mill, if not for Marx, technological progress was the principal impediment to the onset of a "stationary state" in which economic growth ceased.

It remained, however, for Schumpeter (1942) to argue for a sharp distinction between the organization of firms and markets most conducive to solving the static problem of resource allocation and those organizational forms most conducive to rapid technological progress. In Schumpeter's view, the atomistic firm operating in a competitive market may be a perfectly suitable vehicle for static resource allocation, but the large firm operating in a concentrated market was the "most powerful engine of progress and ... long-run expansion of total output". In this respect, he continued, "perfect competition is inferior, and has no title to being set up as a model of ideal efficiency" [Schumpeter (1942, p. 106)].

Schumpeter's assertions inspired what has become the second largest body of empirical literature in the field of industrial organization, exceeded in volume only by the literature investigating the relationship between concentration and profitability (surveyed in this Handbook by Schmalensee in Chapter 16). Most of this literature focuses on testing two hypotheses associated with Schumpeter: (1) innovation increases more than proportionately with firm size and (2) innovation increases with market concentration.

In focusing on these hypotheses, the profession, abetted partly by Schumpeter himself, has done some disservice to one of Schumpeter's central research missions, the development of a broader understanding of the nature and economic consequences of technological progress. With some notable exceptions, the profession, particularly industrial organization economists of the Harvard school [e.g. Mason (1951)], became preoccupied with investigating the effects of firm size and market concentration on innovation, most probably because Schumpeter's propositions appeared to offer a direct challenge to antitrust orthodoxy. Specifically, the proposition that an industrial organization of large monopolistic firms might have decisive welfare advantages cut sharply against the grain of antitrust thinking. As a result, the more general task of identifying and evaluating other, perhaps more fundamental, determinants of technological progress in industry has received little attention relative to the effort devoted to exploring the effects of size and market structure.

Indeed, we find that the empirical results bearing on the Schumpeterian hypotheses are inconclusive, in large part because investigators have failed to take systematic account of more fundamental sources of variation in the innovative behavior and performance of firms and industries. In this survey, we review the traditional empirical literature, but we also discuss the growing literature on the fundamental determinants of interindustry differences in innovation. We classify these determinants under three headings; the structure of demand, the nature and abundance of technological opportunity, and the conditions governing appropriability of the returns from innovation.

Our review finds the empirical literature on Schumpeter's hypotheses pervaded by methodological difficulties. Equations have been loosely specified; the data have often been inadequate to analyze the questions at hand; and, until recently, the econometric techniques employed were rather primitive. To the extent that preoccupation with the effects of firm size and concentration on innovation encourages omission of important and potentially correlated explanatory variables, estimates of these very effects have tended to be biased. Despite some recent advances in model specification, data collection, and statistical techniques, the results of this literature must be interpreted with caution.

Given the literature's methodological pitfalls, we can at best hope to identify robust findings. Relationships among important economic variables that prove robust to variations in sampling, specification, statistical techniques, and measurement are the "stylized facts" from which theory, and ultimately the formulation of precise and falsifiable hypotheses, develop. A lack of robustness can also advance understanding; although it is too rarely undertaken, thorough diagnosis of the reasons for inconsistent results across samples, specifications, techniques, or measures can produce valuable insights for theory construction. Also, as Schmalensee argues in his related chapter, the search for robust findings should focus not simply on the issue of statistical significance, but on the magnitude of estimated parameters and the contribution of particular variables to explaining variance in the dependent variable. Relationships that are persistently *significant* but miniscule in magnitude and unimportant in the explanation of variance are probably not worth much attention in the formulation of either theory or policy.

This survey critically reviews the empirical literature on the characteristics of markets and firms that influence industrial innovation. In addition to the econometric literature, we will also selectively review the case study and institutional literature that provides a richer, more subtle interpretation of the relationships among innovation, market structure, and industry and firm characteristics. Although the literature considered here is extensive, the survey is primarily confined to industrial organization in a narrow sense. We will not consider the effects on technical advance of national or economy-wide characteristics such as tax policy or the supply of trained engineers. We will not examine the substantial and important economic literatures on productivity measurement and growth, induced innovation, the adoption and diffusion of innovation, and the nature and organization of the R&D process. Nor will we discuss the vast sociological and social-psychological literatures on the innovation process and the effects of internal organization on the generation, adoption, and diffusion of innovations.[1]

In Section 2 we discuss the problems associated with measuring innovative effort and output. We then proceed, in Section 3, to review, thematically and critically, the literature that examines the effects of firm size and concentration upon innovation, as well as the related literature that considers the influence of selected firm characteristics. In Section 4 we discuss the literature on three sources of interindustry variation in innovative behavior and performance: demand, technological opportunity, and appropriability conditions. We pause here more frequently than in the previous section to provide specific details because the literature is less familiar to most industrial organization economists and has been less thoroughly reviewed elsewhere. In the concluding section, we consider the relationship of the econometric literature on innovation and market structure to the theoretical literature, and we suggest directions for future research.

2. Measurement

A fundamental problem in the study of innovation and technical change in industry is the absence of satisfactory measures of new knowledge and its contribution to technological progress. There exists no measure of innovation that permits readily interpretable cross-industry comparisons. Moreover, the value of an innovation is difficult to assess, particularly when the innovation is embodied in consumer products [see Griliches (1979)]. Despite these difficulties, a variety of measures of innovation have been employed by empiricists. They may be broadly classified as measures of either innovative inputs or outputs.

[1]For a recent review of the literature on productivity measurement and growth, see Link (1987). The literature on induced innovation, adoption and diffusion is surveyed by Thirtle and Ruttan (1987). Dosi (1988) covers aspects of the innovation process from the perspective of institutional economics. For an overview of the innovation process that covers the literature of other social sciences, see the survey prepared by the National Science Foundation (1983).

Direct measures of innovative output are the most scarce. Innovation counts have been assembled on a cross-industry basis for the United States by Gellman Research Associates (1976), and for the United Kingdom by a group of researchers at the Science Policy Research Unit (SPRU) at the University of Sussex [see Townsend et al. (1981) and Robson and Townsend (1984) for a description of the U.K. data]. Both of these efforts involved an elaborate process of using technical experts to identify significant innovations. Unavoidably, the innovations thus identified are heterogeneous in economic value, and despite the care taken in assembling the data, they are likely to reflect numerous unexamined biases. Little work has been done with the Gellman data, but the SPRU data have been quite fruitfully exploited [e.g. Pavitt (1983, 1984), Pavitt et al. (1987), Robson et al. (1988)].

Data on significant innovations have been assembled for particular industries. Mansfield (1963), for example, developed innovation counts for the steel, petroleum refining, and bituminous coal industries. In the pharmaceutical industry, data on the number of new chemical entities developed by firm and by year are readily available and have been widely used [e.g. Baily (1972), Peltzman (1973), Schwartzman (1976)]. Data on significant innovations in the semiconductor industry have been assembled by Tilton (1971) and Wilson et al. (1980).

Patent counts have been used most frequently to approximate the innovative output of firms or industries. A few early studies required considerable effort to assemble the data [e.g. Scherer (1965a), Grabowski (1968)]. More recently, automation of the U.S. Bureau of the Census' Patent File has facilitated the use of patent data, especially at the level of the firm [see Bound et al. (1984) and Griliches et al. (1987)].

There are significant problems with patent counts as a measure of innovation, some of which affect both within-industry and between-industry comparisons. Most notably, the economic value of patents is highly heterogeneous. A great majority of patents are never exploited commercially, and only a very few are associated with major technological improvements. Moreover, a patent may consist of several related claims, each of which might be filed as a separate patent. Indeed, although the quantity of patents is often used to measure national technological advantage [see National Science Board (1987)], comparisons are distorted by the tendency of U.S. inventors to bundle claims in one patent, while Japanese inventors typically file separate patents for each claim.[2]

Other difficulties specifically reduce the value of patent data in cross-industry applications. The propensity to patent varies considerably across industries. In

[2]Even if patents were homogeneous in economic value, their use as a measure of innovation in econometric studies would require special care. Because patents are integer-valued and because their distribution across firms or business units is highly skewed, standard assumptions about the distribution of the error term in a regression explaining patenting activity cannot be maintained. Solutions to this problem are suggested by Hausman, Hall and Griliches (1984).

the electronics industries, entire categories of economically significant innovations are typically not patentable. Computer software, for example, is normally eligible for copyright but not patent protection, and integrated circuit designs are neither patentable nor copyrightable.[3] Even where patents are available, the nature of an industry's technology and its competitive conditions tend to govern the tradeoff between patenting innovations and keeping them secret. In some industries, but not in others, patents reveal to competitors technological information that cannot be readily ascertained by other means (such as reverse engineering the product). In such cases, patenting may be inhibited and secrecy favored. By contrast, patents may be preferred where they serve as "signals" of technological competence to suppliers of capital, a phenomenon of particular importance to small firms.[4]

There have been several attempts to measure the value of innovations by examining the stock market's response to patent grants [Griliches (1981), Pakes (1985), and Cockburn and Griliches (1988)]. Cockburn and Griliches found that the stock market responds more strongly to changes in a firm's R&D spending than to changes in the stock of patents, although the valuation of both R&D and patents is significantly influenced by the "effectiveness" of patents in the firm's principal industry.[5] A promising alternative approach to measurement of the value of patents was taken by Schankerman and Pakes (1986) and Pakes (1986), who estimated the distribution of patent values from European data on annual patent renewals. The renewal data, however, have not yet been studied at the industry level because most national patent offices do not classify patents by industry. There is also evidence, recently developed by Trajtenberg (1987) for the computed tomography scanner industry, that a measure weighting patents by their citations in other patent applications may provide a relatively accurate index of the value of innovations within an industry.

In the majority of studies concerned with the effects of firm size or market structure on innovation, the dependent variable is a measure of input to the innovation process, rather than a measure of innovative output. Most commonly, innovative effort is measured by expenditures on R&D or by personnel engaged in R&D. Although both measures are intended to represent the current flow of resources devoted to the generation of innovation, both are flawed. R&D employment excludes flows of services from research equipment and laboratory materials, which may be combined with labor in variable proportions, while

[3] In the United States, passage of the Semiconductor Chip Protection Act in 1984 made integrated circuit designs (as represented on photolithographic "masks") eligible for a special form of intellectual property right that is neither a patent nor a copyright.

[4] For additional discussion of the strengths and weaknesses of patents as a measure of innovation, see Kuznets (1962), Pavitt (1985), Basberg (1987), and Griliches, Hall and Pakes (1987).

[5] Cockburn and Griliches used data on the effectiveness of patents developed by Levin et al. (1987) from a survey of R&D managers in 130 industries. The survey results are discussed in greater detail in Section 4.

R&D expenditures include the purchase of long-lived equipment that is expensed rather than capitalized under current accounting rules. R&D employment and expenditure data are also subject to considerable error in reporting, because the definitions used for financial reporting give firms considerable latitude in the classification of activities. Even the more rigorous definitions used in the annual National Science Foundation survey are subject to misinterpretation. Moreover, the discrepancy between the NSF definitions and the rules governing financial reporting leads to systematic differences across widely used data sets.[6]

Some investigators, notably Griliches (1979), have argued that the proper measure of innovative input is not the knowledge generated in any one period, but the services of an accumulated stock of knowledge upon which the firm draws. The construction of an operational measure of a knowledge stock, sometimes referred to as R&D capital, is problematic. Griliches identified three issues: (1) the determination of an appropriate depreciation rate, (2) the specification of the lags with which current R&D effort is added to the stock, and (3) the extent to which spillovers of knowledge generated by other firms, other industries, government agencies, or universities supplement the knowledge created by a firm's own R&D.

