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INDIRECT R&D AND PRODUCTIVITY GROWTH

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This paper examines the indirect effect of R&D, the productivity gains obtained by downstream industries which purchase capital equipment or materials which contain R&D. Previous studies have concentrated on determining the rate of return to indirect R&D. This study, in contrast, presents the first available evidence on the stocks of indirect R&D used in the national economy. Stocks of indirect R&D have grown remarkably quickly, even more rapidly than direct R&D. Indirect R&D grew 8.22 percent annually between 1947 and 1987, largely because the R&D contained in capital equipment grew so rapidly. Because indirect R&D increased quickly, the rates of return to indirect R&D suggested in the relevant economics literature imply that indirect R&D has been a substantial contributor to economic growth.

JEL categories O3, O4.

This paper examines evidence on how much indirect R&D contributes to productivity growth. Indirect R&D refers to the productivity benefits obtained by downstream industries which purchase R&D embodied in capital equipment and in materials. In contrast, the direct return to research describes the productivity gains obtained by the industries directly undertaking research.

Griliches (1992) and Nadiri (1993) recently reviewed the evidence concerning indirect R&D and R&D spillovers. Both of these authors conclude that these further returns to R&D are

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substantial. Both authors also believe that these broader facets of R&D can explain a considerable portion of multifactor productivity growth. However, several issues have to be clarified before a plausible measure of the effect of indirect R&D on productivity growth can be constructed.

One major issue is the size of the indirect R&D stock. It does not help us understand productivity much if we know the rate of return to indirect R&D, but don't know the size of the indirect R&D stock to which this applies. The present paper provides the first available evidence on the size and growth of the indirect R&D stock. This information makes it possible to obtain a more accurate understanding of the effect of indirect R&D on productivity.

A second major concern deals with the role of measurement error. As Griliches (1992, page S36) remarks, indirect R&D effects can reflect either genuine technology transfer or measurement error. Presumably, the concern with measurement error is that, if reported downstream effects reflect measurement error, they cannot credibly be used to explain multifactor productivity growth. As Jorgenson (1966) has shown, if there are unmeasured increases in capital quality, the increased capital inputs tend to reduce MFP, but are offset by the greater output of capital goods, which tends to increase MFP.

However, a recent paper (Sveikauskas (a, forthcoming) showed that the existence of unmeasured quality change which Jorgenson discusses also has a further implication. The more rapid growth of output in the research-intensive capital goods sector greatly increases the implied return to R&D. Since more of output growth is thereby assigned to R&D, less is left over to be included in the residual. Allowance for measurement error in capital can in fact reduce the residual.

To put the matter in another way, apparent downstream R&D benefits can reflect either technology transfer or errors in measurement. If these benefits reflect technology transfer, they should unambiguously be counted as an influence of R&D on productivity. On the other hand, if they reflect errors in measurement, these errors reflect the substantial role of R&D in producing high levels of unmeasured output in the capital goods sector, and can therefore equally well be attributed to R&D.[1] From this perspective, indirect R&D reflects previously unmeasured real effects of R&D on productivity, at least somewhere in the economy.

A third issue concerns the different roles of indirect R&D and of R&D spillovers in understanding the growth contribution of

[1] In a sense, if indirect returns to R&D are due to measurement error upstream, they can be viewed as either increased (upstream) direct returns, once prices are measured correctly, or as observed downstream returns, using current price deflators. In either case, these returns extend beyond the direct returns to R&D so far measured.

R&D. Early work on R&D, such as Terleckyj (1974), concentrated on indirect R&D. However, more recent studies have paid much more attention to R&D spillovers. In particular, the imaginative work of Jaffe (1986, 1989) has been central in altering the emphasis in discussions of R&D spillovers, away from interindustry transfers and towards the spillover of ideas from other firms or universities engaged in research in the same technical areas.

However, from the relatively narrow perspective of growth accounting, which deals with only the more proximate determinants of growth, the externalities associated with information obtained from other firms or from universities are already implicitly included within the high rates of return which firms or industries obtain from their own direct research.[2] Such spillovers are therefore already reflected in existing growth accounting estimates of the direct effect of R&D on observed productivity. However, because of the lack of explicit stocks of

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[2] For example, Jaffe (1986, page 984) states that his work evaluates the spillover phenomenon "by looking at the average effect that other firms' R&D has on the productivity of a firm's own R&D." Typical values of such spillovers are therefore clearly already included in existing estimates of the overall return to a firm's or an industry's own research.

Jaffe's work can therefore be interpreted as showing that a portion of the high returns customarily associated with the private or direct effect of R&D actually occurs because of the presence of spillovers from R&D conducted elsewhere. The present paper examines a different and complementary question. What is the indirect effect of R&D, the impact on the productivity observed in downstream industries, many of which themselves conduct little or no R&D?

indirect R&D and because of the unresolved issue of measurement error, the growth accounting literature has so far not provided a satisfactory measure of the indirect effects of R&D on productivity growth. This paper aims to produce credible measures of the effect of indirect R&D on productivity.

According to the work carried out in this paper, indirect R&D stocks grew extremely rapidly, with an 8.22 percent average annual rate of growth between 1947 and 1987. In contrast, the direct stock of R&D grew at only a 6.68 percent rate over the same period. Indirect R&D grew very rapidly primarily because the R&D included in capital equipment increased 9.75 percent a year over this period.

In addition, the analysis considers the relative importance of various different channels through which indirect R&D operates. For example, the indirect R&D effect can operate through capital or through materials. The effect of R&D through capital can occur because equipment grows especially rapidly, because all forms of capital equipment become more research intensive, or because equipment shifts towards more research intensive assets. This paper develops some quantitative understanding of each of these alternative channels.

The growth in the indirect R&D stock is estimated to have contributed 0.19 percent a year or more to annual productivity growth. The indirect R&D effect is therefore somewhat greater than the 0.15 percent estimated annual contribution of direct R&D over this same period (U.S. Department of Labor, (1989)), and consequently more than doubles the amount of economic growth which can be attributed to R&D.

