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R&D and Productivity Growth: A Review of the Literature

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Abstract

This paper reviews the literature on R&D to provide guidelines for recent efforts to include R&D in the national income accounts. The main conclusions are:

1. Measures of R&D as an asset held by a particular owner must be complemented by estimates of the spillover effect of R&D in order to obtain a reliable measure of the overall effect of R&D on productivity growth.
2. If research financed by the government and research financed by business are both counted as investment, some double counting occurs and growth accounting analysis overstates the role of research relative to other factors.
3. The overall rate of return to R&D is very large, perhaps 25 percent as a private return and a total of 65 percent for social returns. However, these returns apply only to privately financed R&D in industry. Returns to many forms of publicly financed R&D are near zero.
4. Firm R&D should be allocated to the different industries in which a firm produces, rather than all credited to the firm's main industry. An allocation procedure is proposed.
5. Much further work needs to be carried out to understand how R&D conducted in the richest countries is transmitted to developing countries. Detailed microeconomic data on firms or establishments in developing nations will be necessary to understand the channels of technology transfer more fully.

Journal of Economic Literature categories: O30, O40.

Keywords: R&D stocks, R&D spillovers, R&D and productivity growth

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[1] This paper reviews several portions of the scholarly literature on research and development which are relevant to current efforts to establish R&D satellite accounts. I appreciate comments from Michael Harper, Peter Meyer, Carol Robbins, and Larry Rosenblum, and remarks from seminar participants at the Bureau of Economic Analysis and the Bureau of Labor Statistics. However, the views expressed in this paper are solely those of the author, and do not reflect the views or policies of the U.S. Bureau of Labor Statistics or the Bureau of Economic Analysis.

R&D and Productivity Growth: A Review of the Literature

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Recent years have seen substantial progress towards including research and development (R&D) as a capital investment within the national income accounts (Canberra Group II (2003)). Economists at the United States Bureau of Economic Analysis, or BEA, (Carson, Grimm and Moylan (1994), Fraumeni and Okubo (2005); Okubo et al (2006b)) have prepared initial versions of a potential R&D satellite account. The U.S. National Science Foundation has agreed to support BEA's further work on R&D accounts, and the BEA is committed to publish R&D accounts for the United States. Economists in Australia (Australian Bureau of Statistics (2004)) and in the Netherlands (de Haan (2004)) have also reported initial R&D stocks for their countries.

One main motive for adding R&D is to broaden the accounts to include a further important source of economic growth. Present international discussion has largely concentrated on treating R&D as an asset for private firms, the government, universities, and other nonprofit organizations. However, most gains from R&D typically do not accrue to the original investors. Benefits instead spill over to a wide variety of other economic agents. Consequently, it is necessary to establish links between the role of R&D as an asset and the total effect of R&D on economic growth, which reflects both asset returns and spillovers.

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[2] The views expressed here are those of the author, and do not represent the Bureau of Labor Statistics.

Many central characteristics of R&D stocks, such as the rate of depreciation, the lag until R&D becomes operative, and the rate of return, differ widely between the asset and spillover effects. In a sense, analysts have to prepare two different sets of calculations to describe the asset and spillover effects of R&D. From this perspective, the stocks of R&D assets the U.S. Bureau of Economic Analysis is currently preparing neatly complement the spillover R&D stocks which the U.S. Bureau of Labor Statistics has published for many years.[3] Other countries currently measuring R&D assets will similarly have to expand their analyses to include spillovers in order to describe the full impact of R&D on productivity growth.

This paper examines the relationship between R&D as an asset and R&D as an ingredient in growth. Section I considers recent measures of asset and spillover R&D stocks in the United States, and also examines which portions of R&D should be included in national R&D stocks. Section II reviews the economics literature on the private and social (private plus spillover) impact of R&D. Section III considers some difficulties associated with measuring R&D accurately in each industry. Section IV examines the international transmission of R&D, a major source of spillovers for most of the countries in the world. Section V concludes.[4]

I. Introduction: Understanding Asset and Spillover Returns to R&D; What Portions of R&D Should be Included in National R&D Stocks?

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[3] Okubo et al (2006b) describe BEA work on R&D as an asset, and U.S. Bureau of Labor Statistics (1989) presents the BLS work on R&D spillovers.

[4] An earlier version of the present paper was prepared as a background paper for the Canberra II discussion of research and development.

Most Canberra II group discussion of R&D concentrated on similarities between R&D and other assets already recognized as capital.[5] For example, firms commit resources to R&D in the hope that this investment will create an asset which eventually lead to greater profits, much as in the case of plant or equipment.

The comparison is valid, and supports the proposal that R&D expenditures should similarly be treated as capital investment. However, R&D differs from other forms of capital investment in several respects. A central characteristic is that payoffs from R&D are not limited to the original investors, but also accrue to competitors, other firms, suppliers, and customers.[6] Consequently, it is too narrow to view R&D as essentially an asset held by a particular owner. A broader perspective on R&D has to include knowledge spillovers, which have often been a central theme in discussions of productivity growth.[7]

To illustrate the importance of the diffusion of knowledge from firms undertaking research to the broader community, consider technical change in pharmaceuticals. Statins are a new class of anti-cholesterol drugs which have contributed greatly to the decline of heart disease. A major pharmaceutical firm introduced the first commercial

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[5] The March 2004 meeting of the Canberra II group, held in Washington, discussed R&D as an asset, and concentrated on similarities between R&D and other assets.

[6] Romer (1990, pp. 73-76) discusses nonrival goods, for which the use by one firm or person does not limit its use by another. Romer also considers excludability, and points out that the results from research can only partially be excluded from use by others.

[7] Section II reviews the literature on the effect of R&D on productivity growth.

In addition to the nonrival characteristic of R&D knowledge, it is typically difficult to determine the value of output from research because research results are typically not sold on the open market. Economists have measured research outcomes from statistical relationships between R&D and several indicators of technological success. Most studies determine the return to research from its relationship with productivity growth. Other work evaluates the effectiveness of research from its connection with profits or stock market value.

statin product in 1987, and conducted pioneering research demonstrating that statins were safe, lowered cholesterol, and successfully reduced the death rate from heart disease. Since 1987, several firms have introduced new and improved statins. A different firm now produces a new and greatly improved statin, which lowers cholesterol more effectively, and has therefore become the market leader.

Although the second firm now dominates the market for statins, it is <u>not</u> the case that the second firm's private investment in R&D is now the only relevant R&D. From the point of view of private returns, much of the early research which the initial firm carried out is indeed no longer profitable.[8] However, in a broader sense all the initial research which demonstrated that statins were safe, highly effective, and reduced the incidence of heart disease still provides the core knowledge of the present day industry. The first firm's initial investment in R&D is still relevant to the industry and still provides important social returns, even though most of the private returns now go to the second firm.

To take another example, two leading firms have competed in producing microprocessors for many years. When the technology leader introduces a new chip, the second firm soon matches, and prices fall rapidly. As a result, microprocessor prices have declined sharply. Most of the benefits of innovation have been captured by consumers through lower prices. The profit of the innovators, obtained through returns to the R&D they conduct, is only a small part of the picture.

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[8] In fact, the initial drug, introduced in 1987, is no longer under patent.

These examples illustrate how the knowledge and benefits obtained from R&D typically leak out from the original performers of R&D to competitors, to other firms, to consumers, and, eventually, to other countries. Many forms of knowledge are useful to other firms (and so have a social return) even when they no longer pay off to the firm initiating the research (no longer have a private return). Similarly, consumers obtain better or cheaper products (benefit from social returns) even if the private return to firms turns out to be low.[9]

As knowledge gradually leaks out, private benefits decline and spillover effects increase. Consequently, private and spillover returns follow different time paths. Quite reasonably, spillover effects are considerably more long lived than private effects. Okubo et al. (2006b) calculate R&D asset stocks assuming a 15 percent (or greater) annual depreciation rate. In contrast, the Bureau of Labor Statistics (1989), measuring the longer lasting spillover effects, assumes 10 percent depreciation for applied research and development and zero depreciation for basic research, which implies an overall depreciation rate of less than 9 percent.[10]

Such substantial differences in depreciation have an important impact on the implied size of R&D stocks and the time pattern of anticipated benefits. For example, in 2000 the BLS spillover R&D stock is 44 percent greater than it would have been if calculated at 15 percent depreciation. A 15 percent depreciation rate implies that a quarter of an

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[9] Measured benefits are limited to those which have a market evaluation. Some benefits, such as clean air or some types of medical advances, are not evaluated through market prices, and are typically not included in economic statistics.

[10] Since the BLS assumes zero depreciation of basic research, the basic research proportion of the overall BLS stocks is greater than data on annual R&D investments would suggest.

investment has depreciated after two years, half by five years, and three-quarters by 9 years. In contrast, 9 percent depreciation indicates a quarter of investment has depreciated by 4 years, half by 8 years, and three-quarters by 15 years.