Despite some impressive efforts to grapple with these measurement problems, it remains unclear whether a meaningful index of a firm's or an industry's knowledge stock can be constructed. If, as Griliches suggested, the private rate of depreciation depends on obsolescence and the extent of spillovers to competitors, then the depreciation rate is not a given technological parameter; it is endogenous to the process of innovation and dynamic competition. In any event, it is clear that – to the extent that depreciation rates, lag structures, and spillovers differ systematically across industries – even a correctly measured flow of current R&D effort will not serve as an adequate proxy for the services of R&D capital in cross-industry comparisons.

Moreover, it is heroic to assume that even a properly measured representation of R&D stock or flow can fully summarize a firm's effort devoted to technological innovation. Hollander's (1965) account of incremental innovation on the shop floor, as well as numerous studies of learning by doing [e.g. Hirsch (1952) and Lieberman (1984)], indicate that considerable effort is devoted to technological innovation outside a firm's formal R&D operation. Moreover, many small firms simply have no formal R&D operation; effort devoted to technological innovation is typically an unmeasured fraction of the time worked by the firm's engineers and managers [see, for example, Kleinknecht (1987)].

[6]Cohen and Mowery (1984) found that Standard and Poor's Compustat data indicate that firms conduct 12 percent more R&D, on average, than indicated by the Federal Trade Commission's Line of Business Program data covering the same firms and years. The FTC applies the more restrictive NSF definition of R&D, while the Compustat data is derived from firms' annual 10-K reports to the Securities and Exchange Commission, which permits a more liberal definition.

A final problem common to the use of input as well as output measures of innovation is that when such measures are used, inventive effort and innovations are usually assumed to be qualitatively homogeneous. In most studies, process innovation is not distinguished from product innovation; basic and applied research are not distinguished from development. Such homogeneity assumptions, Lunn (1986) has emphasized, make it difficult to specify correctly an empirical model; some variables expected to influence process innovation, for example, may be thought to have no influence on product innovation. The importance of particular explanatory variables may also differ across types of activities. For example, the availability of patent protection would be expected to have a stronger effect on product R&D than on process R&D [Levin et al. (1987)], and a firm's degree of diversification would be expected to have a stronger effect on basic research than on applied research and development [Nelson (1959)].

For many purposes, data that distinguish types of inventive activity are unavailable. The National Science Foundation publishes a breakdown of expenditures for basic research, applied research, and development at a relatively high level of aggregation (corresponding mainly to two-digit industries, with some subdivision into groups of three-digit industries). Mansfield (1981) and Link (1982, 1985) have collected and analyzed a limited amount of data distinguishing basic research from applied research and development at the firm level. Although there are no official sources of data on the relative effort devoted to process and product innovation, Scherer (1982a, 1984a) classified all U.S. patents granted within a 15-month period in the mid-1970's by industry of origin and industry of use. In this framework, process innovations are those represented by patents used in their industry of origin. Scherer's data provide an interesting picture of interindustry flows of technology, and they have been used by Scherer (1982b, 1982c, 1983a, 1983b) and others for numerous purposes.[7]

3. Empirical studies in the Schumpeterian tradition

In this section we examine empirical research on the central Schumpeterian relationships between innovation, on the one hand, and firm size and market structure, on the other. We also discuss methodologically similar work that considers the influence on innovative activity of corporate characteristics that are correlated with size, such as diversification and financial capability. Three recent

[7]In some applications, Scherer's data have been used to divide an industry's R&D expenditures between process and product R&D [Lunn (1986), Levin and Reiss (1988)] by assuming that each industry devotes to processes a percentage of R&D equal to the percentage of its patents assigned to processes. This assumption is suspect to the extent that process innovations are less likely to be patented (and more likely to be protected by trade secrecy) than are product innovations.

literature surveys [Scherer (1980), Kamien and Schwartz (1982), and Baldwin and Scott (1987)] have ably summarized findings concerning the two "Schumpeterian" hypotheses and related propositions. For this reason, our summary of results will be brief. We focus instead on the methodological issues raised by this substantial body of work.

3.1. Firm size and innovation

A literal reading of Schumpeter's (1942) classic discussion suggests that he was primarily impressed by the qualitative differences between the innovative activities of small, entrepreneurial enterprises and those of large, modern corporations with formal R&D laboratories. Nonetheless, the empirical literature has interpreted Schumpeter's argument as a proposition that there exists a continuous, positive relationship between firm size and innovation. With a few exceptions [e.g. Nelson et al. (1967), Gellman Research Associates (1976), Pavitt et al. (1987)], the Schumpeterian hypothesis about firm size has been tested by some type of linear regression of a measure of innovative activity (input or output) on a measure of size.

Several arguments (only some of which were suggested by Schumpeter) have been offered to justify a positive effect of firm size on inventive activity. One claim is that capital market imperfections confer an advantage on large firms in securing finance for risky R&D projects, because size is correlated with the availability and stability of internally-generated funds. A second claim is that there are scale economies in the technology of R&D. Another is that the returns from R&D are higher where the innovator has a large volume of sales over which to spread the fixed costs of innovation. Finally, R&D is alleged to be more productive in large firms as a result of complementarities between R&D and other nonmanufacturing activities (e.g. marketing and financial planning) that may be better developed within large firms.

Counterarguments to the proposition have also been suggested. Perhaps the most prominent is that, as firms grow large, efficiency in R&D is undermined through loss of managerial control. Also, as firms grow large, the incentives of individual scientists and entrepreneurs become attenuated as their ability to capture the benefits from their efforts diminishes. Indeed, Schumpeter (1942) himself suggested that this feature of the bureaucratization of inventive activity could undermine capitalist development.

The balance of evidence on the relationship between firm size and innovation has shifted over the past twenty-five years. In the mid-1960s, the studies of Horowitz (1962), Hamberg (1964), and Comanor (1967) found that R&D intensity, the ratio of R&D to firm size (usually measured by sales), increased weakly with size. Mansfield (1964), however, found little evidence of such a relationship.

Scherer (1965a, 1965b) suggested a more subtle relationship – that inventive activity, whether measured by input (personnel) or output (patents), increased more than proportionally with size up to a threshold, whereupon the relationship was either weakly negative or did not exist.

Several subsequent cross-sectional studies found evidence of a positive, monotonic relationship between size and R&D [Soete (1979), Link (1980), Loeb (1983), and Meisel and Lin (1983)]. Also a number of studies found a positive relationship in selected industries, particularly chemicals [Mansfield (1964), Grabowski (1968)]. Despite the lack of unanimity, Scherer's findings, confirmed to varying degrees by a number of other investigators [Phlips (1971), Malecki (1980), and Link (1981)], were widely regarded as the profession's tentative consensus by the early 1980's.[8]

Recent work has cast doubt on the basis for this consensus. Employing data from the FTC's Line of Business Program for 1974, Scherer (1984b) himself found that business unit R&D intensity increased with business unit size in about 20 percent of the sample lines of business; no size effect was detected in most of the remaining industries. A different dissenting note was sounded by Bound et al. (1984). Using a larger and more comprehensive sample of American firms than any previously employed to study the size-innovation relationship at the firm level, they found that R&D intensity first falls and then rises with firm size. Both very small and very large firms were found to be more R&D intensive than those intermediate in size. Cremer and Sirbu (1978), using data on French firms, obtained similar results.

Using data from the FTC's Line of Business Program combined with the Levin et al. (1987) survey of appropriability and technological opportunity conditions in industry, Cohen et al. (1987) resurrected the earlier consensus, although in a slightly different form. They showed that once care was taken to control for industry effects and distinguish between the size of the firm and that of the business unit, neither size variable significantly affected R&D intensity in the (selected) sample of R&D performers.[9] A threshold effect was found, however, though different from that found earlier by Scherer. Using Tobit and probit estimation techniques, Cohen et al. concluded that the size of the business unit – but not that of the firm as a whole – affected the decision of the business unit to engage in R&D. They also highlighted a point neglected by other studies in this tradition. The importance of the size variables was found to be minute,

[8]See, for example, the review of the literature by Kamien and Schwartz (1982), as well as Scherer's (1980) own account in his widely used textbook.

[9]Cohen et al. found, however, that their results were surprisingly sensitive to the presence of a mere seven outliers in a sample of over 2000 business units. Each of these observations appeared to be subject to some form of measurement error. When these observations are included in the sample, firm size had a very small, but marginally significant effect on R&D intensity. When the outliers were excluded, the effect vanished.

both in terms of variance explained (less than 1 percent) and magnitude of the coefficients (a doubling of mean firm size increased R&D intensity by only one or two tenths of 1 percent).

A distinctive feature of the study by Gellman Research Associates (1976) is the use of an output measure covering a broad spectrum of industries, a count of some 500 innovations judged by experts to be among the major innovations introduced in the United States between 1953 and 1973. They found that the share of innovations introduced by the largest firms was barely greater than their share of employment. This is roughly consistent with much of the regression literature. Contrary to the Schumpeterian hypothesis, but consistent with the findings of Bound et al. (1984) concerning R&D intensity, they also found that companies with fewer than 1000 employees accounted for 47.3 percent of the important innovations, although their share of employment was only 41.2 percent in 1963, the sample period midpoint. Scherer (1984b) suggested that small firms may be a more important source of innovation in the United States than elsewhere; he noted that in a methodologically similar study using data on significant innovations in the United Kingdom between 1945 and 1980 [Pavitt (1983)] the largest firms were found to have the highest ratio of innovations per employee. Pavitt et al. (1987), however, using an updated version of the same British data set, found that both very small and very large firms were responsible for a disproportionate share of innovations.

The most notable feature of this considerable body of empirical research on the relationship between firm size and innovation is its inconclusiveness. Apart from the measurement problems we have identified, there are at least two reasons for this apparent disarray. First, most of the samples used in the regression studies are highly non-random, and with a few exceptions [Bound et al. (1984), Cohen et al. (1987)], no attempt has been made to study the presence or the effects of sample selection bias. Many of the earlier firm-level studies confined attention to the 500 or 1000 largest firms in the manufacturing sector, and, quite typically, firms that reported no R&D were excluded from the sample.

Second, the studies vary in the degree to which they control for characteristics of firms (other than size) and industries, despite the demonstrated importance of firm and industry effects [Scott (1984)], and the likely collinearity between them and firm size.[10] A few studies controlled for industry effects with separate regressions for each industry [e.g. Mansfield (1968), Scherer (1984b)]; others used fixed industry effects [e.g. Bound et al. (1984), Scott (1984), Cohen et al. (1987)]. It is not, however, a simple matter to control properly for industry effects in a

[10] The size distribution of firms varies markedly across industries, in part because of differences in the degree of scale economies in production and distribution. Thus, there is good reason to believe that fixed industry effects are correlated with firm size and that the omission of such effects will bias estimates of the effects of size on innovation. Similarly, firm characteristics such as diversification and some measures of financial capability are correlated with firm size.

sample of data at the level of the firm, because most larger firms are aggregations of business units engaged in a variety of industries.