Section I of this paper describes the construction of stocks of indirect R&D used in the private nonfarm business economy between 1947 and 1987. Section II lists and discusses the stocks obtained from these calculations. In particular, Table 1 in Section II provides the first available evidence on the size and rate of growth of the indirect R&D stock. Section II also briefly examines the relative role of capital and materials in the growth of the indirect R&D stock. Equipment accounts for approximately 70 percent of the overall growth of the indirect R&D stock. Consequently, Section III analyzes the impact of several different factors which have contributed to the rapid growth of the R&D contained in equipment.

Section IV considers the rate of return to indirect R&D, as suggested by several relevant strands of the economics literature. The main source of information is Nadiri's (1993) review of econometric evidence on the indirect returns to R&D. A second major source of information on rates of return is the work on detailed studies of individual innovations, begun in Mansfield et al. (1977), and continued in two replications.

Section V shows that the rates of return discussed in Section IV, in conjunction with the indirect R&D stocks reported in Section II, imply that indirect R&D has been a substantial influence on economic growth.

I. Concepts and Measures of The Stock of Indirect R&D.

The concept of indirect R&D adopted here follows Terleckyj (1974). In the Terleckyj approach, indirect R&D is determined from the R&D expenditures contained in purchases of equipment and materials. However, in the present study R&D is measured by R&D stocks, which reflect R&D expenditures over many years, rather than by the flow of current research expenditures.

The process of creating stocks of indirect R&D begins with construction of direct R&D stocks. Information on direct R&D is first gathered for forty-three different industries over the period 1921-1987. From 1921 to 1960, information on R&D employment in each of these industries is obtained from various editions of the National Research Council's publication on Directory of Industrial Research Laboratories in the United States. The employment data for these years are transformed to match estimates of national R&D expenditures during these years from Terleckyj (1982). This information based on R&D employment is then blended with 1960-1987 data on applied product field research expenditures in the same industries, as obtained from standard National Science Foundation sources.[3]

Once this information has been combined into a single series measuring R&D expenditures in each industry over the 1921 to 1987 period, the resulting expenditures data are deflated to convert them into estimates of real R&D expenditures. Next, the data on real expenditures are in turn used to construct (direct) stocks of privately financed R&D for each of the forty-three industries. These industry R&D stocks are calculated using the same assumptions and procedures previously used in creating national R&D stocks (U.S. Department of Labor (1989)).[4]

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[3] The analysis conducted in this paper extends only until 1987 because the National Science Foundation series on applied product field expenditures was altered greatly after the early 1980's. Since the data extend only until the 1980's, they cover a period in which the great majority of R&D was conducted in manufacturing.

It is necessary to begin the R&D stocks in an early year because some forms of capital equipment are long lived, with useful lives of twenty or more years. Therefore, in order to understand the R&D stocks contained in capital in 1947, we start preparation of industry stocks of R&D with data for 1921.

[4] However, the industry R&D expenditures, and consequently also the industry R&D stocks, do not exactly add up to the national totals. For example, the 1987 R&D stock in the aggregate data is $427 billion, whereas the sum of the 1987 industry stocks in the present data is $415 billions, a difference of 2.8 percent. This discrepancy occurs because the aggregate stocks include R&D financed by industry conducted in universities and in nonprofit institutions, and because of a variety of minor adjustments. Reasons for this discrepancy are discussed more fully in Sveikauskas (b, forthcoming).

Next, the R&D stocks within these forty-three industries are converted into measures of the R&D included in purchases of capital and materials. To start this process, the stocks of direct R&D in each industry are first divided by shipments to obtain a measure of research intensity (research per unit of output). Research intensity (RD/Y, where RD is the research stock and Y is output) is a concept which is free of the largely arbitrary size of different industries.[5] Expenditures on new vintages of equipment or on purchases of materials are each assumed to contain the research intensity characteristic of the industry, and year, in which they are produced.

5 Several modifications of the concept of research intensity may potentially also be useful. For example, a declining R&D stock to output ratio is inconsistent with the notion that succeeding vintages of products are necessarily more technologically advanced. Research intensity could be measured alternatively by the highest previous value of the R&D stock to output ratio, which excludes technological regress. Similarly, it may be possible to allow for economies of scale to R&D within the industries producing capital goods or materials. However, in the present study we avoid these possibilities, and assume that the Terleckyj procedure, through which observed research intensity is passed on indirectly to other industries, is valid.

The specific definition of output used when RD/Y is calculated conforms to the corresponding definition used in the input-output tables and in the investment by detailed asset category information prepared by the Bureau of Economic Analysis. For example, for industries which produce materials RD/Y is measured by R&D stocks per unit of current dollar shipments, so that the R&D stocks flowing through materials can be calculated readily from successive input-output tables, each of which is expressed in terms of current dollar shipments. In the case of equipment, RD/Y is measured by R&D stocks per constant dollar of output, so that the concept of output used as the denominator in RD/Y corresponds to the output concept used in Bureau of Economic Analysis data on investment by detailed asset category, which the Bureau of Labor Statistics uses as the basis for its calculations of capital stock. Note, therefore, that in the present context we do not use the chain-weighted definition of output which is now standard in the national income accounts.

Information on the types of equipment purchased by each industry in each year is obtained from the detailed investment data prepared by the Bureau of Economic Analysis. The specific R&D stocks contained in equipment are determined by tagging each vintage of investment in each capital asset with its research intensity. The R&D contained in each vintage of every type of capital is assumed to deteriorate at the same rate as the capital itself does.[6] With these assumptions, the R&D stock contained in equipment can be determined through standard perpetual inventory calculations. Since research on capital is highly concentrated in equipment, we measure R&D only in equipment; R&D within

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6 In these calculations, we first distinguish between specific capital assets, such as metalworking machinery, computers, and communications equipment. We then distiguish between different vintages of each asset, such as computer investment in 1968 or 1974 or 1980. Every vintage of each asset category is then assigned a research intensity, which reflects the R&D stock to shipments ratio (RD/Y) in the industry supplying that class of asset in that year. Every vintage of each capital asset is assumed to contain the amount of research implied by its research intensity.

The R&D contained in each type of capital asset is assumed to deteriorate at the same rate as the type of capital in which it is included; for example, if metalworking machinery deteriorates at a 7 percent rate, the R&D contained in metalworking machines is similarly assumed to deteriorate at a 7 percent rate. This makes it possible to utilize the wealth of detailed information used by the Bureau of Labor Statistics to describe deterioration of its capital stocks to describe deterioration of the R&D contained in capital as well.