The influence of depreciation is accentuated by differences in the lags with which R&D investment enters the R&D stock. BEA R&D investments enter the asset stock immediately, whereas BLS investments enter the spillover stock with a lag of two years for applied research, and five years for basic research.[11] The longer lags further imply that spillovers occur later than asset returns.

There are also major differences in the returns to asset and spillover R&D. Somewhat surprisingly, it is quite difficult to determine exactly how much of R&D returns accrue through private returns and how much through spillovers. Most of the economics literature typically reports the amount by which the average social return to R&D exceeds the private return.[12] Remarkably few studies (Schankerman (1981); Cuneo and Mairesse (1984)) actually examine the actual return to private firms, which is most relevant in considering R&D as an asset.

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[11] In the BEA stocks, if investment occurs in 1990, half enters the R&D stock at the start of 1990 and half at the start of 1991. In the BLS calculations, 1990 investment in applied research enters the research stock at the start of 1992.

[12] Studies typically include the capital, labor, and other factors used in research within the inputs used to measure productivity growth. Therefore, the private value of research is removed from such productivity measures. Consequently, when R&D is used to explain productivity growth, the estimated return is the amount by which the return to R&D exceeds the private value of these resources. Griliches and Lichtenberg (1984b, page 475) and U.S. Bureau of Labor Statistics (1989, page 36) provide a more formal statement of this argument.

In other relevant literature, Nordhaus (2004) emphasizes that only a very small portion of the returns to R&D accrues as abnormally high returns to the innovator. Baumol (2000) describes how firms continually improve the quality of their products, through R&D, and leapfrog beyond the products produced by their competitors' R&D; this churning process reduces the value of their competitors' private R&D.

Nevertheless, the existing literature generally finds that spillovers are greater than private returns. Griliches (2000, page page 70) concludes that the excess return to firms[13] is 10 percent, whereas the social return, which includes private returns, is 25 percent. Section II of the present paper reviews the evidence and suggests the private return to R&D is 25 percent, while the social return is 65 percent. Okubo et al. (2006a, page 27) examine many different studies, and conclude that the private return is 26 percent and the social return 66 percent. Each of these three judgements indicates spillovers contribute approximately three-fifths of the total return to R&D.

Of course, the conclusion that spillover effects are primary is necessarily tentative because the available evidence is incomplete. Clearly, most studies do not include the private value of resources used in research, and thereby understate the contribution of R&D.[14] Studies of specific innovations offer an alternative method of measuring actual returns to private firms; subsection II.5 below examines evidence from the innovation studies and reaches roughly similar conclusions concerning the relative importance of private and spillover effects. In addition, most studies omit the international effects of R&D (Coe and Helpman (1995)) and thereby miss an important element of spillovers.

Another central question in the capitalization of R&D is which portions of R&D should be included as investment. The current consensus is that all private, government,

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[13] Footnote 10 explains why the R&D literature typically reports excess returns which exceed the private return.

[14] Since most studies report only a portion of total returns to R&D (the excess return), the implied total effect of R&D will clearly be greater if the value of the private inputs used in R&D is also included.

In this context, a BEA analysis of industry data (Schultz (2006)) has the great virtue that it isolates the capital, labor, and materials used in R&D and removes these inputs from the factors used in production. If similar adjustments could be made within firm data, it would be possible to obtain better estimates of actual overall returns to each firm's private R&D.

or university R&D should be treated as investment.[15] However, two issues arise here. First, many forms of R&D have little economic value and do not contribute to growth. Should they all be counted as investment? Second, if publicly financed basic research and subsequent private research are both treated as investment, a certain amount of double counting occurs. The rest of Section I examines these two topics.

In considering which forms of R&D should be designated as investment, the asset and growth views of R&D once again offer contrasting perspectives. The 1993 System of National Accounts defines an asset, in part, by requiring that "Economic benefits may be derived by their owners by holding them or using them over a period of time". In this definition, the word "may" leads to an extremely broad definition of assets. Even if a broad category of research spending brings almost no demonstrated economic returns, just the possibility that a very small portion of these expenditures "may" be able to bring returns leads to the entire sum being classified as an asset. So it is not surprising that current discussion suggests that all R&D expenditures by firms, universities, and governments (as R&D is defined in the OECD Frascati Manual) should be treated as investment.

In contrast, from the point of view of growth, what matters is the proportion of an expenditure category which can be expected to provide returns and the magnitude of the returns. From this perspective, most discussion has emphasized privately financed research, which has been amply demonstrated to bring high returns. Of course, as Scherer (1999) pointed out, most private R&D projects do not actually earn positive

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[15] Canberra II group (2006); Robbins (2006); Okubo et al (2006b).

returns. Nevertheless, all private R&D expenditures can plausibly be treated as investment because these expenditures are all undertaken with the expectation of a commercial return and "may" obtain such returns.

In contrast, broad slices of university and government research are conducted with very little expectation or prospects of direct commercial returns.[16] For example, only a very small part of the research conducted by universities and colleges brings commercial returns.[17] As President Richard Levin of Yale University recently remarked "We're not trying to drive university science by commercial objectives. We want to do great science. Some of that will have commercial potential; most of it won't." Also "Our technology transfer strategy is not to maximize revenue. Our primary goal is to get the findings of our laboratories out into practice."[18]

Federally financed industrial research accounted for more than half of industrial research in the late 1960s, though this proportion is now less than one tenth. Evidence on the productivity impact of federal research in industry is mixed. The industry studies and the best study of firm data (Leonard (1971); Terleckyj (1974); Lichtenberg and Siegel

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[16] Fraumeni and Okubo (2005) assume the return to public research is two-thirds of the return to private research, which is clearly an overstatement because they are working within the framework of the current national income accounts, which do not include the returns to federal investment in R&D within output.

More recently, government statisticians have decided to include returns to government capital as output, and it is clearly appropriate to include returns to government R&D stocks as well. Nevertheless, as the text points out, many forms of federal and university research have little economic value and do not contribute to growth. Even though such expenditures are classified as R&D, I would argue that, because there is no evidence of a positive return, such expenditures are actually a form of government consumption, often for quite useful purposes, but do not deserve to be treated as investment.

[17] Even universities as eminent as Michigan, Rochester, and Yale earn surprisingly small amounts from patent royalties. For example, over the last decade Yale earned approximately $21 million dollars a year from patent royalties

[18] Yale Alumni Bulletin, November 2006.

(1991)) conclude federal research in industry does not improve industrial productivity.[19] In contrast, Griliches (1986) concluded federal R&D in industry had a positive effect on productivity, though less of an impact than privately financed research. Even beyond university and federally financed industrial research, Piekarz (1983) reviews evidence indicating that many federally funded research programs have not been very effective.

It is disturbing to assign investment status to broad categories of research spending, such as university research or federally financed R&D in industry, when the fundamental evidence indicates that, though returns "may" exist, actual returns are unlikely or at best accrue to only a small proportion of expenditures. In my judgement, large batches of expenditures where direct economic value is unlikely should not be treated as R&D investment, on the same basis as private R&D, merely on the off chance that some small amounts of these expenditures "may" turn out to have economic value.[20] If all expenditures in government and university R&D are treated as investment, the true

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[19] In the United States, federally financed research expenditures refer to research financed by the national, or federal, government. On the basis of the type of evidence summarized in the text, the U.S. Bureau of Labor Statistics (1989), in its work on productivity growth, chose to include only privately financed R&D conducted in industry in its measures of the relevant R&D stock.

Lichtenberg and Siegel (1991) is the best study of these matters within firm data because their paper adjusts the firm output deflators to reflect the different industries in which each firm actually produces.

Some papers find that federally financed research in industry has a positive effect. Bonte (2003) argues that federally financed research contributes to productivity growth in the United States, but his analysis is based on a cointegration analysis of aggregate data, and does not use the highly detailed firm data analyzed in Lichtenberg and Siegel (1991).

A potentially important recent study (Guellec and van Pottelsberge de la Potterie (2004)) argued that government research expenditures, given private R&D, contribute to the rate of economic growth. This analysis is based on aggregate data for 16 OECD countries. Such conclusions run counter to most of the literature, which indicates that public research affects measured growth only through its effect on private research (OECD (2003) in addition to the U.S. studies mentioned in the text). Without more detailed microeconomic evidence establishing specific channels through which public science affects productivity growth in these 16 countries (such as a more rapid growth of high-tech industries), the direct importance of government R&D in growth remains an open question.