Most scholars who have attempted to control for industry effects have assigned each sample firm to a primary industry and then used either a fixed effects model or specific industry characteristics as covariates. Such assignments are typically made at the two-digit SIC level, a procedure that introduces measurement error to the extent that relevant industry characteristics exhibit substantial variance across the constituent four-digit industries. On the other hand, when industry assignments are made at the three- or four-digit level, there is also systematic mismeasurement, because many firms (and most large ones) conduct the bulk of their business outside their designated primary industry.

It is useful to reconsider briefly the Schumpeterian hypothesis in light of the fact that most large firms operate business units in numerous industries. Although some arguments advanced to rationalize Schumpeter's hypothesis refer to the overall size of the firm (e.g. the ability to overcome capital market imperfections), others are more plausible at the level of the business unit (e.g. cost spreading). Moreover, scale economies in R&D may be relevant to the firm as a whole or to the firm's activities in particular industries. Although the great majority of the studies we have discussed examine the effect of firm size on firm-level R&D, the Federal Trade Commission's Line of Business data make it possible to separate the effects of business unit and firm size. Scherer (1984b) and Scott (1984) studied the effects of business unit size on business unit R&D, while Cohen et al. (1987) examined the effects of both business unit and firm size on business unit R&D.

A methodological problem common to almost all the studies of the relationship between size and innovation is that they overlook the effect of innovation on firm growth (and hence, ultimately, firm size).[11] It is curious that the endogeneity of firm size, central to Schumpeter's notion of creative destruction, has been neglected, while the simultaneity associated with creative destruction has been recognized in some studies of the relationship between innovation and market concentration. This lacuna probably reflects the profession's primitive understanding of the determination of the size and growth of firms, an area of research that has just recently been revived.[12]

Two other critiques of the literature under review derive from exegesis of Schumpeter. Fisher and Temin (1973) argued that to the extent that Schumpeter's hypothesis can be given a clear formulation, it must refer to a relationship

[11]An exception is Mowery (1983b), who found that R&D contributed to firm survival over the period 1921 through 1946.

[12]Although some effort was devoted to this question decades ago [Simon and Bonini (1958), Mansfield (1962), Scherer (1965c)], relatively little work has been done until recently [e.g. Gort and Klepper (1982), Klepper and Graddy (1986), Evans (1987a, 1987b), Hall (1987), and Pakes and Ericson (1987)].

between innovative output and firm size, not to a relationship between R&D (an innovative input) and firm size, which is the one most commonly tested in the literature. They demonstrated, among other things, that an elasticity of R&D with respect to size in excess of one does not necessarily imply an elasticity of innovative output with respect to size greater than one. Kohn and Scott (1982) established the conditions under which the existence of the former relationship does imply the latter.

More fundamentally, Markham (1965) and Nelson et al. (1967) suggested that most empirical studies tend to test a proposition that is quite different from Schumpeter's. They argued that Schumpeter did not postulate a continuous effect of firm size on innovation. Rather, by the time he wrote *Capitalism, Socialism, and Democracy*, he believed that industrial research no longer depended upon the initiative and genius of independent entrepreneurs; it had become the province of professional R&D laboratories run by large, bureaucratic corporations. Neither Schumpeter nor Galbraith (1952), who elaborated the argument, indicated that inventive activity should increase more than proportionately with firm size. The proposition was a weaker one, suggesting that formally organized R&D labs administered by large corporations are the source of most innovation in modern capitalist society.[13]

Even in this weaker form, Schumpeter's proposition is controversial. There is little doubt that large firms account for most of the R&D undertaken. For example, Scherer (1980), using NSF data, found that in 1972 U.S. firms with 5000 or more employees accounted for 89 percent of all R&D expenditures, but only 53 percent of manufacturing employment. It is much less clear that large firms are the source of most innovations. Indeed, Scherer found that a sample of 463 of the 500 largest manufacturing firms in 1955 contributed a share of the U.S. patents that was barely greater than their share of employment.

Recent work by Acs and Audretsch (1987) and Dorfman (1987) has indicated that the relative contributions of small and large firms to innovation may depend on industry conditions, and in particular on market structure. Acs and Audretsch found that large firms are more innovative in concentrated industries with high barriers to entry, while smaller firms are more innovative in less concentrated industries that are less mature. In a comparative study of four electronics industries, Dorfman (1987) reached a similar conclusion.

Some of the arguments rationalizing the hypothesized relationship between innovation and size suggest the existence of a direct relationship between innovation and other attributes of firms that are typically correlated with size. For example, a link between innovation and a firm's internally-generated funds is suggested by the argument that large firms are favored by the availability of

[13] We thank Richard Nelson for urging us to distinguish between Schumpeter's views and the profession's interpretation of those views.

internal funds in a world of capital market imperfections. A link between diversification and innovation is suggested by the argument that large firms are better positioned to exploit complementarities among their diverse activities.

A number of scholars have studied the influence of these correlates of firm size.[14] Cash flow, a measure of internal financial capability, has been the most thoroughly examined [e.g. Mueller (1967), Grabowski (1968), Elliot (1971), Branch (1974), Teece and Armour (1977), Kamien and Schwartz (1978), Armour and Teece (1981), and Link (1981)]. Many, but not all, of the studies, have found that a firm's cash flow is associated with higher levels of R&D intensity. Scholars have disagreed over the interpretation of this finding. Some have argued that it is difficult to distinguish cash flow as a measure of liquidity from its possible function as a signal of the future profitability of R&D investment [Elliot (1971)]. Others question whether cash flow encourages R&D or whether it simply reflects the profitability of past R&D [Branch (1974)].[15]

The other widely studied corporate attribute is diversification. The influence of product diversification upon basic research spending was first suggested by Nelson (1959), who argued that, because the results of basic research are inherently unpredictable, the diversified firm possesses more opportunities for the internal use of new knowledge. This argument implicitly assumes what Arrow (1962) later enunciated clearly: the market for information is imperfect and appropriability is better achieved by the internal application of knowledge than by its sale.

The most frequently tested variant of the Nelson hypothesis is that a higher degree of diversification encourages R&D expenditures. Scherer (1965a) found that an index of diversification was highly significant and explained considerable variance when introduced into simple cross-section regressions of patents and R&D intensity on firm size. The effect of diversification, however, was barely discernible in separate regressions at the two-digit industry level, which suggests

[14] We focus here on work done by economists concerning traditional economic attributes of firms. There are extensive literatures concerned with the effects on innovative performance of numerous organizational, managerial, sociological, and social psychological attributes of firms. A notable study that assessed the firm characteristics favorable to innovations was the SAPPHO project. In a detailed study of 43 matched pairs of successful and unsuccessful innovations, Rothwell et al. (1974) found that the most important determinants of success were: (1) close attention to user needs, (2) effective marketing (3) efficient management of the development process, (4) ability to utilize outside technology and communicate with the external scientific community in areas specifically relevant to the innovation, and (5) project management in the hands of a relatively senior individual who could serve effectively as a "product champion" within the organization. Rothwell et al. found that measures of firm size did not distinguish successful from unsuccessful innovations. Additional discussion of the SAPPHO project and related research on innovation is found in Freeman (1982).

[15] There is reasonably robust evidence, from case studies [Mansfield et al. (1971)] and from econometric work [Ravenscraft and Scherer (1982)], that the mean lag in returns from R&D expenditure is on the order of four to six years.

that Scherer's diversification measure may have reflected the influence of omitted two-digit industry effects in the full cross-section.

Subsequent results have been mixed. For example, Grabowski (1968) found that diversification encouraged R&D spending in chemicals and drugs, but not in petroleum; McEachern and Romeo (1978) got precisely the opposite results. More recently, Scott and Pascoe (1987) examined the hypothesis that R&D expenditures depend on the particular pattern of a firm's diversification. They found that when a firm diversifies into technologically-related industries, its pattern of R&D expenditures differs from the case where diversification is not so "purposive". In particular, such a firm tends to allocate a large share of R&D to industries in which appropriability is high. MacDonald (1985) looked at the reverse direction of causation, attempting to explain a firm's direction of diversification as a consequence of accumulated intangible R&D capital in its primary industry.[16]

The absence of robust findings concerning the roles of diversification and cash flow is unsurprising, since this research is beset with many of the problems discussed in connection with studies of the influence of firm size. For example, with the exception of Doi (1985), little attention has been paid to the influence of industry-level variables. Also, measurement problems are pervasive. Accounting measures of cash flow are deceptive to the extent that R&D and other investments in intangible capital are expensed and not capitalized [Grabowski and Mueller (1978)], and diversification is often represented by crude measures, such as the number of industries in which the firm participates.

Most of the literature considered thus far focuses on attributes that are hypothesized to make an individual firm most innovative – size, liquidity, and diversification. In a remarkable collection of case histories of 61 innovations, Jewkes, Sawers and Stillerman (1958; 2nd edn. 1969) illustrated that the innovative process within industries is considerably more complex than this focus implies. They argued that innovation is realized through the interactions of firms that are distinguished by size, expertise, and other attributes. For example, large firms tend to buy out small ones to bring an innovation to market, and they often enter into contracts with small firms or independent inventors to acquire critical skills or knowledge. In a view subsequently echoed by Nelson, Peck and Kalachek (1967), Scherer (1980) and Dorfman (1987), Jewkes, Sawers and Stillerman suggested that, "It may well be that there is no optimum size of firm but merely an optimal pattern for any industry, such a distribution of firms by

[16]Among the other corporate characteristics that might influence innovative activity is a firm's degree of vertical integration. Little quantitative work has been done in this area, but some case studies suggest the presence of economies of scope to R&D in vertically-related industries. For example, Malerba's (1985) work on the semiconductor industry suggests that the advantages of vertical integration for innovative activity have varied over the life cycle of the technology.

size, character and outlook as to guarantee the most effective gathering together and commercially perfecting of the flow of new ideas" (1969, p. 168). This conjecture provides a subtle view of the innovative process that undermines the quest to identify any single type of firm that is most innovative.

The conjecture of Jewkes, Sawers and Stillerman should be interpreted as an invitation to pursue the inquiry begun by Nelson (1986, 1989) to explore the complementarities and relationships among firms and other institutions (e.g. universities, technical societies, government) that facilitate successful innovation. We need to consider the circumstances under which a division of labor between the institutions generating new knowledge and the firms engaged in its commercialization occurs and is efficient. We also need to consider the circumstances under which the generation of new knowledge requires the cooperation of firms within an industry or the cooperation of firms with their customers or suppliers. Some theoretical work has considered the first of these issues in the context of licensing [e.g. Katz and Shapiro (1985a), Shepard (1987), Farrell and Gallini (1988)] and the second of these issues in the context of cooperative R&D [e.g. Katz (1986)]. Economists have, however, contributed little empirical research on these subjects, although there has been some econometric work on licensing [Wilson (1977), Caves et al. (1983)] and cooperative R&D [Link and Bauer (1987, 1988)], as well as descriptive studies of cooperative R&D [Johnson (1973), Peck (1986), Mowery (1988)] and the role of users and suppliers in innovation [e.g. von Hippel (1988)].

To enrich further the vision of Jewkes, Sawers and Stillerman, it would be useful to know how the distribution of firms types and relationships varies with industry conditions, such as appropriability and technological opportunity. No research has yet addressed this daunting agenda of considering the effects of various combinations of firm, contractual, and industry characteristics on innovative acivity and performance.