Finally, once the R&D contained in the surviving investment of every vintage of every asset has been calculated, these amounts of R&D are aggregated across vintages and assets for each year to determine the total stock of indirect R&D contained within capital assets.

structures, inventories, and land is quite small and is therefore excluded from our analysis.

Similarly, information on the types of materials purchased by each industry is obtained from the input-output tables. For each year in which a full input-output table is available, the R&D contained in materials is determined by multiplying materials purchases from each industry times that industry's research intensity, and summing up the R&D contained in all the materials purchases. Finally, the total stock of indirect R&D used by a single industry is defined as the R&D stock included in equipment plus the R&D stock contained in materials purchases.[7]

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[7] It is useful to state the methodology more formally. RDI_j, the total R&D obtained indirectly by industry j, can be expressed as the sum of the R&D obtained indirectly through capital equipment, $RDIE_j$, and the R&D obtained through materials, $RDIM_j$. Formally:

$$RDI_j = RDIE_j + RDIM_j \qquad (a)$$

The R&D obtained through equipment is calculated by multiplying the research intensity of the supplying industry i in year t ($(RD/Y)_{it}$ (the research stock in the supplying industry divided by output in that industry)) by I_{ijt} (the amount of investment provided from the supplying industry i to consuming industry j in year t). The research contained in each type of asset is assumed to deteriorate at the same rate, δ_i, at which the corresponding capital stock deteriorates during Bureau of Labor Statistics multifactor productivity calculations. A summation is then conducted across each type of capital equipment i, from 1 to 28, and across each vintage of investment, from year t equals 1 to year n. Formally, in year n:

$$RDIE_j = \sum_{t=1}^{n} \sum_{i=1}^{28} (RD/Y)_{it}\, I_{ijt}\, (1 - \delta_i)^{n-t} \qquad (b)$$

Deterioration is not assumed to be geometric in the BLS capital stock calculations, so within the actual data δ_i differs across different years and industries. The procedure used to calculate deterioration (a hyperbolic function) is actually considerably more complex than implied by expression (b). Expression (b) is used in the exposition above because it presents the essential principles most clearly.

Stocks of the indirect R&D contained in capital and in materials are calculated in this way for each of fifty-one industries which together comprise the private nonfarm business economy. Thirty-one of these industries are outside manufacturing. The stock of indirect R&D in the private nonfarm business economy is then defined as the sum total of the indirect R&D stocks from each of the fifty-one industries. Sveikauskas (b, forthcoming) describes the procedures used to prepare these stocks in much greater detail.

II. The Stock of Indirect R&D.

Table 1 reports the stock of indirect R&D in the private nonfarm business economy, as determined by these procedures, for each year from 1947 to 1987. The table also shows more detailed information on the portions of the indirect R&D stock contained in the existing stock of capital equipment, or included in the

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Similarly, the research obtained through materials by industry j is calculated by multiplying the research intensity of each type of materials purchase by M_{ijn}, the dollar amount purchased by industry j from industry i in year n, and summing across each of the 226 types of materials purchases. Formally:

$$RDIM_j = \sum_{i=1}^{226} (RD/Y)_i \; M_{ij} \qquad (c)$$

Because materials are consumed in the same year in which they are purchased, vintage aggregation such as that conducted for equipment is unnecessary, and aggregation across time is therefore not required in expression (c).

flow of materials purchases. The total indirect R&D stock is defined as the sum of these two components.[8]

To obtain an impression of the relative sizes of the capital and materials effects, note that the R&D in capital increased $484.8 billions between 1947 and 1987, whereas R&D in materials increased $202.5 billions. Consequently, increases in the R&D contained in capital accounted for 71 percent of the observed increases in the indirect R&D stock.

For purposes of comparison, Table 1 also reports the national stock of direct R&D. Over most of the time period considered, the indirect R&D stock is greater than the direct R&D stock. Similarly, total indirect R&D stocks grew at a 8.22 percent rate between 1947 and 1987, considerably faster than the 6.68 percent growth of the direct R&D stock. Most of the growth in indirect R&D came through the R&D contained in capital, which grew at a

[8] In the analysis of indirect R&D stocks, R&D stocks in capital and in materials are assumed to have the same productivity contribution, and therefore the same price. Consequently, Tornquist aggregation of the R&D in capital and in materials provides the same result as simple addition of these concepts. (As described in U.S. Department of Labor (1989, page 39), the rate of return to R&D often refers to the productivity contribution or service price of the R&D stock.)

Sveikauskas (a, forthcoming) established a relationship between the presence of R&D and measurement error in equipment, based upon Gordon's estimates of measurement error in equipment. No work similar to Gordon's is available for materials. We assume that measurement error in materials, in such industries as semiconductors and pharmaceuticals, is similarly attributable to the presence of R&D. As the text below indicates, materials account for almost 30 percent of the overall increase in the indirect R&D stock.

Table 1

Stocks of R&D in Capital and in Materials, and Output, Private Nonfarm Business Sector, 1947-1987.