[20] Consider a similar argument in the case of an auto dealer who is selling 100 cars, of which one or two "may" be used as an investment. In this context, it does not make much sense to consider all 100 cars as investment. Yet this is fundamentally what is being proposed in designating all university and government research as investment.

amount of relevant R&D investment is greatly overstated.[21] In my judgement, any procedure which counts all government or university research as equivalent, on a dollar for dollar basis, to private research spending provides an extremely flawed measure of how much economically relevant research investment actually occurs.

Of course, some government and university research has been greatly successful. Several programs, especially those in which university scientists compete for grants, such as the National Science Foundation, the National Institues of Health, some Department of Agriculture programs, and DARPA in the Department of Defense, appear to have a remarkable record. In addition, much federal and university research is conducted on health care, and Nordhaus (2003) demonstrated the importance of such work. Similarly, much military research substantially improved military effectiveness, as any comparison of the accuracy of precision guided missiles in the Gulf War of the early 1990s and in the Iraq war of the early 2000s clearly indicates.

However, these government successes have been influential primarily through their impact outside the public sector. For example, when physicists developed better methods of transmitting their papers through ARPANET, this precursor to the Internet did not greatly affect government output. Except for some elements of military research, each of

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[21] As an illustration of the importance of properly defining the boundaries of research investment, in Lisbon the European Union adopted a goal that R&D expenditures should be three percent of GDP. Private R&D expenditures are falling far short of this target. The Europeans may therefore consider greater “investment” in university or government R&D. I would argue that the economic returns to public R&D are far lower than those to private R&D and that, if the Europeans follow such a strategy, they will be badly disappointed with the returns. Overall returns for university and government research are low primarily because so much research in these fields has no direct financial payoff.

these major successes has probably had its greatest economic impact through the private sector.

The discussion above demonstrated much university and federal research has little commercial value. On the other hand, perhaps federal R&D produces more government output, and should therefore perhaps be assigned a rate of return, such as the Treasury bill rate. Such suggestions are inherently plausibile. Perhaps R&D is effective in a variety of circumstances, and brings government agencies useful benefits, even if these are currently not included in GDP. However, proposals such as these determine which R&D is useful by assumption rather than through evidence. If the crucial contribution of federal R&D to growth is through increasing government output, advocates of including federally financed R&D, and its returns, in the accounts need to demonstrate that federal R&D actually brings about increased federal output.[22] Lehr and Lichtenberg (1998) showed it is possible to determine how new technology improves the productivity of government agencies. If this channel is crucial in justifying federal R&D as an investment, we need much better evidence on how federally financed R&D improves federal productivity, and on whether there are important areas in which federal R&D is ineffective, before federally financed R&D, and its assumed returns, can be included in the national accounts.

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[22] As Section II below illustrates, the notion that private R&D contributes to growth is supported by a rich variety of evidence which greatly clarifies the returns to private R&D. If evidence did not consistently show that private R&D affects productivity and output growth, the international statistical community would probably not now be supporting the inclusion of private R&D as an investment. Surely, it is just as necessary to have sound empirical evidence demonstrating that there are returns to federal R&D before such expenditures are included as an asset.

It is not sufficient to finesse these points by simply assigning a lower rate of return to all university and federal research. The more fundamental problem is that many forms of research, however worthy they may be, do not deserve to be designated as investment because they do not contribute to the future growth of output.

Of course, many advances arising from university or government research eventually have an important <u>indirect</u> effect on growth. Consider, however, the usual conventions and methods of growth accounting. Growth accounting typically examines only the proximate sources of growth. For example, growth due to a higher number of educated workers is typically attributed to labor quality, and growth due to larger amounts of capital is similarly attributed to capital formation. Even if improvements in technology are the fundamental underlying cause, which creates the demand for a more educated work force or creates the new equipment which makes further capital deepening feasible, growth accounting still attributes these observed output gains to education and to capital deepening rather than to technology. In a similar way, the flow of understanding from federal or university research typically operates by increasing the demand for private R&D. If the National Institutes of Health develop new insights into the treatment of a particular disease, large amounts of further private R&D are usually required to convert these new ideas into new pharmaceuticals (Toole (2007)). Consistent with the treatment of other inputs in growth accounting, growth accounting should include only the private R&D and not the underlying public or university research which makes the private effort feasible. If we count both the underlying government and university research and also the proximate private R&D spending, we are in a sense double counting the investment in R&D in comparison with our treatment of other inputs.[23]

There may be some argument for double counting in the case of military technology, where improved weapons directly meet an important government goal, and the spillovers involved in dual-use technology are peripheral. However, for other government research, in such areas as health, science, technology, and agriculture, the fundamental government goals are downstream, such as the introduction of better medicines or the promotion of industrial growth and technology.[24] In the context of growth accounting, it is not appropriate to include here both the public research which establishes understanding and the private research which implements the new concepts.

In summary, if we are operating within the framework of growth accounting, only a relatively small proportion, perhaps a quarter or less, of the R&D conducted in government or in universities can be expected to have commercial returns or to bring firmly established imputed returns. Such a proportion is sharply lower than the two-thirds suggested by Fraumeni and Okubo (2005).[25]

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[23] Recent empirical studies have established that certain broad economic features, such as legal protections for private property (Scully (1988), La Porta, Lopez-de-Silanes, Shleifer, and Vishny (1998), Djankov, La Porta, Lopez-de-Silanes, and Shleifer (2003)) or the presence of a large financial sector (King and Levine (1993)), have a positive impact on growth. In much the same way, high quality government or university research is likely to create a favorable framework for growth. Nevertheless, economists typically do not treat government expenditures on the legal or financial system as an investment.

In contrast, government investment in transportation infrastructure, where benefits can plausibly be assigned to individual firms, is often included in productivity studies.

[24] Some may argue that the government is really trying to advance science and knowledge for its own sake, which is a useful goal. However, if the process did not eventually lead to better treatment for diseases and a longer life span, funding for NIH would be much lower.

[25] As some readers have suggested, by this logic if a research team in a medical school is hired to do similar work in a pharmaceutical firm, such a change in the work environment will increase measured

II. The Literature on the Rate of Return to R&D.

The effect of R&D on the economy depends on both what expenditures are included in R&D, as discussed in Section I, and what the returns to R&D are. Section II therefore reviews evidence on the returns to R&D. The rate of return to R&D can be examined at many different levels of aggregation, such as the returns to individual research projects, the returns to firms, returns to an industry, returns to a national economy, or even returns within the entire world.

II.1 Private (Firm Level) Returns to R&D.

The return to research has generally been estimated (Griliches (1980)) by comparing productivity growth or profitability in different firms with research expenditures or the growth of the research stock within these firms.[26] Nadiri (1993, Table 1a) reports the results from many studies which examined the return to R&D within data for individual firms.

Several difficulties limit the validity of estimates of the private return to R&D. Substantial complementary resources are often used with R&D. For example, the results from new research have to be put into effective operation. In many cases, producing a new product requires a pilot plant or other new methods of production. This requires

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national investment. The counterargument is that the firm presumably selects this research team, out of many available at the med school, because their work is atypical and has the greatest commercial potential.

[26] Lichtenberg and Siegel (1991) report estimates of the return to R&D based on productivity data for U.S. firms. The Lichtenberg-Siegel estimates are based upon a large sample of firms and greatly improved estimates of firm productivity. Griliches (2000, pp. 65-66) summarizes some of the main results concerning the stock market's evaluation of firm's R&D efforts. Hall, Jaffe, and Trajtenberg (2005) show that highly cited patents strongly affect stock market evaluation, but less cited patents have little impact.

substantial engineering work. In addition to the capital costs involved, managers and workers will have to be trained in the new techniques. Similarly, new products typically require very close coordination with marketing specialists. The potential market has to be evaluated, and salesmen have to be hired and trained to sell the new product.[27] The high returns firms apparently earn on research expenditures may partially reflect returns to such complementary investments.

In addition, returns to private firms may be high because they include a substantial risk premium. Mansfield et al. (1971) and Scherer (1999) show R&D projects have considerable technical and commercial risk and many projects are not very successful. Observed returns to R&D could, in part, reflect a substantial risk premium.

Nelson (1988) raised several important issues which should make analysts quite careful about accepting and using typical estimates of the rate of return to R&D. Nelson points out that R&D and technological opportunity are closely intertwined. Firms with high R&D typically have more favorable technological opportunities. Similarly, firms with low R&D are likely to face weaker technological opportunities. Consequently, it is difficult to determine the extent to which effects attributed to R&D expenditures actually reflect the collateral technological opportunities. For this reason, Nelson argues that standard regressions, across firms or industries, cannot provide plausible estimates of the rate of return to research investments.[28,29]

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[27] Mansfield et al. (1971, pp. 112-114) describes the many different types of additional inputs which are also necessary in the process of innovation.

[28] Griliches (1979, Section 5) also warned about simultaneity problems arising from the mutual dependency between R&D investments and past and future expected output. Olley and Pakes (1996)

II.2 Industry (Direct) Returns to R&D.