3.2. Monopoly and innovation

In Schumpeter's discussion of the effects of market power on innovation, there are two distinct themes. First, Schumpeter recognized that firms required the expectation of some form of transient market power to have the incentive to invest in R&D. This is, of course, the principle underlying patent law; it associates the incentive to invent with the expectation of ex post market power. Second, Schumpeter argued that an ex ante oligopolistic market structure and the possession of ex ante market power also favored innovation. An oligopolistic market structure made rival behavior more stable and predictable, he claimed, and thereby reduced the uncertainty associated with excessive rivalry that tended to undermine the incentive to invent. He also suggested, implicitly assuming that capital markets are imperfect, that the profits derived from the possession of ex ante market power provided firms with the internal financial resources necessary to invest in innovative activity.

The empirical literature has focused principally on the effects of concentration on innovative behavior. The literature has thus directly tested Schumpeter's conjectures about the effects of ex ante market structure and only indirectly tested his claims about ex ante market power. In the empirical work that explores the effects of expected ex post market power on innovation, most of it quite recent, traditional measures of market structure have not usually been employed. Rather, the potential for achieving ex post market power through innovation has been characterized under the general heading of appropriability conditions and measured by specific indicators of appropriability, which are discussed in the next section.

Economists have offered an array of theoretical arguments yielding ambiguous predictions about the effects of market structure on innovation. Some have supported Schumpeter's position that firms in concentrated markets can more easily appropriate the returns from inventive activity. Others have demonstrated, under the assumption of perfect ex post appropriability, that a firm's gains from innovation at the margin are larger in an industry that is competitive ex ante than under monopoly conditions [Fellner (1951), Arrow (1962)]. Still others have argued that insulation from competitive pressures breeds bureaucratic inertia and discourages innovation [e.g. Scherer (1980)].

The majority of studies that examine the relationship between market concentration and R&D have found a positive relationship [first among many were Horowitz (1962), Hamberg (1964), Scherer (1967a), and Mansfield (1968)]. A few have found evidence that concentration has a negative effect on R&D [e.g. Williamson (1965), Bozeman and Link (1983), and Mukhopadhyay (1985)]. A finding that captured the imagination of numerous theorists was that of Scherer (1967a), who found evidence of a non-linear, "inverted-U" relationship between R&D intensity and concentration. Scherer found, using data from the Census of Population, that R&D employment as a share of total employment increased with industry concentration up to a four-firm concentration ratio between 50 and 55 percent, and it declined with concentration thereafter. This "inverted-U" result, in the context of a simple regression of R&D intensity against market concentration and a quadratic term, has been replicated by other scholars using the FTC Line of Business data [Scott (1984), and Levin et al. (1985)].

Phillips (1966) was among the first to propose that industrial organization economists should explore the possibility that causality might run from innovation to market structure, rather than in the reverse direction. Although Schumpeter envisioned that the market power accruing from successful innovation would be transitory, eroding as competitors entered the field, Phillips argued that, to the extent that "success breeds success", concentrated industrial structure would tend to emerge as a consequence of past innovation. Phillips' (1971) monograph on the manufacture of civilian aircraft provides a brilliant illustration of how market structure can evolve as a consequence of innovation, as well as how it can affect the conditions for subsequent innovation.

Theoretical support for the proposition that a rapid rate of innovation leads to concentration can be found in the literature on stochastic models of firm growth, notably in the simulation models of Nelson and Winter (1978, 1982b). Most analytic results concerning this and related propositions, however, are asymptotic [see Rothblum and Winter (1985)]. By contrast, in the short run, the presence of long-lived capital and costly adjustment by firms and consumers implies that innovation, even dramatic innovation, can make a market more or less concentrated, a proposition for which Mansfield (1983) finds empirical support. The short-run effect of innovation on market structure depends, in part, on whether established leaders or new entrants are the source of innovation.[17]

Recognizing the potential simultaneity between innovation and concentration, some investigators [Howe and McFetridge (1976), Levin et al. (1985)] have used instrumental variables for concentration in regression studies of the effects of market structure on innovative activity. Others [Farber (1981), Levin (1981), Wahlroos and Backstrom (1982), Connolly and Hirschey (1984), Levin and Reiss (1984, 1988)] have used industry-level data to estimate multi-equation models in which concentration and R&D are both treated as endogenous.[18] There is a suggestion that such techniques are appropriate. Levin (1981), Connolly and Hirschey (1984), Levin and Reiss (1984), and Levin et al. (1985) all find that Wu–Hausman tests reject the hypothesis (maintained in the OLS specification) that the concentration variables are orthogonal to the error term. This result, however, may well arise from misspecification or omitted variables. In any event, Howe and McFetridge (1976) found that, relative to ordinary least squares, two-stage least squares produced little change in the coefficient on the concentration term in the R&D equation.

Perhaps the most persistent finding concerning the effect of concentration on R&D intensity is that it depends upon other industry-level variables. Scherer (1967a) found that the statistical significance of concentration was attenuated

[17]Innovation can also affect market structure by increasing or decreasing the efficient scale of production. If technological change causes the efficient scale of a firm to grow more rapidly than demand, concentration tends to increase over time. For a theoretical treatment in which such changes in scale and concentration are both endogenous, see Levin (1978). For evidence that technical change has increased efficient scale in various industries, see Hughes (1971) on electric power generation, Levin (1977) on several chemical industries, and Scherer et al. (1975) on steel, cement, brewing, refrigerators, paints, and batteries.

[18]Data limitations have made it convenient to treat concentration and R&D intensity as *simultaneously* determined variables, but this is inconsistent with the underlying Schumpeterian theory, as interpreted by Phillips (1966, 1971). Contemporaneous concentration, in this view, should indeed influence R&D spending, but current concentration is the consequence of past innovative activity. Only Levin (1981) estimates a model in this form, where a distributed lag of past R&D investment, not the current R&D intensity, appears on the right-hand side of the concentration equation.

with the addition of dummy variables classifying the industry's technology (chemical, electrical, mechanical, and traditional) and its products (durable/ non-durable, consumer/producer goods). The dummy variables, especially those representing technology classes, were highly significant, and they explained considerably more variance in the dependent variables than did concentration. Wilson (1977) attained similar results, and Lunn and Martin (1986), splitting their sample into two technology classes, found that concentration had a significant effect on R&D intensity only in "low opportunity" industries.

Among others who have found the validity of the Schumpeterian hypothesis to depend on industry characteristics, Comanor (1967) found that the degree of product differentiation conditioned the relationship between concentration and R&D intensity, but he used advertising intensity, a jointly determined decision variable, to represent what should more properly have been represented by a set of predetermined product characteristics. Somewhat more defensibly, Shrieves (1978) obtained a similar result by classifying industries according to the nature of the final product market.[19] Angelmar (1985) suggested that the effect of concentration on innovation might depend on the degree of technological uncertainty, but the appropriateness of his measure of uncertainty – the average lag between initiating the development of a new product and its market introduction – is subject to serious doubt. Mueller and Tilton (1969) offered some evidence that the role of market structure depends importantly upon the industry's stage in the technology life cycle.

Scott (1984) and Levin et al. (1985) provide strong evidence that results concerning the effect of concentration on innovation are sensitive to industry conditions. Using the FTC data on R&D intensity at the business unit level, Scott found that the addition of fixed company and two-digit industry effects rendered statistically insignificant the coefficients on concentration and its square. Using the FTC data at the line of business level (a level of aggregation between the three- and four-digit SIC level), Levin et al. found that the addition of a set of measures representing technological opportunity and appropriability conditions (at the line of business level) replicated Scott's result in equations for both R&D intensity and innovative performance. With the new variables added, the coefficient and the *t*-statistic on concentration dropped by an order of magnitude in the R&D equation.[20]

Moreover, concentration contributes little to an explanation of the variance in R&D intensity. Scott found that line of business concentration and its square explained only 1.5 percent of the variance in R&D intensity across 3388 business units, whereas fixed two-digit industry effects explained 32 percent of this

[19]Shrieves classified industries on the basis of a factor analysis that took account of the composition of industry demand and the durability of the product.

[20]Geroski (1987) obtained a similar result using the SPRU data on British innovations and controlling for various industry conditions.

variance. Similarly, our re-examination of the data used in Levin et. al. (1985) revealed that concentration and its square explained only 4 percent of the variance in R&D intensity across 127 lines of business, whereas Cohen et al. (1987) reported that demand, opportunity, and appropriability measures explained roughly half of the between-industry variance. Together, these results leave little support for the view that industrial concentration is an independent, significant, and important determinant of innovative behavior and performance.

The conclusion that market concentration may exercise no independent effect on R&D intensity suggests that there may be no Schumpeterian tradeoff between innovation and the ex ante market power conferred by concentration. Recall, however, that Schumpeter also argued that the expectation of ex post market power acquired by successful innovation provides an important incentive to undertake inventive activity. Indirect evidence that this latter tradeoff exists can be provided by a demonstration that the ability of the firms to appropriate the returns from innovation encourages R&D investment. Recent work using the Levin et al. (1987) survey data [e.g. Levin et al. (1985), Cohen et al. (1987)] has begun to generate such evidence.

3.3. Evaluation of empirical research in the Schumpeterian tradition

The empirical results concerning how firm size and market structure relate to innovation are perhaps most accurately described as fragile. The failure to obtain robust results seems to arise, at least in part, from the literature's inadequate attention to the dependence of these relationships on more fundamental conditions. This overview highlights the basic methodological lesson that the omission of important and potentially correlated variables that influence the dependent variable – in this case, some measure of innovative activity or performance – can lead to misleading inferences concerning the effects of explanatory variables of particular interest – in this case, firm size and concentration. A clear implication is that further evaluation of the Schumpeterian hypotheses should take place within the context of a more complete model of the determination of technological progress.

Obtaining a better understanding of the Schumpeterian hypotheses is only one reason to move toward more complete models of technological change. There are other good reasons to move the profession's agenda beyond the Schumpeterian hypotheses and to focus attention on more fundamental determinants of technological progress. First, the effects of firm size and concentration on innovation, if they exist at all, do not appear to be important. Second, the welfare gains associated with technological progress are likely to be large relative to the efficiency losses associated with imperfect market structure.[21] Third, we have, at present, only a limited understanding of the primary economic forces driving innovation and how they differ across industries.

We thus proceed to consider the present state of empirical research on those fundamental determinants of innovation that appear to vary substantially across industries.

4. Industry characteristics

In seeking to understand why industries differ in the degree to which they engage in innovative activity, empirical researchers have come to classify explanatory variables under three headings: product market demand, technological opportunity, and appropriability conditions. Although the importance of each of these classes of variables has been acknowledged and illustrated in the historical literature and in case studies, economists have made relatively little progress in specifying and quantifying their influence. As we have suggested, one reason for this relative neglect has been the profession's preoccupation with the effects of firm size and market structure. Another reason is the absence of a clear and precise understanding of how the forces classified under the headings of technological opportunity and appropriability should be conceptualized and given operational definitions. Finally, even where a particular variable is well defined and a clear hypothesis is formulated regarding its influence, the data necessary for empirical work are often unavailable or unreliable.[22]

In the subsections that follow, we summarize and interpret what is known about how demand, technological opportunity, and appropriability conditions vary across industries and how they contribute to an explanation of interindustry differences in innovative activity and performance. We also offer suggestions to guide further exploration of this still relatively uncharted terrain.