All stocks in billions of 1987 dollars

	R&D in Capital		R&D in Materials		Total Indirect R&D		Direct R&D Stock		Output
Year	Stock	Rate of Growth	Stock	Rate of Growth	Stock	Rate of Growth	Stock	Rate of Growth	Private Nonfarm Business
1947	12.0		18.5		30.5		32.2		921.0
1948	14.4	.200	20.1	.088	34.5	.131	35.1	.090	967.4
1949	16.6	.154	21.9	.088	38.5	.116	38.5	.096	949.3
1950	18.6	.118	23.8	.088	42.4	.101	41.8	.086	1044.1
1951	20.5	.102	25.9	.088	46.4	.094	43.9	.049	1118.4
1952	22.2	.083	28.2	.088	50.4	.086	46.6	.064	1160.3
1953	23.8	.073	30.7	.088	54.5	.081	49.4	.060	1208.1
1954	25.6	.075	33.3	.088	58.8	.079	53.7	.086	1196.8
1955	27.8	.086	36.3	.088	64.1	.090	60.0	.117	1286.4
1956	30.6	.100	39.5	.088	70.1	.094	66.0	.101	1325.7
1957	34.1	.114	42.9	.088	77.0	.098	71.9	.089	1344.9
1958	38.1	.117	46.7	.088	84.8	.101	80.5	.119	1321.6
1959	42.3	.111	49.7	.064	92.0	.085	88.3	.097	1411.8
1960	47.4	.120	52.9	.064	100.3	.090	96.1	.087	1434.0
1961	53.2	.123	56.3	.064	109.5	.092	104.5	.088	1464.4
1962	59.2	.112	59.9	.064	119.1	.088	113.5	.086	1542.6
1963	65.4	.105	63.8	.064	129.2	.085	122.4	.079	1615.7
1964	72.4	.106	67.9	.064	140.3	.086	131.4	.073	1715.6
1965	80.5	.112	72.3	.064	152.5	.087	140.6	.070	1820.2
1966	89.7	.114	76.9	.064	166.6	.092	150.2	.068	1917.0
1967	99.6	.111	81.9	.064	181.5	.089	160.9	.071	1958.4
1968	110.6	.111	88.5	.080	199.1	.097	172.4	.071	2051.5
1969	123.0	.112	95.5	.080	218.5	.097	184.8	.072	2111.7
1970	136.9	.113	103.2	.080	240.1	.099	197.3	.068	2098.9
1971	152.0	.110	111.5	.080	263.5	.097	210.5	.067	2159.2
1972	168.4	.108	120.4	.080	288.8	.096	222.1	.055	2302.8
1973	186.9	.110	124.9	.038	311.8	.080	232.3	.046	2453.5
1974	205.9	.102	129.7	.038	335.6	.076	242.6	.044	2405.3
1975	223.9	.087	134.6	.038	358.5	.068	253.6	.046	2354.5
1976	241.0	.077	139.6	.038	380.6	.062	264.3	.042	2497.1
1977	258.9	.074	144.9	.038	403.8	.061	272.8	.032	2638.9
1978	278.5	.076	147.0	.014	425.5	.054	282.1	.034	2790.8

	R&D in Capital		R&D in Materials		Total Indirect R&D		Direct R&D Stock		Output
Year	Stock	Rate of Growth	Stock	Rate of Growth	Stock	Rate of Growth	Stock	Rate of Growth	Private Nonfarm Business
1979	299.8	.076	149.1	.014	448.9	.055	291.8	.034	2845.7
1980	321.2	.071	151.2	.014	472.4	.052	302.6	.037	2794.4
1981	343.0	.068	153.3	.014	496.3	.051	314.6	.040	2841.1
1982	365.0	.064	155.5	.014	520.5	.049	328.5	.044	2777.0
1983	387.5	.062	166.8	.073	554.3	.065	343.6	.046	2900.8
1984	412.5	.065	179.0	.073	591.5	.067	360.3	.048	3145.1
1985	439.2	.065	192.0	.073	631.2	.067	379.2	.053	3252.2
1986	467.7	.065	206.0	.073	673.7	.067	402.0	.060	3344.5
1987	496.8	.062	221.0	.073	717.8	.065	427.0	.062	3483.5
Average annual growth rates									
1947-87		.0975		.0640		.0822		.0668	.0338
1947-73		.1113		.0762		.0935		.0790	.0384
1973-87		.0723		.0416		.0614		.0444	.0254

Note: The research contained in materials is calculated for the years between input-output tables by interpolation.

The R&D stocks are reported in 1987 dollars, rather than in 1992 dollars, because, as discussed in footnote 3, it is only possible to calculate the indirect R&D stocks for years up until 1987.

9.75 percent annual rate over this period. R&D in capital was smaller than R&D contained in materials in the 1950's, but was much greater by the 1970's.

Each of the different facets of the R&D stock, including the R&D stock contained in capital, the total indirect R&D stock, and the direct R&D stock, grew rapidly in the postwar years, and then grew much more slowly in the 1970's and 1980's. Section III below analyzes the influences which have driven the increases in the R&D contained in equipment, and the indirect R&D stock, since 1947.

III. Decomposition of Increases in the R&D Contained in Capital.

It is clear that increases in the research contained in equipment drive the observed growth of the indirect R&D stock. Consequently, this section examines the channels through which increases in the R&D contained in equipment have operated. Between 1947 and 1987, output grew at a 3.38 percent rate, while the equipment stock increased at a 4.73 percent rate. Some portion of the rapid increase in the indirect R&D contained in capital therefore occurred because equipment grew more quickly than output. However, since the R&D contained in capital grew at an overall rate of 9.75 percent, the dominant influence in the growth of the indirect R&D stock must have been the increase in the R&D stock contained per unit of equipment.

We define the R&D content (as distinct from R&D intensity) of each type of equipment as the R&D stock contained in all vintages of an asset divided by the corresponding capital stock.[9] With this terminology in mind, the economywide change in the overall R&D content can be decomposed into three elements. The first term expresses the effect of increases in the R&D content of individual types of equipment, holding each asset's share of total equipment constant. The second term expresses the result of a shift towards types of equipment with a greater R&D content; this influence can be measured by allowing each asset's share to change, holding the R&D content of each type of equipment constant. The third term is an interaction term, which expresses the extent to which changes in the R&D content occur together with changes in each asset's share of the total equipment stock. These three effects can be expressed formally as:

$$\Delta\ RD_K/K = \Sigma_i\ (\Delta(RD_K/K)_i\ SK_i) + \Sigma_i\ (RD_K/K)_i\ \Delta\ SK_i) + \Sigma_i\ (\Delta(RD_K/K)_i\ \Delta SK_i)$$

in which RD_{Ki} is the research contained in each capital asset (type of equipment) i and K_i is the corresponding stock of capital equipment for asset i. Consequently, $(RD_K/K)_i$ is the

9 Section I above discussed research intensity, which is the ratio of the R&D stock to output in industries producing capital, and is a measure of the intensity of R&D in new vintages of investment. In contrast, R&D content refers to the R&D contained in all vintages of an asset divided by the capital stock. This concept depends on the pattern of investment and depreciation, as well as on research intensity in succeeding vintages of investment.

amount of indirect R&D contained per dollar of equipment stock for asset i, and RD_K/K is the corresponding ratio for the private nonfarm economy. SK_i is the share of each asset type, i, in the total stock of capital equipment. Σ_i indicates that a summation is conducted across each of the i types of equipment, and Δ indicates the change in a variable.