Studies of the direct return to research examine the relationship between R&D and productivity within data for different industries. By examining industry data, analysts are able to include spillovers between the different firms within an industry.

There are important differences between firm and industry returns to R&D.[30] As Griliches (1979, page 101) remarks, firm knowledge leaks out fairly rapidly, so firm R&D depreciates rapidly. On the other hand, much of this knowledge is gained by other firms, so social returns depreciate more slowly than firm returns. Similarly, there is a greater lag before social returns take effect, and social returns are substantially greater than private returns. Consequently, many of the central features of R&D stocks are

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suggest an important method of addressing such concerns about simultaneity, but do not apply their procedure to R&D. Acharya and Keller (2007) usefully apply some of the Olley-Pakes ideas to R&D. Such methods are important because they provide estimates of the return to R&D which are much less subject to the problem of endogeneity.

[29] If R&D is thought to reflect some other influence, the standard econometric procedure would be to attempt to find an instrumental variable which influences R&D growth but is independent of the productivity of R&D. Barro (1998, p. 20) comments “R&D spending may respond to exogenous changes in productivity growth so that the estimated coefficient on the R&D variable would proxy partly for exogenous technological progress. Satisfactory instrumental variables to avoid this problem may not be available.” Few studies have estimated the return to R&D using instrumental variables; Jaffe (1986) is perhaps the major exception. Lewbel (1997) uses instrumental variables in a study of the effect of R&D on patents.

Fung (2004) measures intraindustry and intrafirm spillovers from patent citations, and includes measures of the overlap in patent citations and the scope (number of patent classes involved in a firm’ research) of patents. He finds several of these influences are significant in explaining the effectiveness of R&D. Furthermore, allowing for technological opportunity generally increases estimates of the R&D elasticity. Fung also considers some of the relationships between his data and the technological characteristics of industries. Any progress in this direction is very welcome, but a more fundamental understanding of how industry characteristics affect R&D patterns in a broad group of industries is necessary before we can understand why technological opportunities differ so widely among industries. Klevorick, Levin, Nelson, and Winter (1995) take an interesting initial step in this direction.

[30] Many R&D deflators (U.S. Bureau of Labor Statistics (1989); Okubo et al. (2006b)) combine labor costs and output price indices, which permits R&D deflators to rise less rapidly than input costs, reflecting increases in productivity. However, Griliches (1990) and especially Kortum (1997) show that over time greater amounts of research are necessary to generate a new patent. Though there are valid questions concerning the use of patents as a measure of research output and how the economic meaning of a patent has changed over time, this evidence suggests that the productivity of R&D does not increase over time.

sharply different in industry data than in firm data. If satellite accounts for R&D are to include the economic impact of spillovers, the key channel through which R&D affects productivity and output growth, national income accountants will have to move beyond asset effects to examine spillovers, using alternative values to measure central concepts such as depreciation, lags, and the rate of return.[31]

Considerable evidence describes leakage of R&D from firms to the broader industry. Mansfield (1985) showed information about new technology leaks out to rival firms within a year or two. Caballero and Jaffe (1993) similarly find rapid leakage. Jaffe (1986) found the pool of nearby research affected technological progress (the number of patents) more strongly than it affects private returns (the profits or market value of firms).[32]

Nelson's argument that R&D reflects the presence of collateral technological opportunities applies with particular force at the industry level, where major differences in technological possibilities are most visible. For example, no one would reasonably

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[31] Though spillovers are important within an industry, many spillovers of course take place in a broader context, to other industries, within a national economy, or internationally.

In practice, it is often difficult to determine the rate of depreciation and the lag until research becomes effective. For example, a detailed study of 133 firms (Griliches and Mairesse (1984)), which was designed to examine the effects of various ways of defining and measuring physical and R&D capital (p. 347), was not able to establish definitive estimates of the depreciation rate and the lag (pp. 372-373).

Market share structure also affects the difference between firm and industry results. Blundell, Griffith, and Van Reenen (1999) show firms with higher market share tend to have a greater number of innovations and patents, and the effect of innovation on stock market value is greater for when firms with larger market share. Such results show firms with larger market share are able to appropriate a larger proportion of the industry gains to R&D.

[32] Baumol (2000) emphasizes that the different firms within an industry often use R&D to compete on the basis of product quality, and that the cumulative nature of progress ensures that product quality improves greatly over time. As Sena (2004, p. F314) summarizes Baumol's argument, "spillovers and voluntary dissemination allow technological knowledge to spread in the economy so as to increase productivity of other firms and this way guarantee the continuous growth and improvement in living standards Western economies have experienced in the last two centuries."

expect productivity growth to become as rapid in lumber as it is in computers if R&D intensity in lumber were raised to the levels prevalent for computers. Yet, that is what the usual cross-industry regressions assume. Nelson recommended that the return to research should be determined not from regressions across firms or industries, but instead from careful study of the returns to individual innovations. Subsection II.5 examines rates of return obtained from innovation studies.

II.3 Estimates of Indirect Returns to R&D – Downstream Analyses of R&D.

The notion of complementary investments has been important for a long time in the understanding of indirect returns to R&D. For example, it has long been the case that, when a new computer is introduced, the purchasing firm must deploy considerable resources to use the new equipment effectively. Bresnahan and Greenstein (1996) describe such complementary investments as coinvention, and Bresnahan (1999) emphasized firms must adjust their organizational structure and their work processes, which is a long and slow procedure, to take full advantage of the new technologies.

In recent years, economists have begun to pay far more attention to the idea that new technology requires very substantial complementary investments. Brynjolfsson, Hitt, and Yang (2002) argue that such complementary investments are very large. They show that financial markets valued a dollar’s worth of computer capital as ten dollars. Other kinds of investments do not have such large effects in the financial markets. The authors argue that the great effect which computers have on firm financial value occurs because large complementary investments, in such areas as software, organizational redesign, and worker training, are typically made together with the purchase of computers. As they point out, such adjustments eventually extend to many fundamental characteristics of the firm, such as the extent of centralization or decentralization of decisions, patterns of work flow, work compensation and incentive patterns, relationships with customers and suppliers, and even corporate culture. Expenditures on improving business practices of this type are typically expensed. As Brynjolfsson, Hitt, and Yang (2002) argue, if expenditures in these areas increase substantially with computer spending, and are a source of unmeasured investment and value to the firm, then the observed increase in firm value with computers can provide an estimate of the associate increased investment in intangibles. Bresnahan (1999) also provides a very useful discussion of the ways in which organizations have to restructure in order to use new technology more effectively. Finally, Brynjolfsson and Hitt (2003) have recently reported that the observed "return" to computer investments, at the firm level, grows steadily over time, which they interpret as ever increasing investment in complementary assets.[33]

The clear importance of complementary assets makes it far more difficult to determine the appropriate rate of return to R&D. If downstream complementary investment is substantial, it becomes very difficult to determine how much of the

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[33] Bloom, Sudun, and Van Reenan (2006) provide important support for the idea that corporate knowledge of information technology applications is central by showing that, in Great Britain, U.S. multinationals are more productive than non-U.S.multinationals or domestic firms, and that these productivity advantages are associated with higher returns to information technology. Furthermore, these high returns to information technology are greatest in sectors such as trade and finance where the U.S. productivity advantage over Europe, as measured within industry data, has grown most rapidly,

observed downstream returns are attributable to indirect R&D and how much is due to the many different forms of complementary investment.

Does indirect R&D reflect the presence of measurement error

Griliches has pointed out (Griliches (1992)) that observed indirect returns to R&D could represent either measurement error or true spillovers, which are ideas borrowed by one research team from another.[34] In practice, as many authors have pointed out, the line between measurement error in prices and genuine technology transfer is difficult to distinguish. For example, when an aircraft manufacturer prepares a new plane, they consult carefully with customers, adapt the plans so as to ensure consumer satisfaction, and spend considerable resources on training airlines to use the new aircraft. All these mechanisms create genuine technology transfer. When statisticians create a price for aircraft, no matter how detailed the specification for an airplane is, such detailed characteristics of a sales package are not likely to be included. A single transaction can therefore represent both technology transfer and measurement error in prices.

Nevertheless, there is important evidence that a lot of the indirect returns to R&D reflect measurement error. Griliches and Lichtenberg (1984a) present a model in which errors in the price of equipment or the price of materials are related to the R&D intensity of the sector supplying these goods; the underlying logic of their model implies that the indirect effects of R&D primarily represent measurement error. In addition, Gordon (1990) demonstrated that equipment prices for highly research intensive capital goods

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[34] Measurement error occurs if the price of output, in an industry such as computers, does not fully reflect improvements in the quality of output. The purchaser then obtains greater quality benefits than the measures of price suggest.

contain substantial measurement error. More recently, Greenwood, Hercowitz, and Krusell (1997) argued that a declining relative price of equipment, heavily influenced by Gordon's estimates of the quality-corrected price of equipment, has been an important ingredient in growth.