[21] For example, suppose an economy could eliminate all dead weight loss and experience a 2 percent growth rate of productivity or it could tolerate a 10 percent dead weight loss and experience a 3 percent growth rate of productivity. It can be shown that, for any real social discount rate below 12 percent, total welfare over an infinite horizon would be greater under the more dynamically efficient regime. If the dead weight loss were only 5 percent, the higher growth rate would be preferred for all social discount rates under 22 percent.

[22] For example, a straightforward implication of many models is that interindustry differences in R&D investment can be explained in part by the parameters of industry demand functions. The researcher who hopes to estimate such a model, however, must choose between two unpleasant alternatives: locating data of suitable quality to identify and estimate demand functions for each industry in the sample or extracting from the literature a set of previously estimated parameters that are likely to be internally inconsistent or unreliable.

4.1. Demand

In his seminal work on technological change in various capital goods industries, Schmookler (1962, 1966) demonstrated that cycles in the output of capital goods and in capital expenditures by downstream industries "led" cycles in the time series on relevant capital goods patents. He argued from these findings that demand, rather than the state of technological and scientific knowledge, determined the rate and direction of inventive activity. Schmookler's contribution sparked a lively debate among economic historians and other economists concerning whether "demand-pull" or "technology-push" was the primary force behind technological change. In the terminology that has since come into use in industrial organization, the debate was about the relative importance of demand and technological opportunity.[23]

In arguing for the primacy of demand, Schmookler claimed that scientific knowledge and technological capability were applicable to a wide range of industrial purposes. Although he recognized that generic knowledge and capability tend to grow, he argued that at any point in time a common pool was uniformly available for industrial application. The industries that made use of this common resource, that made their own complementary investments in applied research and in process and product development, were those induced to do so by large and growing markets. Though he presented an impressive array of data to support the view that demand matters, Schmookler never attempted to test the maintained hypothesis that the supply conditions for innovation (technological opportunities) were uniform across industries.

Schmookler's proposition that demand almost alone determines the rate and direction of technical change has not survived empirical scrutiny. The consensus, after dozens of case studies, is that the Marshallian scissors cuts with two blades. Perhaps the most persuasive refutation of Schmookler's proposition is offered by Parker (1972) and Rosenberg (1974), who document several important historical examples (e.g. the mechanization of hand operations in agriculture, the use of coal as an industrial fuel) in which the sequence of particular applications of a "generic" technological idea was determined not by demand, but by the state of knowledge and inherent technological complexity of particular industrial applications. More recently, Scherer (1982c) offered statistical evidence that both blades matter. He found that dummy variables classifying industries by technology (chemical, electrical, mechanical, etc.) and variables representing demand conditions were statistically significant in a regression analysis of line of business patenting activity, but the technology variables explained considerably more variance.

[23]The early debate has been thoroughly reviewed by Mowery and Rosenberg (1979) and does not require detailed attention here.

A particularly interesting perspective on the demand-pull/technology-push debate is offered by Walsh (1984), who combined the case study approach with the time series methods of Schmookler. Walsh found that in several chemical industries the production series does indeed lead the patent series, but growth in production tends to follow not large numbers of patents, but one or several major innovations. An interpretation of this pattern is that relatively exogenous major innovation induces growth in demand, which in turn creates the incentive for subsequent incremental innovation.

The suggestion that major technological innovations may induce changes in demand, obvious as it may seem to the historian, gives pause to the economist, who typically models tastes as given and immutable. No reasonable economist believes that tastes never change. When we claim that demand, technological opportunity, and appropriability are "more fundamental" than firm size or market concentration in determining interindustry differences in the rate and direction of technological change, we are not asserting that the former conditions are strictly exogenous and the latter endogenous. We are simply suggesting that the demand, technological opportunity, and appropriability conditions confronting an industry tend to change more slowly than firm size and market structure, and, therefore, these conditions are reasonably taken as given for purposes of analyzing interindustry differences in innovative activity and the evolution of market structure.

There are two principal respects in which interindustry differences in demand conditions might be expected to affect the incentives to engage in innovative activity. First, as Schmookler himself emphasized, there is the size of the market, which might be represented in static terms by a scale parameter and in dynamic terms by a rate of growth. The argument is straightforward. The (expected) investment required to produce a given reduction in unit cost or a given improvement in product quality is independent of the level of output that will be produced once the innovation is made. The benefits realized by such investment, however, are proportional to the size of the market in which the innovation is used. More inventive activity would therefore be expected in the larger of two markets, holding constant the cost of innovation; in two markets of equal size, more inventive activity would be expected in the market that is expected to grow more rapidly.

Second, Kamien and Schwartz (1970) suggested that the price elasticity of demand will also affect the marginal returns to investment in R&D. They demonstrated that the gains from reducing the cost of production (process innovation) are larger the more elastic is demand. On the other hand, Spence (1975) demonstrates that the gains from improvement in product quality (product innovation) will, under many circumstances, be larger the more inelastic is demand, since inelastic demand tends to magnify the gains from a rightward shift in the demand curve. Thus, the effect of price elasticity will be ambiguous in empirical studies that do not distinguish between process and product innovation.

The distinction between process and product innovation raises the subtle conceptual and operational question of how to characterize the demand conditions relevant to product innovation. In the case of intermediate products, such as those studied by Schmookler, there is no mystery. The demand function for inputs of higher quality can in principle be derived from estimates of final product demand and the downstream production technology. It is more difficult to characterize and estimate the demand for consumer product innovation. A variety of econometric techniques can be used to estimate the demand for routine improvements in some measurable dimension of product quality (e.g. hedonic price models, Lancasterian demand models, and discrete choice models, where applicable). Such techniques, though useful in particular applications, are unlikely to be fruitful in cross-industry analysis, since they require very detailed data and special modelling efforts for each specific product.[24] A vastly more difficult problem is posed by major innovations that introduce an entirely new product (e.g. the television, the automobile). In such cases, there is no straightforward way to characterize latent demand from data on existing products, particularly if one acknowledges that tastes themselves may change as a consequence of a major innovation.

In regression studies of R&D investment, demand conditions, although rarely featured, have often been considered. To capture market size and growth effects, sales and the rate of growth of sales are typically used, despite the obvious problem that these variables measure not demand conditions, but the endogenous interaction of demand and supply conditions. A variety of categorical variables have been used, presumably as proxies for interindustry differences in price elasticity. Most common are those distinguishing durables from non-durables, as well as those distinguishing consumer goods from material inputs or investment goods. Some researchers have used input–output data on the disposition of industry output (i.e. the shares of output destined for personal consumption, intermediate use, exports, the government sector, etc.). Although these categorical and input–output variables are sometimes statistically significant in regressions explaining a measure of innovative activity, there are no notably robust findings.

In an attempt to develop demand measures that conform more closely to the requirements of theory, Levin (1981) calculated, from a set of estimated constant elasticity demand functions for consumer goods and the input–output table,

[24] Economists have used such techniques in a variety of applications, notably in predicting demand for new transport alternatives, a problem for which discrete choice models are particularly well suited. Economists have done little, however, to estimate the demand for new consumer products, though a variety of techniques, using both market and consumer survey data, have been employed by scholars in the fields of marketing [e.g. Keeney and Lilien (1987)] and technological forecasting [e.g. Alexander and Mitchell (1985)].

three demand parameters for each four-digit industry: a price elasticity, an income elasticity, and an exponential shift parameter. Although these parameters were significant as explanatory variables in simple regressions of R&D intensity on size and other industry characteristics [Cohen et al. (1987)], their contamination with measurement error may have hampered their usefulness in the estimation of more complex specifications [Levin and Reiss (1984, 1988)].[25]

4.2. Technological opportunity

Much of the empirical literature takes for granted that innovation, at prevailing input prices, is "easier" (less costly) in some industries than in others. Although it is widely accepted that industries differ in the opportunities they face for technical advance, there is no consensus on how to make the concept of technological opportunity precise and empirically operational. In the framework of the standard neo-classical theory of production, technological opportunity can be regarded as the set of production possibilities for translating research resources into new techniques of production that employ conventional inputs. Some theoretical treatments have thus represented technological opportunity as one or more parameters in a production function relating research resources to increments in the stock of knowledge, with the stock of knowledge entering in turn as an argument, along with conventional inputs, in the production function for output [Griliches (1979), Pakes and Schankerman (1984)]. Related approaches treat technological opportunity as the elasticity of unit cost with respect to R&D spending [Dasgupta and Stiglitz (1980a), Spence (1984)], as a shift parameter determining the location of an innovation possibility frontier representing the tradeoffs in the direction of technical change [Levin (1978)], and as a shift parameter determining the location of a frontier describing the tradeoff between the time and cost of an R&D project [Scherer (1984b)].

These formulations lend themselves in principle to direct econometric estimation, if only adequate data were available to identify the technological opportunity parameter(s) and other relevant parameters for each industry. To date, only Pakes and Schankerman (1984) have attempted this type of structural estimation. The panel data they used did not permit identification of the parameter representing technological opportunity or its contribution to the explanation of variance in R&D intensity. They were, however, able to identify the fraction of

[25] The quality of industry-level price elasticities does not inspire confidence. Mueller (1986) could not reject the hypothesis that Levin's price elasticities were uncorrelated with another set of estimates provided by Ornstein and Intriligator.

variance explained jointly by opportunity and appropriability, which they found to be substantial.

Most other attempts to represent technological opportunity as a determinant of innovative activity in regression studies have followed the practice introduced by Scherer (1965a), who classified industries on the basis of the scientific or technological field with which each was most closely associated. Scherer's initial classificatory scheme (chemical, electrical, mechanical) was refined in his subsequent work (1967a, 1982c), and variants have been used by numerous investigators.[26] Although Scherer's intention was to capture interindustry differences in the vigor of advance of underlying scientific and technological knowledge, he recognized that statistical results obtained with the use of such crudely defined categorical variables might also reflect the influence of unspecified industry practices or demand effects not captured by other regressors. Nonetheless, the simple classification of industries into a small number of technology groups has powerful statistical consequences; it has explained a substantial fraction of variance in patenting activity [Scherer (1965a, 1982c)] and R&D intensity [Scott (1984)].

Several investigators have used proxy variables thought to be associated with technological opportunity to explain innovative activity. Shrieves (1978) performed factor analysis on the distribution of scientific and technological employees by field across 411 firms to develop several technology factors; these constructed variables fared poorly in a regression analysis of R&D expenditures. Jaffe (1986) used data on the distribution of patents across patent classes to assign firms to twenty "technological opportunity clusters". The vector of cluster dummies was statistically significant in regressions to explain interfirm differences in patents, profits, and Tobin's q. Jaffe found, however, that conventional industry dummy variables performed equally well.[27]

In the optimization model of Levin and Reiss (1984), specific parameters of the cost function were interpreted as unobservable measures of technological opportunity and appropriability conditions. Each parameter was then formally treated as a function of observable variables. To represent technological opportunity, Levin and Reiss augmented a set of technology class dummy variables with measures of industry age (intended to capture the effects of technological life cycles), the fraction of R&D devoted to basic research (intended to capture an industry's "closeness" to science), and government R&D (intended to capture

[26]Some scholars have attempted to represent technological opportunity by assigning industries to "high" and "low" technological opportunity groups [Wilson (1977), Link and Long (1981), Lunn and Martin (1986)]. This practice introduces considerable risk of selecting on the dependent variable.