The above expression can be rewritten in percentage rate form by dividing each term by RD_K/K:

$$\frac{\Delta\, RD_K/K}{RD_K/K} = \frac{\Sigma_i\ (\Delta(RD_K/K)_i\ SK_i)}{RD_K/K} + \frac{\Sigma_i\ (RD_K/K)_i\ \Delta\, SK_i)}{RD_K/K} + \frac{\Sigma_i\ (\Delta(RD_K/K)_i\ \Delta SK_i)}{RD_K/K}$$

Table 2 shows the results when the decomposition described above is carried out for each year. The average annual effect of increases in the research content within each asset is 2.03 percent. The average annual effect of shifts between assets is 2.70 percent. Finally, the effect of the interaction term is -0.18 percent.

Neglecting the small annual interaction term, 43 percent of the increase in the R&D contained in capital can be attributed to increases in the research content of the individual assets, while the remaining 57 percent is due to compositional shifts towards

Table 2

Contribution of Changing Research Content of Individual Assets and of Changes in the Composition of Capital to Changes in the Overall Research Content.

(in percentage rate terms)

Year	Overall Increase in Research Content	Higher Research Content in Each Asset	Change in Asset Composition	Interaction
1948	.076	.031	.044	.002
1949	.069	.036	.032	.001
1950	.055	.024	.031	.000
1951	.036	.013	.023	.000
1952	.022	.003	.020	-.001
1953	.017	-.007	.026	-.002
1954	.026	.004	.022	-.001
1955	.038	.018	.020	-.000
1956	.044	.026	.019	.000
1957	.058	.038	.019	.000
1958	.078	.058	.019	.001
1959	.082	.062	.019	.001
1960	.083	.060	.022	.001
1961	.088	.063	.025	-.000
1962	.079	.056	.024	-.001
1963	.067	.050	.017	-.001
1964	.060	.049	.011	-.000
1965	.051	.044	.008	-.001
1966	.040	.031	.009	-.001
1967	.040	.029	.011	-.000
1968	.045	.035	.011	-.001
1969	.044	.033	.011	-.001
1970	.051	.037	.013	.000
1971	.058	.043	.015	.001
1972	.056	.039	.017	.000
1973	.045	.020	.026	-.000
1974	.033	.005	.030	-.002
1975	.036	.009	.029	-.002

Year	Overall Increase in Research Content	Higher Research Content in Each Asset	Change in Asset Composition	Interaction
1976	.040	.011	.031	-.002
1977	.032	.006	.027	-.002
1978	.022	-.004	.028	-.002
1979	.018	-.016	.037	-.003
1980	.020	-.022	.047	-.006
1981	.027	-.018	.052	-.007
1982	.034	-.005	.044	-.005
1983	.040	-.001	.047	-.006
1984	.034	-.011	.055	-.010
1985	.024	-.019	.054	-.011
1986	.025	-.013	.046	-.008
1987	.028	-.003	.037	-.005
Arithmetic averages 1947-87	.046	.020	.027	-.002
1947-73	.054	.034	.020	-.000
1973-87	.030	-.006	.040	-.005
1973-79	.030	.002	.030	-.002
1979-87	.029	-.012	.048	-.007

forms of equipment with a greater research content.[10]

Pulling together all this information on why R&D contained in equipment grew so rapidly, we find that between 1947 and 1987 the equipment stock grew 1.35 percentage points more rapidly than the growth of output. Increases in the R&D contained within individual assets caused R&D in capital to grow 2.03 percent more rapidly, and shifts towards more research intensive forms of equipment contributed a further 2.70 percentage points. Neglecting the effect of interaction terms, R&D in capital grew 6.08 percentage points more rapidly than output. Reflecting these contributions, the greater growth of equipment than output therefore contributed approximately 22 percent of the overall growth in R&D in equipment, the increase in R&D within individual assets contributed a further 33 percent, and the shift towards more research intensive assets contributed 44 percent.

The data in this paper end in 1987 because the National Science Foundation published data on R&D expenditures for many fewer capital goods industries after 1983. However, the results established here do show that shifts towards more research

10 Beginning in 1978, the change in the research content in each asset term in Table 2 begins to make a negative contribution. This is entirely due to computers, since the R&D stock in this industry did not keep up with the massive increase in output. If the ratio of the R&D stock to capital had remained constant at its 1977 value in computers, the greater research content included within each asset would have contributed an average of .014 percent a year to the economywide increase in research content over the 1978-1987 period, instead of the -.011 average effect reported for these years in Table 2.

intensive assets have occurred continuously over the postwar period. In the 1990's many observers have commented on the more rapid growth of technology intensive forms of equipment, such as computers and information technology. Table 2 shows that equipment shifted towards more technology intensive assets throughout the postwar period.

IV. Rates of Return to Indirect R&D.

This section examines evidence on the rate of return to indirect R&D. Such information is necessary to determine how much effect indirect R&D stocks, such as those shown in Table 1, have on productivity growth.[11] Evidence on the rate of return to indirect R&D is obtained from two different types of sources. Each of these is considered in turn.

IVA. Rates of Return to Indirect R&D from Econometric Studies.

Nadiri (1993) recently carried out a comprehensive review of fifty-five econometric studies on the return to R&D.[12] Fifteen

[11] It would be possible to sidestep the issue of the rate of return to indirect R&D and determine the productivity implications of indirect R&D directly from growth rates, such as those reported in Table 1, if one were willing to adopt a Cobb-Douglas formulation in which the indirect R&D share of output is constant over time (Griliches (1992)). However, Table 1 shows that the ratio of the indirect R&D stock to output varies greatly, from .033 in 1947 to .206 in 1987. Under these circumstances, it is not reasonable to assume that the indirect R&D share of output is constant over time.

[12] Griliches (1992) also reviewed the evidence on the social returns to research, and reached broadly similar conclusions. We rely on Nadiri's work here because the studies reviewed by Griliches are largely a subset of the analyses examined by Nadiri.

of these studies (summarized in Table 2b of Nadiri's paper) examine the social or indirect return to R&D at the industry level, which is the concept closest to that considered in this paper. We use the mean of the range which Nadiri reports for each of these studies. For four studies, the average social (direct plus indirect) return to R&D is 87 percent. For eleven studies, the average indirect rate of return, is 63 percent. These values suggest that the rate of return to indirect R&D is very high.