If observed spillovers associated with indirect R&D primarily reflect measurement error in prices rather than the transmission of ideas, these returns cannot be used as a contributor to productivity growth and as a source of output growth. As Jorgenson (1966) showed long ago, if a correction is made to increase the growth of output in a poorly measured capital goods sector, this adjustment will increase output and multifactor growth, but the corresponding increase in higher quality capital input, purchased by customers, will reduce multifactor productivity. The two effects roughly offset each other, and there is little net effect on multifactor productivity growth. It is therefore an important issue whether the spillovers associated with indirect R&D reflect only measurement error. In the likely instance in which a large proportion of indirect R&D spillovers reflect measurement error, this portion of the spillover cannot be used to explain multifactor productivity growth. When Fraumeni-Okubo (2005, Table 1) include indirect rates of return in their estimates of the overall return to R&D, they implicitly assume that none of the spillovers associated with estimates of the social return to R&D reflect measurement error, which is not likely to be correct (Gordon (1990)). Their reference to the possibility of measurement error (footnote 9) does not sufficiently warn the reader that, if measurement error is important, most of the estimates of the indirect return to R&D should not be used to help determine the overall return to R&D.

In view of these considerations, estimates of indirect returns are subject to important limitations. Heavy downstream complementary investments distort the picture, and there is evidence of considerable measurement error, which implies that any substantial net effect on productivity is questionable. In view of these difficulties, one has to be extremely careful about adopting estimates of the rate of return to R&D which rely heavily on estimated indirect returns.

II.4. The Spillover of Ideas.

Early work on R&D concentrated on the returns to firms and industries. However, more recently, spurred by comments in Griliches (1979; 1992), attention shifted towards true spillovers of ideas. Many studies have used detailed information from patent records to trace the evolution of ideas.

Jaffe (1986; 1988) examined the effects of knowledge spillovers between firms, where intrafirm spillovers depended on the similarity of firm's patent portfolios. Not surprisingly, the spillover of nearby R&D had a greater impact on technical progress, as measured by patents, than on profits or stock market value. Verspagen (1997a; 1997b) and Frantzen (2002) used detailed information from patent records to describe knowledge spillovers between countries and industries.[35]

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[35] These studies examine the effect of R&D in the domestic industry, R&D in related industries, foreign R&D in the same industry, and foreign R&D in associated industries. Though an overall R&D effect is clear, the more detailed measures often face collinearity difficulties (Verspagen (1997b).

In other work, Park (2004) examines international and intersectoral spillovers of R&D, and concentrates on spillovers to production outside manufacturing, an important issue which deserves further consideration. Moretti (2004) examines human capital spillovers within metropolitan areas using several measures of technical connection between different industries obtained from the R&D literature. He finds

Jaffe and Trajtenberg (2002) carried out extremely comprehensive work which provides detailed information on each individual U.S. patent from 1963 to 1999. Their work emphasizes the forward citations gained by each patent.[36] In conjunction with evidence from Trajtenberg (1990), Harhoff, Narin, Scherer, and Vopel (1999), and especially from Hall, Jaffe, and Trajtenberg (2005), this line of work shows how important forward citations are.[37]

Jaffe and Trajtenberg (2002) include a diskette, which makes their detailed data on United States patents easily accessible. Their generosity in making these data available has already led to a broad literature (Peri (2005); AlAzzawi (2004)) which has begun to make important contributions to a variety of issues.[38] Somewhat fortuitously for the purposes of the present discussion, the release of the Jaffe-Trajtenberg data provides an example of the vast downstream spillovers potentially associated with important technological progress.[39]

Though much of the literature on spillovers concentrates on spillovers across industries or countries, work has also begun to examine spillovers in many other

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input-output connections and Jaffe's measure of the similarity between industry technologies work better than interindustry patent citations.

[36] Forward citations are citations a patent earns in the future. Backward citations are citations a patent application makes to prior work.

[37] Lanjouw and Schankerman (2004) consider the relative importance of several indicators of patent quality, including forward cites, backward cites, and the number of claims made in each patent. All three of these effects have some importance.

[38] Almeida (2004) analyzes highly detailed information on the identity of individuals who have filed important patents to study the effect of labor mobility on technical change. Almeida's work on individual inventors illustrates the rich potential of the more detailed information included in each patent.

[39] The availability of the Jaffe-Trajtenberg data is an example of within industry spillover, if the relevant industry is defined to be economic research. Clearly, the importance of within industry spillovers depends on the definition of an industry.

circumstances. Jaffe, Fogarty, and Banks (1998) studied how research carried out by NASA spilled over to industry. Adams, Chiang and Jensen (2003) examined how research conducted in Federal research laboratories, which accounts for 14 percent of total United States research expenditures, spilled over to private firms. Building on Mansfield (1995), Adams (2004) investigated how research conducted in specific university departments affected industrial users. Darby and Zucker (2003) described how star scientists have been influential in transferring ideas to biotechnology firms.[40] It is useful to understand the transfer of ideas through all these different types of linkages. These articles show that, beyond the firm to firm transfers that comprise the core of the R&D literature, substantial technology is also transferred from government or universities to private firms.

IV.5 Evidence on Private and Social Returns from Studies of Individual Innovations.

In view of the difficulties associated with estimates of direct and indirect returns (Subsections IV.2 and IV.3 above), it is tempting to follow Nelson (1988) and obtain private and social returns to R&D from studies of individual innovations. The major article which examines individual innovations is Mansfield et al. (1977).

There are two problems with relying on Mansfield's results. First, the study included only 17 innovations. However, the National Science Foundation soon replicated Mansfield's work (Tewksbury, Crandall, and Crane (1980); Nathan Associates (1978)). The three studies together consider 57 innovations.

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[40] See also Zucker, Darby, and Armstrong (1998).

Second, Mansfield et al. (1977) emphasize the median rate of return to individual research projects (25 percent private returns and 56 percent social returns). If one is interested in the return to a typical scientific project, the median rate of return is relevant. However, to understand the effect of R&D on productivity and output growth, the mean project return is relevant. As Scherer (1999, Chapter 5) shows, most research projects are not particularly successful, but a few very large successes drive total returns. If one looks only at median returns, the very large effects which the most successful projects have on output and productivity growth will be missed.

In all 57 innovations, the median private return to research is estimated to be 28 percent, and the median social return is 71 percent. This information suggests social returns exceed private returns by 43 percent. The three innovation studies include 7 observations where the private return is negative, and 5 where social returns are negative. The studies do not report specific losses for failing innovations. Assuming negative returns are losses of 50 percent, average private returns are 32 percent, and average social returns, boosted by 11 innovations where the reported social return is greater than 150 percent, are 87 percent.[41]

There is one potential problem with these innovation data. Scherer (1999) showed most innovations are typically not profitable. However, the private rate of return was negative for only 7 of the 57 innovations. The low incidence of negative returns suggests that the innovations considered may not be representative.

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[41] Social returns of the magnitudes mentioned in this paragraph imply that private returns represent considerably less than half of the total social return.

In summary, Mohnen (1996, p. 50) concluded, based on a broad overview of the R&D literature, that "On average, the social return to R&D exceeds the private return by 50 to 100 per cent." The innovation studies provide important further evidence that social returns are very large and exceed private returns by a substantial margin.[42]

IV.6 The Fraumeni-Okubo Summary of Evidence on the Rate of Return to R&D.

Fraumeni and Okubo (2005, Table 1) recently selected nine studies to determine the rate of return to privately funded R&D.

Table 1. Evidence on the Rate of Return to Private R&D. (from Fraumeni and Okubo)

Author (year)	Private return	Social return
Sveikauskas (1981)	7-25 %	50 %
Bernstein-Nadiri (1988)	10-27	11-111
Bernstein-Nadiri (1991)	15-28	20-110
Nadiri (1993)	20-30	50
Mansfield (1977)	25 (median)	56 (median)
Goto-Suzuki (1989)	26	80
Terleckyj (1974)	29	48-78
Scherer (1982, 1984)	29-43	64-147

Five of the nine papers (Sveikauskas (1981), Goto-Suzuki (1989), Terleckyj (1974), and Scherer (1982, 1984)) are industry studies, and report the return to research conducted "Within" the industry and the return to R&D "From Outside", that is R&D carried out by other industries.[43] Although some text (Goto and Suzuki (1989, p. 561)

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[42] Wolff (1997) concludes the social return is 53 percent and the private return is about 10 to 12.5 percent, which also implies social returns exceed private returns by 40 percent.