[27]Waterson and Lopez (1983) attempted to explain interindustry differences in R&D intensity in the United Kingdom with two variables claimed to be closely related to technological opportunity: capital intensity and the contemporaneous rate of labor productivity growth. The justification for an association of opportunity with capital intensity is questionable, and it seems inappropriate to treat productivity growth as exogenous.

externally generated opportunities for privately-funded R&D). Each of these variables was statistically significant in an equation for R&D intensity.

The survey of R&D executives in 130 lines of business discussed by Levin et al. (1987) attempted to measure several variables thought to represent an industry's technological opportunity. Among these are measures of the contribution of various basic and applied sciences to each industry's technological advance and the contribution of several other external sources of technical knowledge – upstream suppliers of the industry's materials, production, and research equipment, downstream users of the industry's product, universities, government agencies and labs, professional and technical societies, and independent inventors. Although these survey variables, constructed from responses along a semantic scale, are contaminated with considerable measurement error, they have performed well in regression studies of innovative activity. Levin et al. (1985), Cohen et al. (1987), and Cohen and Levinthal (1988b) have all found opportunity variables representing closeness to science and the sources of extraindustry knowledge to be jointly significant and to explain a substantial fraction of interindustry variance in R&D intensity.[28] The survey variables performed less well in estimates of the more structured optimization model of Levin and Reiss (1988), reflecting no doubt the shortcomings of the highly stylized model as well as the imprecision of the data.

For a fuller account of the role of technological opportunity, it is useful to consider the rich institutional and historical literature, as well as a few interesting theoretical conjectures. Consider first the role of science. Among economists, Rosenberg (1974) has argued most strongly for a close link between scientific and technological advance. Although he gave a convincing account of why certain technological innovations could not have occurred without certain foundational scientific advances, he did not provide historical examples to support the stronger claim that advances in science lead to technological innovation.

In a case study of the invention of the transistor, Nelson (1962) demonstrated that the contribution of science to invention is by no means simple. He explained, first, that the essential scientific knowledge required and utilized by the inventors of the transistor was in place more than fifteen years before the invention. He also illustrated how scientific knowledge directed and structured the thinking of the Bell Labs' research team at various steps along the way to the

[28]To the extent that the relevance of science and the contribution of extraindustry knowledge sources reflect an industry's technological opportunity, one would expect a positive relationship between these variables and innovative output. Greater opportunity, however, need not imply greater expenditure on R&D. Thus, Levin et al. (1985) found that each measure of opportunity derived from the R&D survey had a positive coefficient in an equation to explain each industry's self-reported rate of innovation. Levin et al. (1985) and Cohen et al. (1987), however, found that an increase in the contribution of its equipment suppliers *reduced* an industry's own R&D intensity, while increased contributions from the users of the industry's product and from government agencies and laboratories increased own R&D intensity.

ultimate discovery. Most remarkably, however, the invention of the device itself preceded and actually triggered the inquiry leading to a full scientific understanding of how it worked.[29]

Rosenberg (1974) also suggested a simple mechanism by which the growth in scientific knowledge encourages innovation; he claimed that "as scientific knowledge grows, the cost of successfully undertaking any given, science-based invention declines..." (p. 107). Conceptualizing R&D as a stochastic search process, Evenson and Kislev (1976) and Nelson (1982a) suggested that "strong" science affects the cost of innovation by increasing the productivity of applied research. Nelson in particular argued that a "strong" science base narrows the set of research options and focuses attention on the most productive approaches. The consequence is that the research process is more efficient. There is less trial-and-error; fewer approaches need to be evaluated and pursued to achieve a given technological end. From this perspective, the contribution of science is that it provides a powerful heuristic to the search process associated with technological change.

The historical and case study literature also illustrate how the development of technology may follow a course that is relatively independent of market influences. At any given time, innovative efforts within an industry, or a complex of related industries, tend to be concentrated on a limited number of distinct, identifiable problems. A breakthrough in one area typically generates new technical problems, creating imbalances that require further innovative effort to realize fully the benefits of the initial breakthrough. Rosenberg (1969) identifies this phenomenon as a "compulsive sequence", citing examples from the history of technology in the machine tool industry. The development of high speed steel, for instance, improved cutting tools and thus stimulated the development of sturdier, more adaptable machines to drive them. Similar "bottleneck-breakthrough" sequences have been described in nineteenth-century textile manufacture, iron and steel, and coal and steam technology [Landes (1969)], in twentieth-century petroleum refining [Enos (1962)], and in other technologies [Ayres (1988)].

A related phenomenon is the tendency for technologies to develop along "natural trajectories".[30] The notion is that in certain instances technological development proceeds along a relatively clear path, as if moving toward some physical limit. Engineers do not move myopically from one bottleneck to the next; they repeatedly focus on a particular class of engineering problems, drawing upon and strengthening a familiar method of solution. A good example of a natural trajectory is the progressive extension of the range of output over which scale economies are attainable, which has been documented for electric

[29] Rosenberg (1982) elaborated the point that technological developments may stimulate and focus basic scientific research.

[30] The term is attributable to Nelson and Winter (1977); the idea has been further developed by Sahal (1981) and Dosi (1982).

power by Hughes (1971) and for several chemical industries by Levin (1977). For a period that lasted approximately twenty-five years in both cases, engineers understood that lower production costs were possible if they could solve the design problems associated with building bigger plants. Another example is the progressive miniaturization of semiconductor devices [Braun and Macdonald (1982), Levin (1982)]. In this instance, engineers have understood for more than three decades that a tighter packing of circuit elements would lead to higher speeds for performing logical or data storage operations, but a host of related technological problems – such as obtaining sufficiently pure materials and etching ever-finer lines in silicon – have required solution with each successive generation of devices.

Although the case study literature provides many examples, we know very little about the degree to which phenomena such as natural trajectories, compulsive sequences, and other "patterns" are representative of the manufacturing sector as a whole.[31] The presence of such identifiable "technological regimes" in at least some industries, however, suggests two potentially fruitful and complementary directions for empirical research. First, in such industries, the participants in the R&D process probably have a relatively clear idea about how to characterize technological opportunities and the constraints on technical advance. Thus, interview and questionnaire methods may be a particularly appropriate way to gather useful data. Second, where a particular natural trajectory or other technological regime is present, careful modelling on an industry-specific basis may permit identification and estimation of the technological opportunity parameters that have proven elusive in cross-industry econometric work. Indeed, within the context of particular, well-characterized technological regimes, questions concerning the optimal size of firms and the market organization most conducive to innovation might be re-examined.

Just as Nelson (1982a) argued that a strong science base narrows the set of approaches that a researcher must seriously evaluate to achieve a given techno-

[31]Another pattern, widely discussed in the institutional literature, is the idea that industries experience a life cycle over which the nature of innovation changes in a predictable manner [Abernathy and Utterback (1978) and Utterback (1979)]. In the early years of an industry's evolution, the emphasis is on product innovation, as numerous small firms compete to establish a market position. Radical new product ideas are tested, and eventually a "dominant design" emerges. With the dominant design comes product standardization and a new emphasis on process innovation. In this phase "natural trajectories" associated with process innovation are pursued; effort is concentrated on realizing the benefits of large-scale production, mechanization, improving production yields, etc. The industry becomes more concentrated, the potential for further process innovation is eventually exhausted, and the industry becomes subject to external threats from competing products that eschew the dominant design.

The life cycle model provides a coherent interpretation of the history of the U.S. automobile industry [Abernathy (1978)], but its generality may be limited. For example, the model fits the experience of some segments of the worldwide semiconductor industry (memory devices) but not the experience of others (logic devices and microprocessors).

logical objective, it might be argued that working within a particular technological regime narrows the set of objectives to be pursued, and hence the range of specific technological problems to be investigated. Linkages to science and natural trajectories can thus both be understood as ways of coping with, and reducing, the enormous uncertainty inherent in the complex decision problem of formulating an optimal R&D strategy.

Powerful heuristics are less readily available to guide firms at those historical moments when they face a choice among technological regimes. Such moments occur with some regularity, and they can have important consequences. In the transitions from steam to diesel locomotives, from propeller to jet aircraft engines, and from vacuum tubes to transistors, leading firms changed regimes too late or with too little commitment. In the spirit of creative destruction, established market structures were entirely overturned in each of these cases. Although economists have neither analyzed nor quantified the consequences of choosing among regimes when more than one is available (e.g. steam, electric, or gasoline engines for automobiles), they have considered the related issue of the impact of technical standards that permit the realization of external economies (e.g. a railroad gauge, a color television standard, a programming language). David (1985) has provided a fascinating account of how the QWERTY typewriter keyboard became "locked-in" despite the presence of a demonstrably superior alternative. Arthur (1985) has offered other examples and a theoretical explanation of why, in such cases, the hidden hand does not necessarily work its magic.[32]

Just as a close link to science and the availability of engineering heuristics affect an industry's technological opportunity, so does the contribution of technical knowledge from sources external to the industry: suppliers, customers, universities, technical societies, government, and independent inventors. A voluminous institutional literature documents the contribution of extraindustry spillovers to technological progress.[33] The case studies of Jewkes, Sawers and Stillerman (1958) contain instances of virtually every type of external influence. A notable example of institutional-empirical work on this subject is von Hippel's (1976, 1977, 1988) treatment of the contributions of users to technological development in a variety of industries, including scientific instruments and semiconductor process equipment. The contribution of universities to technological progress in industry, particularly in collaborative research ventures, has been the subject of numerous recent reports [e.g. Blumenthal et al. (1986)].

[32]Among others, Farrell and Saloner (1985, 1986) and Katz and Shapiro (1985b, 1986) have developed theoretical models in which the choice of a Pareto-inferior standard is possible. With appropriate modification, some of these models could be adapted to consider the selection of technological regimes.

[33]To cite just a few examples, Brock (1975) indicates that most of the computer industry's innovations could be traced to technological developments outside the industry. Peck (1962) makes the same point in his study of innovation in the aluminum industry.

By far the most extensively studied extraindustry influence on technological opportunity has been that of government. In numerous sectors – notably agriculture, aircraft, and electronics – government has contributed to reducing the cost of innovation by its own research, by subsidizing and sponsoring private sector research, and by disseminating or subsidizing the dissemination of technological knowledge developed in its own labs and elsewhere.[34] The distribution of government expenditures on R&D across industries is highly skewed, especially in the United States, where industries supplying the military are the principal recipients of R&D support.[35]

Although the government's influence on innovation through its direct role in the creation and dissemination of knowledge is substantial in some sectors, its indirect influence is also felt through a variety of other channels that have a differential impact across industries. Most important is the impact of government demand on the rate and direction of innovation.[36] Regulation has had an important impact on innovation in several industries by altering demand conditions, constraining legally permissible choices from the set of technological opportunities, and limiting appropriability.[37]

Just as spillovers from extraindustry sources may augment a recipient firm's technological opportunity, so may spillovers within an industry reduce the own R&D required to achieve a given level of technical performance. Within-industry spillovers, however, also reduce the incentive to engage in R&D, because a firm must share with its competitors the benefits of its investment. We defer further discussion of this incentive effect to the next subsection and focus here on what Spence (1984) calls the "efficiency effect" of spillovers – the extent to which they enhance technological opportunity.