Within the data for fifty-one industries prepared for this study, the rate of return to indirect R&D, obtained through the Terleckyj procedures, is 30 percent. However, this estimate depends heavily on the presence of the observations from the telephone and telegraph industry, and is not robust.[13]

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[13] These estimates of the rate of return to indirect R&D are obtained from regressions of the form:

$$\dot{A}/A = a + b\,\Delta RD/Y_{t-1} + c\,\Delta RD_I/Y_{t-1}$$

where RD is the direct R&D stock, RD_I is the indirect R&D stock, and Y is output. c is the rate of return to indirect R&D. The observations represent industry data between input-output years. For example, the coal industry between 1963-67, 1967-72, 1972-77, 1977-82, and 1982-87 represents five of the observations. Within data for all fifty-one industries, the estimate of c is .30, and is significantly greater than zero at the 95 percent level, with a t ratio of 2.16. However, as mentioned in the text, this estimate is not robust.

Measurements of the return to downstream R&D like these are consistently hampered by the difficulty of measuring prices accurately in downstream industries, especially those industries classified as services. In particular, unobserved quality change in the output prices of downstream industries can be expected to be associated with their technology inputs, as measured by their purchases of indirect R&D. Further work is under way to determine whether, or to what extent, stocks of indirect R&D can help in understanding unmeasured quality change in industries such as banking, securities markets, trade, and medicine. While

A further relevant strand of evidence comes from Sveikauskas (a, forthcoming) which reports that, when data on output and inputs are adjusted to allow for Gordon's evidence of unmeasured quality change in the capital goods sector, there is a very substantial (75 percentage points or greater) increase in the implied rate of return to R&D. If the role of R&D in measurement error upstream is this high, much of the return to R&D which is missed upstream can, if the official deflators are used, be expected to appear as a return to downstream R&D. However, because Nadiri's review covers evidence from many different studies, we believe that his conclusions are preferable to the result obtained from any single study.

IVB. Rates of Return from the Innovation Studies.

The three studies conducted by Mansfield et al. (1977), Nathan Associates (1978), and Tewksbury, Crandall and Crane (1980) cover fifty-seven innovations in all. The innovations cover improvements in both capital and materials. The main limitation of these studies is that the innovations are not randomly selected, so it is uncertain whether they are representative of all R&D.

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adjustments in such areas might well increase the implied measures of output and productivity growth, they would not be useful in explaining the residual as currently defined, which is the goal of the present paper.

In Mansfield et al., the median private return is 25 percent, whereas the median social return is 56 percent, which implies an externality of approximately 31 percent. In Tewksbury, Crandall, and Crane (1980), the median private return is 27 percent and the median social return is 99 percent, which implies externalities of 72 percent. Nathan Associates (1978) found a median private return of 36 percent and a median social return of 70 percent, suggesting externalities of 34 percent. For all fifty-seven innovations, the median private rate of return is 28 percent and the median social rate is 71 percent, implying externalities of 43 percent. The three studies frequently mention that they attempt to err on the conservative side, so true returns may well be higher.

The median rates of return reported in these studies provide evidence on the typical return to an industrial project. However, observed data on productivity and output will be disproportionately affected by the relatively few projects with atypically high returns, which are not fully reflected within the median data.[14] For example, the social rate of return exceeds the private rate of return by 345 percent and 280 percent in the two innovations with the largest spillovers. More generally, the social return exceeds the private return by more than 100 percent in thirteen of the fifty-seven innovations. From this perspective, the mean difference between the social and private

[14] Scherer (1999, Chapter 5) shows how the returns to technological innovation depend heavily on the very high returns obtained from a relatively small number of innovations.

rates of return, which more sharply reflects the large social returns associated with the most influential innovations, should provide a preferable measure of spillovers.[15] The mean excess of social returns is 45 percent, 65 percent, and 49 percent, respectively, in the three studies. Overall, the mean excess of the social return among the fifty seven innovations is 53 percent.

These results suggest that, for productivity purposes, the social returns to R&D exceed the private returns by 53 percent. The next question is to what extent these externalities are obtained by industries outside the specific industry which initially conducts the research. It is clear from the innovation studies that many of the benefits are realized outside the original industry, but the precise extent of interindustry spillovers is uncertain.

A recent summary of evidence on the direct return to research, (U.S. Department of Labor (1989)) suggested that the social return to R&D within a given industry exceeded the private

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[15] The three innovation studies do not report private or social rates of return when these are negative. Following Nathan Associates (1978), we assume that any negative returns are zero when the difference between private and social returns is calculated for each innovation. Private rates of return are negative for seven of the innovations, and the social return is negative in five cases. (The authors of the innovation studies all realize that unsuccessful projects have to be included to make the sample representative; however, it is unclear whether the choice of specific projects for inclusion in the studies fully corrects for these possibilities.)

return to R&D by approximately 30 percent.[16] If this estimate is correct, the 53 percent social return from the innovation studies suggests that approximately a 23 percent indirect return to R&D is obtained by downstream industries.

IVC. <u>Overview of Evidence on the Rate of Return to Indirect R&D</u>.

The studies reviewed in Nadiri (1993) and the evidence provided in Sveikauskas (a, forthcoming) on measurement error upstream suggest that the rate of return to indirect R&D may be extremely high, perhaps even in the range of 60 percent or greater. On the other hand, the innovation studies, as interpreted in Section IVB, suggest a much lower rate of return to indirect R&D, in the range of 23 percent. However, the innovation studies consistently attempt to provide conservatively low estimates of the rate of return.

The innovation studies were very influential in the 1980's in reaching a consensus on the effects of direct R&D. Regression studies are subject to many potential biases of specification and estimation. Many analysts believed that the results from the innovation studies were highly valuable in generating a firmer basis for estimates of the return to direct R&D.

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[16] When multifactor productivity growth is calculated for United States industries, the capital, labor, and other inputs used in R&D are included in industry inputs and subtracted from output growth. Therefore, the private marginal products of research inputs have already been removed from the MFP measures. Consequently, industry regressions which explain MFP by R&D provide estimates of a social return to R&D, which extends beyond the private return to firms.