[43] Section III of Goto-Suzuki reports estimates of the private return to firms, but Sections IV and V of their paper, which deal with social returns, are based on industry data.

interprets these coefficients as private and social returns, “private” returns here reflect industry returns, not firm returns. Industry returns correspond to firm returns only if there are no spillovers within an industry.[44]

Bernstein and Nadiri’s (1988, 1991) work is slightly different. They analyze industry data, but remove the capital (1988, page 431) and labor and materials (1991, page 37) used in research from the BLS or NIPA factor inputs typically used to study U.S. productivity. By making this adjustment, they are able to estimate total returns to R&D rather than just R&D spillovers.[45] However, the coefficients they estimate at the industry level show the sum of the private return to the firm undertaking R&D investment plus spillovers to other firms in the industry. These returns are not the same as “private returns”, the total returns to an individual firm undertaking research, as described in Mansfield et al. (1977).

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[44] Fraumeni and Okubo (2005, Table 1) list the private and social returns to R&D reported in these studies. They attribute the numbers to a Council of Economic Advisers file, which no longer exists on the Web. Joseph Stiglitz, then Chairman of the Council, distributed a handout based on this file during a talk in Washington. Fraumeni and Okubo report the Council’s summary accurately. However, the columns of the Council table were not properly labeled. As discussed in the text, only Mansfield et al. (1977) reports a private rate of return, in the traditional sense of the total returns to a private firm. Some of the ambiguity comes from Griliches (1992, Table 1, part II), which combines information on the private and social return to R&D with parallel information on the direct and indirect return within a single table. The text of that paper (page S43) comments that the estimated social rates of return look surprisingly uniform, but does not emphasize that many of the rates of return reported in the left column of Table 1 (listed as Within and From Outside, respectively) include elements of social returns (the within industry spillover, and the excess return, which exceeds the costs of R&D) and does not represent the traditional private return to firms. (Griliches (2000, pp. 60, 61, and 70) shows returns to R&D are considerably greater in industry data than in firm data.)

[45] Current BEA work on R&D (Schultz (2006)) now removes factor expenditures on R&D from factor inputs, using recently expanded NSF data on the composition of research costs in each industry. This important advance permits BEA to estimate the total return to research, rather than just the spillover component of returns. For a discussion of why standard procedures estimate only the spillover effect see U.S. Bureau of Labor Statistics (1989, page 36).

Nadiri (1993) summarizes results from many different studies, on both a firm and industry basis. The only study on the Fraumeni-Okubo list which actually estimates private and social returns is Mansfield et al. (1977), which is fundamentally different because it measures the return to individual innovations rather than firm and industry regressions. Except for Mansfield, the studies cited do not provide information on the private and social rates of return to R&D.

In view of these many difficulties, what R&D expenditures should be included as investment and what rate of return should be attributed to them? First, in industry, all privately financed research should clearly be counted as investment. However, the evidence indicates federally financed research in industry, on net, does not have a positive return, so such expenditures probably do not qualify as investment. Second, because of the issues of relevance to growth and double counting discussed in Section I, only a small proportion of the research financed by government or universities should be classified as investment.

Third, the studies Fraumeni-Okubo (2005) list in their Table 1 are far too heavily weighted towards industry studies of direct and indirect returns. Such estimates depend much too heavily on indirect returns to R&D, which are unreliable because they depend on the amount of complementary investment, and at least partially reflect measurement error, so that the estimated indirect effects are probably not a genuine effect on productivity. Fourth, because of the many difficulties with the regression estimates it is probably useful to emphasize rates of return obtained from the innovation studies, which also indicate that social returns are very large and considerably exceed private returns. On balance, private returns of 25 percent and social returns of about 65 percent, which more than double the private return, seem reasonable. However, these extremely high returns are relevant only for privately financed research.

III. R&D Stocks on an Industry Basis.

In the growth accounting literature, residual income, which remains after all other factors of production are compensated, is generally attributed to capital. The standard treatment of capital in growth accounting, due to Jorgenson and Griliches (1967), first removes payments to labor and materials from income, and then, using the Hall-Jorgenson (1967) procedure, assigns the sum which remains, property income, to specific capital assets. These procedures first allow for depreciation, taxes, and other costs of capital, and then allocate the rest of capital income to the internal rate of return, or capital profit.

Much evidence suggests that observed profit income is not just a return to capital, but also reflects returns to research and development and other intangible assets. For example, Grabowski and Mueller (1978) examine a sample of 86 firms which conduct at least some R&D. They report (p. 342) the overall variance in profit rates was reduced approximately in half when R&D was capitalized rather than expensed. They conclude that the after-tax return to R&D is between 15 and 20 percent, considerably above the rate of return earned on other assets, but comparable to the returns reported in Mansfield et al. (1977). The Grabowski and Mueller study clearly shows that some of the income typically included in the return to capital actually represents a return to R&D.

Recently, economists have discussed investments in many types of intangibles which extend far beyond R&D. Corrado, Hulten and Sichel (2003) estimate that expenditures on intangibles in the United States were $1221 billion, annually, in the United States from 1998 to 2000. R&D expenditures, as defined by the National Science Foundation, were $185 billion, or only about 15 percent of the total. Investments in knowledge in other areas, such as finance, movies, and books, which the NSF does not count as research because they are not based on an explicit scientific or technological field, were estimated to be $199 billion.[46] Among other items, computer software accounted for $154 billion, advertising for $254 billion, employee training for $123 billion, and management improvement for $306 billion. R&D accounts for only a small share of the amount firms spent, beyond capital expenditures, to increase future output.[47]

The Multifactor Productivity program of the Bureau of Labor Statistics currently includes plant, equipment, inventories, land, and software as capital assets, and calculates the internal rate of return, service price, and income paid for each asset. A separate internal rate of return and industry-specific asset service prices are calculated for 56

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[46] The National Science Foundation publication Research and Development in Industry does not include R&D in the social sciences or psychology, so research in financial economics does not appear in these data.

[47] Many of the assets Corrado, Hulten, and Sichel (2003) consider depreciate considerably more rapidly than tangible capital and R&D, so the proposed new items account for a smaller proportion of the overall capital stock than these figures on investment indicate.

different industries. If R&D is to be treated as an investment, it would be natural to expand the BLS calculations, on an industry basis, to include R&D as a further asset.[48]

Unfortunately, it is difficult to determine the relevant R&D stock within each industry in the United States. As Scherer (2003) discusses, in the U.S. most data on R&D are collected at the firm level. Many large firms invest substantial sums in R&D. However, these firms frequently operate in many different industries, and it is not clear how much of each firm's total research portfolio supports production in any particular industry.[49] As an illustration of the difficulties involved, Wolfe (2003) reports the U.S. National Science Foundation assigns large amounts of R&D to the trade industry, even though relatively little research actually takes place in trade. The problem occurs because all research conducted by a firm is assigned to the one industry in which its payroll is greatest. If a pharmaceutical firm has many sales representatives, its research efforts could well be assigned to trade, even though all the research actually takes place in pharmaceuticals.

Because these procedures assign all research conducted by a firm to a single industry, current National Science Foundation data are not accurate enough to create a reliable measure of R&D stocks within each of the BLS industries.[50] In my judgement, it

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[48] The BLS calculates a separate internal rate of return for each of 56 industries included in the nonfarm private business sector. To extend these calculations to R&D requires R&D stocks for each of these 56 industries.

[49] Brown, Plewes, and Gerstein (2004) discuss the limitations of available measures of R&D in specific industries in considerable detail.

[50] The Bureau of Economic Analysis faces similar issues in establishing industry R&D stocks. Carson, Grimm, and Moylan (1994), and much of the rest of the R&D literature, has used the existing NSF data on industry R&D expenditures to create industry R&D stocks.

is necessary to modify the NSF data on industry R&D expenditures considerably before they can provide a sound measure of R&D assets in each industry.

A potential method of assigning R&D spending conducted by individual firms to specific industries could follow the well-established procedures which the Bureau of Economic Analysis currently uses to allocate profits earned by firms to specific industries. The BEA takes Internal Revenue Service measures of the profits earned by firms classified in each industry, and allocates these profits to establishments in particular industries on the basis of data showing the industries in which these firms actually employ workers, as determined from the Enterprise Statistics.

Similar procedures are likely to improve the accuracy of measures of the R&D actually committed to each industry. A separate allocation can be conducted for every firm, allocating that firm's research in proportion to its own industry distribution of employment or payroll. Furthermore, firm R&D could be assigned to particular industries not only on the basis of employment or payroll, but also on the basis of the intensity of scientific and technical employment within each industry. Through such a methodology, trade, where scientific input is typically low, would for that reason be assigned less of a firm's research than pharmaceuticals, where scientific input is typically high.[51] A simple allocation procedure of this type is likely to provide better estimates of

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[51] As an example, each firm's proportion of its work force in a given industry, s_i, could be multiplied by the proportion of technological employment in that industry in general, t_i. Then, that firm's R&D expenditures could be allocated to specific industries in proportion to $s_i t_i$ as a share of the firm's total $s_i t_i$ across all i industries. If R&D is allocated by payroll, in the second stage industry totals would have to be adjusted to reflect the technological employment/payroll or technological payroll/payroll ratios.