There have been several recent econometric attempts to measure the efficiency effects of both extraindustry and intraindustry spillovers. Pursuing a method suggested by Griliches (1979), Jaffe (1986) used data on the distribution of patents by patent class to measure the technological relatedness of every pair of firms in a sample of over 500 firms. For each firm, he constructed a "spillover pool", defined as the sum of all other firms' R&D weighted by the measure of

[34]A good introduction to the role of government in the United States may be found in the collection of case studies edited and summarized by Nelson (1982b). For a survey of international differences in the contribution of government to technological development in the major OECD countries, see Nelson (1984). A modest econometric literature finds that government R&D and, particularly, government procurement expenditures have a significant impact on private R&D spending [Levy and Terleckyj (1983), Levin and Reiss (1984), Lichtenberg (1987, 1988)].

[35]Aircraft and missiles (SIC 372 and 376) received over 50 percent of the U.S. Federal government's total expenditures on industrial R&D in 1985. Electrical equipment (SIC 36) received over 25 percent [see National Science Board (1987)].

[36]See the case studies of semiconductors, computers, and aircraft in the Nelson (1982b) volume.

[37]See, for example, Temin (1979) and Grabowski and Vernon (1982) on pharmaceuticals, and Caves (1962) on civilian aircraft.

relatedness. He found that the size of the spillover pool had a powerful positive effect on a firm's patents.[38]

Bernstein and Nadiri (1988, 1989) took a more direct approach to estimating the magnitude of spillover effects, by including the R&D capital of other firms or industries in the cost function of the receiving firm or industry. They found evidence of large efficiency gains from both intraindustry and extraindustry spillovers.[39]

Most of the recent work on spillovers has presumed that knowledge acquired from both intraindustry and extraindustry sources is costless. In contrast, Evenson and Kislev (1973) and Mowery (1983a) observed that firms that invest in their own R&D are more capable of exploiting externally-generated knowledge. Extending this observation to a consideration of the incentives to engage in R&D, Cohen and Levinthal (1989b) formulated and tested a model in which firms deliberately invest in R&D with two purposes: to generate new knowledge and to develop "absorptive capacity" – the ability to recognize, assimilate, and exploit outside knowledge. In this model, to the extent that R&D is directed to the latter purpose, variables affecting the ease of learning influence R&D incentives. Using the FTC's Line of Business data and the Levin et al. (1987) survey data, they found evidence suggesting that one such variable – the degree to which outside knowledge is targeted to concerns of the firm – influences R&D spending. Their findings suggest that spillovers from input suppliers can be absorbed with less R&D effort than spillovers from government and university labs.

4.3. Appropriability conditions

To the extent that new knowledge is transmitted at relatively low cost from its creator to prospective competitors and particularly to the extent that such knowledge is embodied in new processes and products that may be copied or imitated at relatively low cost, appropriable rewards may be insufficient to justify innovative effort. Recognition of this problem of appropriability predates classical, let alone neo-classical, economics. Indeed, the notion that monopoly privileges were required to provide adequate economic incentives for inventive activity motivated the Statute of Monopolies, passed by the English Parliament in 1623

[38] Using survey data, Levin (1988) also found that measures of the extent of intraindustry spillovers had a positive and significant effect on an industry's self-reported rate of innovation, but no effect on R&D intensity.

[39] Bernstein and Nadiri (1989) found elasticities of average cost with respect to intraindustry spillovers to be approximately -0.1 in machinery and instruments and approximately -0.2 in chemicals and petroleum. Most of their interindustry elasticities (1988) fell in the range of -0.05 to -0.1.

[Penrose (1951)]. Later, the problem was explicitly recognized by the framers of the Constitution of the United States.[40]

In theory, patents provide a solution to the problem of imperfect appropriability; the exclusive right granted by society enhances the incentive to invent by sanctioning restriction of an invention's use. To the would-be inventor, the prospect of a patent represents the expectation of ex post market power that Schumpeter claimed was an essential spur to innovation. In fact, industries differ widely in the extent to which patents are effective. The evidence suggests that patents are regarded as a necessary incentive for innovation in only a few industries. In many industries, however, firms find other means of appropriation to be quite satisfactory. In some instances, imitation is costly despite the absence of strong patent protection. In others, investment in complementary assets such as marketing, sales efforts, and customer service can facilitate appropriation when neither strong patents nor technical barriers to imitation are present. In this subsection, we first review the growing body of evidence on interindustry differences in appropriability conditions. We then proceed to discuss the more limited evidence on how differences in appropriability conditions affect innovative activity and performance.

In an early investigation that revealed substantial interfirm differences in patenting behavior, Scherer et al. (1959) suggested that the value of patent protection might differ across industries. The suggestion was pursued by Taylor and Silberston (1973), who examined the use and effectiveness of patents with a sample of 27 firms in four British industries. They found that 60 percent of pharmaceutical R&D, 15 percent of chemical R&D, 5 percent of mechanical engineering R&D, and a negligible amount of electronics R&D was dependent upon patent protection. Mansfield et al. (1981), using data on 48 product innovations, found that 90 percent of pharmaceutical innovations and about 20 percent of chemical, electronics, and machinery innovations would not have been introduced without patents.

Recent work by Mansfield (1986) has provided more comprehensive evidence on the extent to which the value and effectiveness of patents differs across industries. Mansfield asked a random sample of 100 firms from 12 (mostly two-digit) industries to estimate the proportion of inventions developed in 1981–83 that would not have been developed in the absence of patent protection. Only pharmaceutical and chemical inventions emerged as substantially dependent on patents; 65 percent of pharmaceutical inventions and 30 percent of chemical inventions would not have been introduced without such protection. Patents were judged to be essential for 10–20 percent of commercially-introduced

[40] In empowering Congress to grant "for limited times to authors and inventors the exclusive rights to their respective writings and discoveries", the express purpose of the framers was "to promote the progress of science and useful arts" (Article I, Section 8).

inventions in three industries (petroleum, machinery, and metal products) and for less than 10 percent in the remaining seven industries (electrical equipment, instruments, primary metals, office equipment, motor vehicles, rubber, and textiles). The last four of these industries reported that patent protection was not essential for the introduction of any of their inventions during the period studied.

Mansfield's findings were reinforced by the results of the Levin et al. (1987) survey of firms in 130 more narrowly defined lines of business. As a means of appropriating returns, product patents were regarded as highly effective (scoring six or more on a seven-point semantic scale) in only five industries – including drugs, organic chemicals, and pesticides – and as moderately effective (five to six on the scale) in about 20 other industries, primarily those producing chemical products or relatively uncomplicated mechanical equipment. Only three industries, however, regarded process patents as even moderately effective. The principal reason cited for the limited effectiveness of patents was that competitors can legally "invent around" patents. Some relatively mature industries, concentrated in the food processing and fabricated metal products sectors, cited difficulties in upholding patent claims in the face of legal challenges to their validity.[41] Only a few industries reported that the information disclosed in patent documents was a significant constraint on patent effectiveness.[42]

The Levin et al. survey revealed, however, that firms in many industries tend to regard other mechanisms as quite effective in appropriating the returns from innovation. In contrast to the 4 percent of industries that regarded product patents as highly effective, 80 percent regarded investments in complementary sales and services efforts as highly effective in capturing competitive advantage from their R&D activities.[43] In numerous lines of business outside the chemical and pharmaceutical industries, firms reported that the advantages of a head start

[41]Levin et al. (1987) suggested that the most probable explanation for the robust finding that patents are particularly effective in chemical industries is that comparatively clear standards can be applied to assess a chemical patent's validity and to defend against infringement. The uniqueness of a specific molecule is more easily demonstrated than the novelty of, for example, a new component of a complex electrical or mechanical system. Similarly, it is easy to determine whether an allegedly infringing molecule is physically identical to a patented molecule; it is more difficult to determine whether comparable components of two complex systems, in the language of the patent case law, "do the same work in substantially the same way". To the extent that simple mechanical inventions approximate molecules in their discreteness and easy differentiability, it is understandable that industries producing such machinery ranked just after chemical industries in the perceived effectiveness of patent protection.

[42]It is argued that firms sometimes refrain from patenting process innovations to avoid disclosing either the fact or the details of the innovation. See Horstmann et al. (1985) for a theoretical treatment of the issue.

[43]Teece (1986) has emphasized the importance of investments in "co-specialized assets" for appropriating the returns from R&D, providing details of several specific cases. Flaherty (1983) has noted that exploitation of a technological leadership position in particular segments of the semiconductor industry requires substantial investments in marketing and customer service.

and the ability to move quickly down the learning curve were more effective means of appropriation than patents. Most industries viewed secrecy as more effective than patents in protecting process innovations, with the notable exception of petroleum refining. Only 11 of 130 industries, all drawn from the food processing and metal-working sectors, reported that no mechanism of appropriating the returns from product innovation was even moderately effective.[44]

More quantitative evidence that patents are not essential instruments of appropriation outside the chemical industries comes from work on the cost and time required to imitate an innovation.[45] Both Mansfield et al. (1981) and Levin et al. (1987) found that patents raise imitation cost substantially in the chemical and petroleum industries but only slightly in electronics. Moreover, Levin et al. identified several industries, concentrated in the aerospace and industrial machinery sectors, that reported very high imitation costs and imitation time lags despite very weak patent protection. In these instances, the relative complexity of the products presumably makes reverse engineering difficult even in the absence of patent protection.[46]

Most empirical work on appropriability has focused on the mechanisms facilitating and constraining the ability of firms to capture the returns from new technology as it is embodied in specific industrial processes or products. It is misleading, however, to think that the only spillovers that reduce appropriability are those that lead to the direct imitation of an innovative process or product. Spillovers of technical knowledge can lead to the development of products that are not direct imitations but that nonetheless compete (perhaps even in different markets) with products of the firm in which the knowledge originated. More generally, spillovers of knowledge can enhance the overall technological capability of the receiving firm, rendering it a more potent rival in the long-run competitive dynamics of an industry. It has been claimed that Japanese firms have a decisive advantage over international rivals in effectively utilizing techno-

[44] Despite the relative inefficacy of patents outside the chemical industry, Mansfield (1986) found that all twelve of his sample industries patented at least half of their patentable inventions during the 1981–83 period. This implies that the benefits of patenting exceed the cost in most cases, but Levin et al. (1987) found some evidence that firms patent for reasons other than protecting their inventions from imitation, such as monitoring the performance of R&D employees and gaining access to foreign markets where licensing to host-country firms is a condition of entry.

[45] More than 85 percent of the industries covered by the Levin et al. (1987) survey reported that the cost of imitating an unpatented major innovation was at least 50 percent of the innovator's R&D cost. More than 40 percent of the responding industries indicated that imitation costs were in excess of 75 percent of innovation costs.