For similar reasons, we give considerable weight to the innovation studies in selecting an estimate of the indirect return to R&D. We choose 25 percent as our preferred estimate of the indirect return to R&D, quite close to the 23 percent estimate drawn from the discussion of the innovation studies. In addition, the 25 percent rate of return selected here is internally consistent in the sense that it is quite similar to the 30 percent return to indirect R&D found (as mentioned on page 23) when the indirect rate of return is estimated from the same industry stocks of indirect R&D later used to construct the national stocks of indirect R&D reported in the present study.

On the other hand, there is considerable evidence in Nadiri (1993) and Sveikauskas (a, forthcoming) that the rate of return to indirect R&D is plausibly considerably higher. Returns of 50 or 60 percent are possible, though unlikely in view of the evidence from the innovation studies. Consequently, we select 50 percent as an alternative, high end, rate of return to indirect R&D for the analyses conducted in Section V below.

V. The Contribution of Indirect R&D to Productivity Growth.

This section examines the implications for the contribution of indirect R&D to long-term productivity growth. Table 3 shows how the indirect stocks of R&D in capital and materials listed in Table 1 affect productivity growth if the rate of return is 25

Table 3

Stocks of R&D in Capital and in Materials, and Their Contribution to Productivity Growth, Private Nonfarm Business Sector, 1947-1987.

All stocks in billions of 1987 dollars

	R&D in Capital		R&D in Materials	
Year	Stock	Contribution to Productivity	Stock	Contribution to Productivity
1947	12.0		18.5	
1948	14.4	.06	20.1	.04
1949	16.6	.06	21.9	.05
1950	18.6	.05	23.8	.05
1951	20.5	.04	25.9	.05
1952	22.2	.04	28.2	.05
1953	23.8	.03	30.7	.05
1954	25.6	.04	33.3	.05
1955	27.8	.04	36.3	.06
1956	30.6	.05	39.5	.06
1957	34.1	.07	42.9	.06
1958	38.1	.08	46.7	.07
1959	42.3	.08	49.7	.06
1960	47.4	.09	52.9	.06
1961	53.2	.10	56.3	.06
1962	59.2	.10	59.9	.06
1963	65.4	.10	63.8	.06
1964	72.4	.11	67.9	.06
1965	80.5	.12	72.3	.06
1966	89.7	.12	76.9	.06
1967	99.6	.13	81.9	.07
1968	110.6	.14	88.5	.08
1969	123.0	.15	95.5	.08
1970	136.9	.17	103.2	.09
1971	152.0	.18	111.5	.10
1972	168.4	.18	120.4	.10
1973	186.9	.20	124.9	.05
1974	205.9	.20	129.7	.05
1975	223.9	.19	134.6	.05
1976	241.0	.18	139.6	.05
1977	258.9	.17	144.9	.05
1978	278.5	.18	147.0	.02

Year	R&D in Capital Stock	R&D in Capital Contribution to Productivity	R&D in Materials Stock	R&D in Materials Contribution to Productivity
1979	299.8	.19	149.1	.02
1980	321.2	.19	151.2	.02
1981	343.0	.19	153.3	.02
1982	365.0	.20	155.5	.02
1983	387.5	.20	166.8	.10
1984	412.5	.21	179.0	.10
1985	439.2	.21	192.0	.10
1986	467.7	.22	206.0	.11
1987	496.8	.21	221.0	.11
1947-1987 average annual growth rate		From capital .13		From materials .06

The annual contribution for capital is calculated from $XK_t = SRK(\log RDK_t - \log RDK_{t-1})$, where RDK is the total research stock contained in equipment and SRK is the average implicit income accruing to the research contained in equipment as a share of private nonfarm output over the years t and t-1; the contribution is $\exp(XK_t) - 1.0$. Similarly, the annual contribution of materials is calculated from $XM_t = SRM(\log RDM_t - \log RDM_{t-1})$, where RDM is the total research contained in materials and SRM is the implicit share of R&D contained in materials.

The share of indirect research is obtained by multiplying the indirect research stock by the rate of return (25 percent) and dividing by private nonfarm output. For most years, the share attributed to R&D contained in equipment is larger than the share estimated for R&D in materials.

R&D stocks are measured in 1987 dollars, rather than in 1992 dollars, because the series extend only until 1987.

percent. These calculations assume that the same rate of return applies to R&D in both capital and materials, and that the rate of return is constant over time; it would be very useful to be able to assess the realism of these assumptions, but, at present, no such information is available.[17]

Table 3 implies that, if the rate of return to indirect R&D is 25 percent, the long-term average annual contribution of indirect R&D to productivity growth was 0.19 percent per year over the 1947-1987 period. The central point is that the indirect R&D stock has increased rapidly, so that, even if the rate of return is relatively modest, indirect R&D makes a substantial contribution to productivity growth.

Estimates of the rate of return to indirect R&D are subject to a wide range of uncertainty. Table 4 shows the productivity contribution of indirect R&D under many other potential rates of return. If the return to indirect R&D is, for example, 30 or 40 percent, the implied productivity contribution is in the range of 0.23 to 0.31 percent a year. With a 50 percent rate of return to indirect R&D, which was selected as a high end estimate in Section IVC, the annual contribution to productivity growth would be 0.39 percent a year. Conversely, if the return to indirect

[17] Sveikauskas (1990) has shown that the return to direct R&D did not decline sharply after 1973. It is more difficult to determine trends in the rate of return to indirect R&D, both because of the lack of annual productivity data covering a large number of industries outside manufacturing (where most indirect R&D is used) and because the output data are questionable in many of these industries. Further work is underway on such topics.

Table 4

1947-1987 Productivity Contribution of Indirect R&D,
Under Different Assumed Values of the Indirect Return to R&D

Assumed Rate of Return to Indirect R&D	Productivity Contribution of Indirect R&D
0	0.00
10	0.08
20	0.16
25	0.19
30	0.23
40	0.31
50	0.39
60	0.46
80	0.62
100	0.78

R&D is as low as 10 percent, the annual contribution is only 0.08 percent a year.

More than two-thirds of the indirect R&D effect shown in Table 4 occurs through the R&D included in capital. For example, in the base case with a return of 25 percent, .13 of the .19 indirect R&D effect is associated with capital.[18]

To place the information given above in the context of other important sources of economic growth, it is useful to compare the results obtained above for indirect R&D with corresponding evidence from the Bureau of Labor Statistics multifactor productivity growth measurement program. Table 5 places the 0.19 percent annual effect found in the base case for indirect R&D together with 1947-1987 estimates of the average annual productivity growth contributed by several other important influences.