In a slightly different, but probably preferable, methodology, each firm's research expenditures can be regressed on its payroll in each relevant industry. The resulting industry coefficients then provide an the R&D actually occurring in each industry than those obtained by assigning each firm's R&D solely to one industry. Furthermore, since a large number of firms contribute to production in any given industry, the proposed alternative procedure is less likely to have problems with disclosure limitations.[52] The procedures proposed here would probably make it possible to publish R&D estimates for a larger number of industries, which would help overcome one of the major limitations of current NSF industry R&D data.[53]

Once the distribution of R&D across industries is better understood, more reliable information on the industries in which R&D actually occurs can in turn be used to determine the industries in which R&D is actually utilized. The literature (Scherer (1982, 1984); Verspagen (1997a; 1997b); Moretti (2004)) has used input-out relationships, information from patent applications, and careful analysis of individual patents to determine the specific industries in which R&D spillovers occur.

The Bureau of Labor Statistics currently uses an interesting framework to understand the role of R&D spillovers in the aggregate economy. Spillovers do not provide income to any particular asset, and are not included within the data on factor inputs and factor earnings which determine the portion of growth attributable to specific inputs. Instead, aggregate spillovers are included "below the line", as one of the determinants of observed

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estimate of research intensity in each industry. It would be of interest to examine how closely such industry coefficients match actual measures of scientific or technical employment in each industry. The procedure suggested in the present paragraph determines research intensity in each industry from a statistical procedure, rather than by assumption, and utilizes the highly detailed data available for each firm. Because more data are utilized, this variant of the methodology seems likely to provide estimates of research intensity for a larger number of industries.

[52] For example, if each firm produces output in five industries, the data cell for a typical industry would contain information from five times as many firms.

[53] I plan to construct and analyze alternative measures of industry R&D, prepared along the lines discussed above.

multifactor productivity growth. Such procedures are helpful in evaluating the role of spillovers in national data. However, further information on the industry distribution of spillovers is necessary to extend this approach to specific industries.

IV. International R&D Spillovers.

As evidence presented below indicates, even for the United States, a very large and highly advanced economy, foreign R&D plays an important role in technical progress. Most of the other countries in the world, which are much smaller and less technically progressive, are far more dependent on foreign R&D. Consequently, most of the statistical agencies in the world will have to understand and evaluate how foreign R&D affects their economies in order to include the full effect of R&D in their accounts.

R&D is heavily concentrated in a few developed countries, essentially in the OECD.[54] Even within the OECD, a few relatively large countries, like Germany, Japan, and the U.S., account for a large proportion of R&D.[55] Once R&D is included in the national income accounts, economists will have to provide the underlying information on how R&D in the leading countries affects production in small rich countries or in the developing world.

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[54] The OECD countries had a particularly large share of world R&D in the 1970s, 1980s, and 1990s. However, in very recent years R&D has increased sharply in several countries outside the OECD, notably China and India.

[55] For example, in 1995 the United States, Japan, and Germany accounted for more than two-thirds of OECD R&D expenditures, and the G7 countries together accounted for about 85 percent of the total. Data are from the OECD Science, Technology, and Industry Scoreboard: 2003.

There are many potential channels through which the undoubted technological advantages of the most advanced countries can be transmitted to less wealthy nations. One branch of the literature emphasizes the mere presence of international trade (Coe and Helpman (1995)). Other analyses emphasize the presence of multinational companies (Gorg and Strobl (2001)) or the role of foreign domestic investment (Borensztein, De Gregorio, and Lee (1998), Aitken and Harrison (1999)).[56] The transmission of ideas (AlAzzawi (2004)), through such mechanisms as the scientific or technological literatures, is another potentially important pathway. Of course, in actual practice many or all of these potential channels of transmission are likely to be influential. Much work still remains to be done to sort out how these potential influences interact and to understand the particular circumstances under which each is important.[57]

Even among rich countries, there is a distinction between the largest countries, such as the U.S., Germany, and Japan, which conduct large amounts of research, and small countries which perform much less research. Within the research leaders, spillovers within an industry and across industries tend to be very important. In smaller countries, many of the equivalent effects come into existence through foreign trade spillovers.[58]

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[56] Although much of the literature concentrates on whether technology from multinationals spills over to domestic production, multinationals of course make a contribution if they produce at a higher level of productivity than domestic firms.

[57] Recent studies have begun to investigate links between different facets of technology transfer. For example, AlAzzawi (2004) examines the extent to which spillovers of knowledge, as measured by patent citations, are associated with foreign domestic investment. Branstetter (2000) examines whether Japanese investment in the United States is a channel of knowledge spillovers to Japanese firms.

[58] Tables 4 and 5 of Coe and Helpman (1995) support the statements made in this paragraph. As in most estimates of this type, spillovers from the U.S., Germany, and Japan are larger than those from other countries. Coe-Helpman also find domestic R&D is more important than foreign R&D in large countries, but foreign R&D is more important than domestic R&D in most small countries.

One branch of the empirical literature examines research spillovers among advanced (OECD) nations. Coe and Helpman (1995) emphasize the volume of foreign trade as a key to research spillovers. Their work also includes imports as a proportion of GDP, which permits technology transfer to vary with the importance of trade. In later work, Lichtenberg and van Pottelsberge de la Potterie (1998) suggest a better measure of R&D flows, and Funk (2001) and Kao et al. (1999) clarify the econometric issues involved. Despite these improvements, Coe-Helpman (1995) remains the classic article which demonstrates the potential importance of international R&D spillovers.

Xu and Wang (1999) is a particularly useful study of R&D spillovers within the OECD. They show R&D in capital goods affects productivity growth, but R&D contained in other forms of trade does not. Xu-Wang include domestic R&D stocks as well as a proxy for the extent of the disembodied flow of information (a distance weighted, or unweighted, measure of other countries R&D stocks) in addition to the R&D contained in capital goods. The broad range of variables allows them to determine the importance of R&D transmitted through each of these channels. Xu and Wang (1999) is one of the most insightful and helpful contributions in the literature because they report estimates of returns obtained through each mechanism.[59]

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[59] Verspagen (1997b) similarly concludes that R&D spillovers embodied in purchased inputs and knowledge floating freely across international borders both play a role in technology transfer across countries. Like Xu and Wang (1999), Verspagen (1997b) shows R&D spillovers from the large technology leaders have the greatest impact on other nations.

Griffith, Redding, and Van Reenen (2004) integrate R&D with international technological convergence. They demonstrate that, in additional to the usual R&D effect (observed at the industry level), there is convergence (in the sense that country-industry observations at a lower level of productivity tend to catch up), and that R&D permits the successful absorption of foreign technology. Keller (2002) studies R&D spillovers from the largest countries to smaller OECD nations.

Another strand of the literature considers R&D transfers to countries outside the OECD, typically developing nations which conduct very little R&D. Coe, Helpman, and Hoffmaister (1997) is the original contribution in this direction. Schiff, Wang, and Olarreaga (2002) and Connolly (2003) conduct more recent work. Schiff, Wang, and Olarreaga (2002) find R&D imported in capital or materials from Northern countries increases productivity in Southern industries, especially in R&D intensive industries.

Many studies of technology transmission to developing countries (Borensztein, De Gregorio, and Lee (1998); Connolly (2003)) examine data for the aggregate economy. More information could be brought into play if economists constructed more reliable measures of industry productivity growth in different countries.[60]

The effect of technology transfer on developing countries will eventually have to be understood on the basis of highly detailed information on firms and establishments. Muendler (2004) recently studied the type of information which is needed.[61] His work on

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[60] Two recent studies illustrate both the potential of international comparisons based on detailed industry data and the need for better measures of productivity. Savvides and Zachariadis (2004) examine the effects of research contained in foreign capital goods, the amount of capital goods imports, and foreign investment on productivity growth in manufacturing. However, economy wide deflators, rather than data specific to manufacturing, are used to measure real ouput. Similarly, Schiff, Wang and Olarreaga (2002) examine how R&D imports affect productivity growth in 16 manufacturing industries in 25 developing countries. Output data are expressed in U.S. dollars and deflated by the U.S. GDP deflator. It is questionable whether this procedure generates productivity measures which are as reliable as studies which use industry specific output price deflators for each country.

The International Comparisons of Output and Productivity (ICOP) project at the University of Groningen has, for many years, measured international productivity differences based on detailed information on unit values in different countries.