[46] Evidence that imitation (a non-cooperative endeavor) is quite costly even in the absence of patent protection is reinforced by findings in the literature on technology transfer (a cooperative endeavor), where it has been found that firms must make substantial investments to utilize technology licensed from other firms, or even technology transferred from another plant operated by the same firm [see, for example, the studies contained in Mansfield et al. (1982)].

logical knowledge developed externally [see, for example, Mansfield (1988) and Rosenberg and Steinmueller (1988)].[47]

Despite a growing body of evidence on interindustry differences in appropriability conditions, there is no clear empirical consensus about whether greater appropriability encourages innovative activity. This reflects, in part, the difficulties of finding suitable data and formulating precise tests to distinguish among competing hypotheses concerning the expected effects of appropriability. The simplest hypothesis, derived from the standard argument supporting the patent system, is that innovative activity will increase monotonically with appropriability, because spillovers create a disincentive to innovative effort. By this argument, the more effective are the means of appropriation, or the less extensive are intraindustry spillovers, the greater will be industry R&D investment. When the "efficiency effect" of spillovers is considered, however, some simple models [e.g. Spence (1984)] predict that although industry R&D intensity will rise with appropriability (fall with spillovers), innovative output may decrease with appropriability (increase with spillovers).

In the more fully developed model of Cohen and Levinthal (1989a,1989b), the simple "disincentive effect" of spillovers remains, but there is an offsetting incentive to invest in "absorptive capacity" to make use of them. In this case, an increase in spillovers (decrease in appropriability) has an ambiguous effect on industry R&D. We conjecture that a similar result could be derived in a model that distinguished innovative from imitative R&D in the spirit of the Nelson and Winter (1982a) simulation models; under appropriate assumptions, an increase in the ease of imitation would discourage innovative R&D and encourage imitative R&D, with an ambiguous effect on total R&D. Finally, Levin and Reiss (1988) have suggested yet another countervailing incentive effect. To the extent that own and rival R&D are heterogeneous, the knowledge produced by a firm's competitor may be complementary to that produced by the firm's own investment, raising the marginal product of own R&D.

The empirical findings to date do not establish whether the net effect of appropriability on R&D incentives is positive or negative, nor do we yet know the extent to which the net effect varies across industries. Although Bernstein and Nadiri (1989) found that intraindustry spillovers have a negative effect on R&D in each of four U.S. industries, Bernstein (1988) found a positive effect in three

[47]A related consideration is that the knowledge that spills out is not necessarily detailed knowledge of how a product or process works. Mansfield (1985) has shown that decisions to develop a new product are typically known to competitors within 12 to 18 months (somewhat sooner in electrical equipment and primary metals). Our conversations with R&D managers suggest that they find it very valuable to know what technical problem a competitor is trying to solve, what technical approach has been adopted, or what approach has succeeded. This suggests, curiously, that the problem of appropriability is not limited to protecting successful innovations. Knowledge that a project has failed may save a competitor money or help a competitor succeed.

R&D intensive industries in Canada. Levin et al. (1985) and Levin (1988) found that various survey-based measures of appropriability were individually and jointly insignificant in regressions that explain R&D intensity at the industry level. Using business unit data, however, Cohen et al. (1987) found some of these measures to have positive and significant effects on R&D intensity in pooled regressions, although the results were not robust across separate two-digit industry regressions. For example, they found a negative effect of appropriability within the electrical equipment sector, a result that Cohen and Levinthal (1989b) replicated and interpreted tentatively as reflecting a high payoff to investment in absorptive capacity. A fuller understanding of the empirical consequences of imperfect appropriability will require tests that distinguish more sharply among the various mechanisms by which spillovers affect the incentives for R&D directed toward innovation, imitation, and investment in underlying technological capability.

Although most of the literature has focused on how appropriability conditions within a single industry affect the volume of its innovative activity, von Hippel (1982) suggested that appropriability conditions in vertically-related industries affect the locus of innovative effort. In an attempt to specify the conditions under which process machinery is developed by machinery manufacturers rather than users of the machinery, von Hippel emphasized considerations such as the extent to which new knowledge is embodied in the machinery, the relative efficacy of patents or secrecy, whether the machinery is used in one industry or many, and the market structures of the manufacturing and using industries. These factors, hypothesized to determine the locus of innovation in vertically-related industries, may also affect the amount of innovation. Although these issues have not yet been thoroughly explored in the econometric literature, Farber (1981) introduced and found some support for the hypothesis that concentration on the buyer's side of the market influences R&D spending on the seller's side.

5. Conclusion

A central theme of this survey has been to emphasize the already perceptible movement of empirical scholars from a narrow concern with the role of firm size and market concentration toward a broader consideration of the fundamental determinants of technical change in industry. Although tastes, technological opportunity, and appropriability conditions themselves are subject to change over time, particularly in response to radical innovations that alter the technological regime, these conditions are reasonably assumed to determine interindustry differences in innovative activity over relatively long periods.

Although a substantial body of descriptive evidence has begun to accumulate on how the nature and effects of demand, opportunity, and appropriability differ across industries, the absence of suitable data constrains progress in many areas. Moreover, understanding could be advanced by a greater interaction between developments in the theoretical and empirical literatures. Some potentially valuable ideas, widely discussed in the theoretical literature, have been neglected by empiricists, while theorists in turn have paid insufficient attention to rationalizing and making coherent what is known empirically.

One neglected issue in the empirical literature is the role of strategic interaction, which has been the major preoccupation of theorists concerned with R&D investment and technical change. Curiously, this issue was given greater attention by empiricists in the 1960s and early 1970s than in more recent years. Although none of the early empirical studies provided rigorous tests of theoretical models, several used theoretical arguments concerning the nature of oligopolistic interaction to justify empirical findings.[48] Scherer (1967b) himself developed one of the first detailed theoretical models of R&D rivalry; its implications, like those deduced by Kamien and Schwartz (1976), were consistent with the empirical finding that an "inverted-U" characterized the relationship between R&D investment and market concentration.

One difficulty with testing the implications of recent game-theoretic models of R&D rivalry is that they analyze behavior in highly stylized and counterfactual settings. For example, many models focus on the interaction of a single incumbent and a single prospective entrant. Moreover, many of the results obtained in this literature, surveyed by Reinganum in Chapter 14 in this Handbook, depend upon typically unverifiable assumptions concerning the distribution of information, the identity of the decision variables, and the sequence of moves.[49] Nonetheless, empirical effort on the effect and importance of strategic behavior is warranted. Inspiration might be drawn from Lieberman's (1987) empirical examination of the role of strategic entry deterrence in affecting capacity expansion in a sample of chemical and metals industries. He concluded that strategic considerations were not paramount in most industries, but he identified several specific instances in which strategic considerations may have been important.[50]

[48]Grabowski and Baxter (1973) found evidence suggesting that firms in the chemical industry engage in "competitive matching" of R&D investment. Wilson (1977) used strategic considerations to rationalize several of the findings in his study of licensing behavior. For example, observing that cross-licensing is more prevalent the smaller the number of rivals, he argued that smaller numbers made a cooperative solution more likely.

[49]See Reinganum (1984) for a discussion of the contrasting propositions of Dasgupta and Stiglitz (1980b) and Loury (1979), on the one hand, and Lee and Wilde (1980), on the other.

[50]A reasonable conjecture, arising from perusal of the case study literature and the trade press, is that the relative importance of strategic considerations in R&D decisions varies across industries. For example, in airframes and some segments of the computer industry, firms appear to monitor rival behavior closely and to modify their own behavior in response. Strategic considerations appear to be less prominent in industries producing relatively homogeneous products, such as basic metals and commodity chemicals.

Another gap in the empirical literature is the absence of a satisfactory explanation for interfirm differences in innovative activity and performance. The variance in business unit R&D explained by fixed firm effects was approximately as large as the variance explained by fixed industry effects. While available measures of industry characteristics (demand, opportunity, and appropriability) account for about 50 percent of the variance explained by industry effects, the most widely used measures of firm characteristics, cash flow and the degree of diversification, jointly explain less than 10 percent of the variance explained by firm effects.

The theoretical literature may provide some guidance in identifying the sources of interfirm differences in innovative activity and performance. The line of inquiry explored by Williamson (1985) has suggested that – in the presence of asset specificity, uncertainty, and opportunistic behavior – differences in internal organization and interfirm contractual relationships may have substantial implications for innovative behavior and performance. Organizational and contractual issues have been given prominence in the literature concerned with management strategy [e.g. Teece (1986), Rumelt (1987)], but they have only begun to appear in econometric studies of R&D behavior or technological performance. The recent study by Clark et al. (1987) – examining how the organization of product development projects affects engineering performance – represents a promising beginning.

The work of Nelson and Winter (1982a) suggests another possibility: in a world of bounded rationality, differences among firms in idiosyncratic technological capabilities, accumulated in part by experience and in part by good "draws" from a stochastic environment, may also be sources of interfirm differences in behavior and performance. Despite recent efforts by Winter (1987) to suggest dimensions of technological capability that are observable in principle, the construction of measures suitable for econometric purposes remains a formidable challenge.[51]

Just as the empirical literature may benefit from importing ideas that have originated in theoretical work, it may also benefit from exporting puzzling results to the theorists for later re-importation in the form of new testable hypotheses. We have already offered one such challenge suggested by anomalous econometric results: can the disincentive and efficiency effects of spillovers on investment in innovation, imitation, and building technical capability be sufficiently disentangled to permit their empirical identification? Another is: How do the effects of opportunity and appropriability on innovation and industry structure differ when

[51]An alternative strategy for explaining interfirm variation in technological activity and performance would take seriously the proposition that much interfirm variation within a given industrial environment is a result of the past history of success and failure in the stochastic process of R&D competition. Such an approach would seek operational measures of the parameters of such a stochastic process (e.g. the degree of technological risk, barriers to market penetration) that might explain how the interfirm variance in R&D intensity, for example, varies across industries.

technologies are discrete rather than cumulative, in the sense that innovation depends upon prior innovation?[52]

One issue to which theorists and empiricists alike have devoted too little attention is the dynamics of innovation and market structure: the Schumpeterian process of "creative destruction". Robust analytical results in dynamic, stochastic models of populations of firms are not easily obtained, although there have been a few impressive attempts [e.g. Futia (1980), Iwai (1984a, 1984b)]. To date, the simulation models of Nelson and Winter (1982a) have provided the most illuminating theoretical treatment of the issues. Serious efforts to formulate dynamic, stochastic models that are empirically testable are just beginning.[53]

We close with the observation that much of our empirical understanding of innovation derives not from the estimation of econometric models, but from the use of other empirical methods. As we have illustrated with examples, the case study literature provides a rich array of insights and factual information. More strikingly, many of the most credible empirical regularities have been established, not by estimating and testing elaborate optimization models with published data, but by the painstaking collection of original data, usually in the form of responses to relatively simple questions. Even as econometric methods advance and the quality of published data improves, it will be important to remain catholic in the application of empirical techniques. Case studies will remain a valuable source of information and a source of inspiration for more rigorous approaches. It would, in addition, be worthwhile to refine the simulation techniques employed by Nelson and Winter, using models calibrated to permit simulation of specific industries, as was recently attempted by Grabowski and Vernon (1987). Finally, given the limitations of available data, advances in our understanding of innovation and market structure will depend importantly on the development of new data sources.

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[52]Industries with strong natural trajectories have technologies that are cumulative in the sense described here; solving the next problem along a trajectory requires knowledge of how the last problem was solved. Semiconductor technology is clearly cumulative [see Levin (1982) for a detailed explanation]; pharmaceutical technology, at least prior to recent developments in genetics and molecular biology, is not. Finding a new chemical entity with good therapeutic properties does not typically require knowledge of how the last drug was found.

[53]One such effort is the "active learning" model developed and tested by Pakes and Ericson (1987), which may be interpreted as a stylized model of innovative activity.

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