These estimates show that, of the influences considered, indirect R&D is the second most important contributor to

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[18] The central role of capital here of course reflects the fact that capital accounts for more than 70 percent of the growth in the indirect R&D stock, as mentioned in Section II.

Recent theoretical work, such as Romer (1990) and Grossman and Helpman (1991), has emphasized that intermediate goods are an important element in economic growth. Capital and materials can both be considered to be intermediate goods. The evidence developed in this paper therefore provides some empirical support, within data for the aggregate economy, for the Romer and Grossman-Helpman contention that research conducted on upstream intermediate goods is an important influence on productivity growth.

Table 5

Influences on Labor Productivity and Multifactor Productivity Growth, Private Nonfarm Business Sector, 1948-1987.

(In percentage points)

	1948-1987 Average Annual Contribution
Labor Productivity Growth	2.24
Less: Capital Deepening	0.84
Education and Experience of the Labor Force	0.17
Equals: Multifactor Productivity Growth	1.23
of which	
Direct R&D Contribution	0.15
Indirect R&D Contribution	0.19

Sources: Bureau of Labor Statistics Multifactor Productivity Listings; U.S. Department of Labor (1989); Table 3 above.

productivity growth. Indirect R&D contributes more to productivity growth than the well established effects of human capital (the education and experience of the labor force) or of direct R&D.

Over the 1947-1987 period, the direct and indirect effects of R&D together account for about 30 percent of total multifactor productivity growth. This proportion would be somewhat higher if data after 1987 could have been included, both because the contribution of research would be greater then, and because observed long-term multifactor productivity growth would then be lower.[19]

Nevertheless, Griliches (1992, page S44) has suggested that R&D might account for about three-quarters of measured MFP growth, and Nadiri (1993, page 36) has suggested that perhaps more than half of MFP growth can be explained by R&D spillover effects. Within the 1947-1987 period considered in this paper, half to three-quarters of MFP growth would imply that overall R&D accounted for about 0.60 to 0.90 percent of the observed 1.23 percent annual growth. Therefore, Griliches' conjecture that total R&D accounts for three-quarters of the residual (0.90),

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[19] Multifactor productivity growth was 1.1 percent in the private nonfarm business sector in 1948-96, so a very large increase in the contribution of R&D would be
r $, < @ D L T 1 $, " * sum. Since relatively few further years are added when the 1948-1987 data are expanded to cover 1948-96, a large change in the average annual contribution of R&D is unlikely. For example, the direct R&D effect, which can be measured after 1987, increased only from .15 in 1948-87 to .16 in 1948-96.

with a 0.15 direct effect, implies the indirect effect is 0.75 percent per year. Similarly, Nadiri's half of MFP implies that spillovers contribute 0.60 percent to annual growth.[20] Given the growth in the stocks of indirect R&D documented in this paper, indirect R&D effects of 0.60 to 0.75 would require a rate of return to the indirect R&D stock of approximately 75 to 100 percent. Although such high returns cannot be completely excluded, it seems far more probable that the impact of indirect R&D, and the implied total R&D effect, represent a considerably smaller proportion of MFP growth than prior estimates have suggested.

Even if the indirect effects of R&D do not represent half or more of MFP growth, indirect R&D still represents an important source of economic growth. As Table 5 shows, the indirect effects of R&D, even using rather conservative assumptions, are as important to growth as the Bureau of Labor Statistics version of human capital (education and experience), which is a well-established important ingredient in growth.[21]

VI. Conclusions.

[20] The Griliches and Nadiri conclusions were each based on a comprehensive review of the literature on the indirect rate of return to R&D. Nadiri found indirect returns to be much smaller within firm data than in industry data. In addition, Nadiri considered information on the international diffusion of technology.

[21] For completeness, it is worth mentioning that human capital had a considerably greater influence on productivity growth during the 1987-1995 period (U.S. Bureau of Labor Statistics (1998)), which extends beyond the 1947-1987 period that can be considered here.

Economists have been reluctant to count indirect R&D as a contributor to growth because a large portion of this influence may reflect measurement error. However, Sveikauskas (a, forthcoming) shows that measurement error is strongest when the nature of production is changing most rapidly, that is when changes in R&D are the greatest. Consequently, indirect R&D reflects genuine improvements in productivity which growth accounting currently does not take into consideration. R&D makes a further contribution to growth, which extends beyond the matters considered by previous estimates.

This paper reports the first existing information on the size and rate of growth of the stock of indirect R&D. The results indicate that, over the 1947-1987 period, approximately 70 percent of indirect R&D operated through capital equipment and 30 percent through materials. Of the capital component, 22 percent occurred because equipment grew more rapidly than output, 33 percent because the R&D content of specific types of equipment increased, and 44 percent because of a shift towards more research intensive types of equipment. Many observers have emphasized the growth of high technology components of the stock of equipment during the 1990's. The evidence presented in this paper shows that the equipment stock has been shifting towards more technology intensive assets steadily throughout the postwar period.[22]

The preferred estimate, based on a 25 percent rate of return, suggests that indirect R&D contributed .19 percent a year to productivity growth between 1947 and 1987. This is a substantial amount, which exceeds the estimated effects of direct R&D or of human capital (the education and experience of the labor force) over the corresponding period.

The empirical results imply that the overall effect of R&D, which includes both the direct and indirect influences, accounted for almost 30 percent of 1947-1987 multifactor productivity growth. Although sizable, the total effect of R&D is not sufficient to explain half or more of the total improvement in MFP, as Griliches (1992) and Nadiri (1993) have suggested may be the case. The construction and analysis of the indirect R&D stocks presented here makes it possible to conclude that, although the indirect effects of R&D are substantial, they are, on balance, somewhat smaller than prior work has suggested.

In summary, despite the uncertainties which still remain, most of which reflect the difficulty of determining a precise indication of the rate of return to indirect R&D, growth

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22 It would interesting to extend the present analysis into the 1990's. However, the National Science Foundation applied product field data, which are the basis for the present work, extend only into the early 1980's.

accounting can now be expanded, as in Table 5, beyond its present emphasis on capital, human capital, and R&D to include indirect R&D as an important further influence on growth.

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