[61] Hallak and Levinsohn (2004) similarly recommend the use of highly detailed micro data, rather than aggregate country data, in the analysis of the closely related issue of whether increased amounts of foreign trade bring a positive effect to the growth rate. As in the present review, they recommend greater emphasis on the analysis of, and discrimination between, the many different channels through which growth effects may operate. Hallak-Levinsohn also argue that different channels are likely to be influential in different circumstances. A recent review (Keller (2004)) also emphasizes the need for detailed data, as well as the usefulness of case study evidence.

productivity in Brazilian firms included measures of the foreign equipment and materials available to each firm. He concluded foreign import competition was more important than foreign technology.[62] If further work, especially with detailed establishment data on other countries, confirms these results, technology may be less important than previous discussion has suggested. In that event, greater weight will have to be attached to product market competition, as emphasized in Parente and Prescott (1994; 1999) and Lewis (2004). It is worthwhile to be reminded that technology transfer can be much more effective when other economic conditions are supportive.[63]

On balance, there is widespread international transmission of knowledge associated both with the imports of R&D-intensive capital equipment (Xu and Wang (1999), Coe, Helpman, and Hoffmaister (1997), and Caselli and Wilson (2004)) as well as R&D included in materials as well as capital equipment (Schiff, Wang and Olarreaga (2002)). This international transmission of R&D typically has a favorable effect on productivity growth. One interesting study finds strong benefits associated with R&D intensive materials (Lichtenberg and Virabhak (2002)).

In addition to Muendler (2004), several further studies examine detailed data on production in developing nations. Basant and Fikkert (1996) analyze panel data for Indian firms between 1974 and 1982. India appears to be a developing country in which many firms conduct their own R&D. They emphasize foreign purchases of technology, as well as the impact of domestic R&D, and construct a foreign R&D spillover measure by weighting R&D in eight wealthy economies by each country's relevance to India, as determined by patents granted in India.

In a production function study, Bartel and Harrison (2005) compare the productivity of public sector and private sector production in Indonesia. Among other topics, they consider the effect which foreign ownership has on productivity. Blalock and Veloso (2006) examine the effect of imports on productivity in Indonesian data. All this work illustrates the usefulness of highly detailed datasets describing productivity growth over time. See also Haskel, Pereira, and Slaughter (2007) for the United Kingdom.

[62] In further evidence supporting the Parente-Prescott and Lewis view, Schiff and Wang (2004) show that, in North-South trade, openness to trade, as measured by the amount of trade, has a greater impact on productivity growth than the knowledge (R&D) content of a unit of trade does.

[63] Some scholars emphasize countries gradually have to develop the capacity to use modern technology. Nelson and Pack (1999) present such a viewpoint, and compare the results with growth accounting.

There is also substantial transmission of knowledge not specifically associated with factor inputs (Xu and Wang (1999)). Such disembodied knowledge flows are often highly localized (Peri (2005), Maursith and Verspagen (2002)). The importance of distance may change greatly over short periods of time (Keller (2002)).

A large advanced economy such as the U.S. generates most of its own technical progress. Foreign R&D could be most influential if it allowed U.S. research to improve more rapidly. However, it is difficult to evaluate the importance of foreign ideas. As U.S. Bureau of Labor Statistics (1989, page 6) remarked:

> “A further issue is whether foreign research investment should be included. Clearly, as foreign technological levels have approached U.S. levels and as American multinational corporations have conducted more research abroad, foreign R&D has become more relevant to U.S. firms. However, the relative weight to be attached to a unit of foreign research and how this may have changed over time are unclear.”

Data on patent citations now make it possible to determine the relative importance of foreign research, and how this changes over time. Consider all U.S. patents granted to inventors located in the United States. Such patents arguably provide a good description of U.S. technical progress each year. Table 2 shows how often these U.S. patents cite U.S. and foreign research.[64]

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[64] I thank Anastasiya Osborne for programming the large data bases containing these patent data.

If one looks only at citations of foreign work patented in the U.S., it is necessary to examine how much foreign research is patented in the U.S., and how this proportion changes over time (Eaton and Kortum (1996; 1999)). However, the data reported in the text include all citations made by U.S. patents, regardless of whether the cited patents are U.S. or foreign. If each citation made by a U.S. patent is assumed to be of equal value, a simple count of the domestic or foreign origin of citations provides direct information on the relative importance of domestic and foreign research. Because large numbers of citations are observed each year, differences in the importance of individual citations should cancel out.

The available data report the country of cited patents only for patents granted in 1963 or later. We estimate the country origin for patents granted prior to 1963 on the basis of time trends in later years. It is

Table 2 Citations of Foreign Patents, in Proportion to Citations of U.S. Patents 1976-2000
(for utility patents, year refers to year of application)

1976	.301	1981	.366	1986	.435	1991	.490	1996	.505
1977	.314	1982	.389	1987	.447	1992	.503	1997	.510
1978	.327	1983	.399	1988	.455	1993	.510	1998	.497
1979	.338	1984	.405	1989	.470	1994	.521	1999	.506
1980	.356	1985	.426	1990	.473	1995	.552	2000	.525

Source: computed from files of individual patents, as provided by the U.S. Government Patent and Trademark Office.

These data suggest that in 1976, in addition to knowledge obtained from U.S. R&D, the United States had access to 30 percent further knowledge from foreign research.[65] By 2000, the increment of foreign knowledge increased to 53 percent.

U.S. productivity growth accelerated sharply in the late 1990's, and the productivity recovery was sharper in the U.S. than abroad. Table 2 shows the proportion of citations of U.S. work declined steadily from 1976 to 1995, but this trend then reversed. Patent citations suggest U.S. technology turned a central corner in 1995; the timing is remarkably similar to the year in which U.S. productivity growth accelerated.

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important not to omit cited patents occurring before 1963, which are overwhelmingly of U.S. origin. Early versions of this paper reported a greater proportion of foreign citations, because citations to patents occurring prior to 1963 were not yet included.

[65] These calculations assume that each citation, whether domestic or foreign, contributes the same amount of knowledge to U.S. innovation. The proportion of foreign citations is greater than found in many other studies because citations of patents granted outside the U.S are included. For example, in 1976 there were 34984 citations of U.S. patents granted to foreign inventors, and 17370 further citations of foreign patents.

If we assume foreign R&D increased U.S. effective R&D stocks by the ratios given in Table 2, and foreign knowledge earned the same 30 percent rate of return, foreign R&D contributed 0.1 percent a year to 1947-2002 U.S. productivity growth.[66]

A major unresolved question is what happens to returns to R&D in the U.S. and other advanced countries as further nations, such as China and India, expand their capability to do R&D. So far, most studies conclude R&D in one country increases productivity in other countries. However, Luintel and Khan (2004) report foreign R&D reduces productivity in the United States. The effect of international competition in technology on the returns from R&D is a crucial question which requires much further analysis.[67] [68]

V. Conclusions.

Recent decisions to include research and development expenditures in the System of National Accounts raise important new questions for statisticians in developed and developing countries. Many of the benefits of R&D are not obtained by the original investors, but instead leak out to other firms, customers and even other nations. Because the asset and spillover influences of R&D have different time horizons, it is useful to establish separate "national R&D stocks" for each purpose.

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[66] Under these assumptions, the 1948-2002 R&D effect increases from .17 percent a year (with the usual BLS estimates based on just domestic R&D) to .24 percent Since information on the country of origin of citations is available only for 1976 and subsequent years, the productivity calculations mentioned above estimate the foreign percent of citations for years prior to 1976. Since information on foreign citations is more reliable for 1973-2002, we mention that, in these years, the domestic R&D contribution of .18 percent a year to productivity growth increased to .29 percent a year when foreign R&D is taken into account. Foreign R&D is important, of course, due to the rapid growth of foreign citations, as reflected in Table 2.

[67] Hall concludes (1993, page 317) that greater competition, much of it foreign, reduced the U.S. private return to R&D in the 1980's, but had less of an impact on social returns to R&D. As R&D increased in other countries, the United States perhaps lost some monopoly power over innovation (Freeman (2005)).

[68] In developing countries, technology typically adopts and modifies advances created in the wealthy nations, so information on innovations, such as patents, provides a less complete picture of new technology.

On the basis of the evidence considered, privately financed R&D in industry should be treated as an investment and included in the relevant R&D stock. Returns to R&D are very high, but these high returns accrue only to privately financed R&D. Many elements of university and government research have very low returns, overwhelmingly contribute to economic growth only indirectly, if at all, and do not belong in investment.

Much remains to be understood about the specific pathways through which R&D in advanced nations is transmitted to developing countries. There are many potential pathways through which this knowledge may spread. Once R&D is included in the accounts, economists will hopefully pay much more attention to understanding exactly which channels are effective in transmitting knowledge to poorer countries.

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