ECONOMIC RESEARCH REPORTS

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by **Edward N. Wolff**

RR# 96-37 **October 1996**

C.V. STARR CENTER FOR APPLIED ECONOMICS

NEW YORK UNIVERSITY
FACULTY OF ARTS AND SCIENCE
DEPARTMENT OF ECONOMICS
WASHINGTON SQUARE
NEW YORK, NY 10003-6687

Spillovers, Linkages, and Technical Change

Edward N. Wolff*

September 1996

Abstract. Using U.S. input-output data for the period 1958 to 1987, I find strong evidence that industry TFP growth is significantly related to the TFP performance of supplying sectors, with an elasticity of almost 60 percent. R&D intensity is also found to be a significant determinant of industry TFP growth, with an estimated return of about 10-13 percent, and the return to embodied R&D is estimated at 43 percent. Direct productivity spillovers, from the technological progress made by supplying sectors, appears more important than spillovers from the R&D performed by suppliers. They also play a key role in explaining changes in manufacturing TFP growth over time. Changes in the contribution made by direct productivity spillovers to TFP growth account for almost half of the slowdown in TFP growth in manufacturing between 1958-67 and 1967-77 and 20 percent of the TFP growth recovery in this sector between 1967-77 and 1977-87. Changes in R&D intensity and embodied R&D are relatively unimportant in explaining movements in manufacturing TFP growth over these three periods.

JEL Codes: 030, 032, 047, 051, C67

Keywords: Input-output, Productivity, R&D, Spillovers, Linkages

* Department of Economics, 269 Mercer Street, New York University, New York, NY 10003 USA [tel. 212-998-8917; fax. 212-995-4196; E-Mail. WOLFFE@FASECON.ECON.NYU.EDU]. I would like to thank Pierre Mohnen and an anonymous referee for their valuable suggestions. I would also like to express my gratitude to the Alfred P. Sloan Foundation and the C.V. Starr Center for Applied Economics for their financial support.

1. **Introduction**

In previous work (Wolff and Nadiri, 1993), we used U.S. input-output data for the period 1947-77 to analyze the relations among R&D, technical change, and intersectoral linkages. Our most novel finding was that among manufacturing industries, an industry's rate of technological progress is positively and significantly related to that of its supplying sectors. As in most previous studies, we also found a statistically significant relation between the R&D intensity of a sector and its rate of productivity growth. The results also showed the presence of spillover effects of R&D embodied in intermediate inputs within manufacturing. The results were statistically significant for private R&D embodied in intermediate inputs, but not for total embodied R&D.

This paper follows up our previous work on the subject. The data analysis is now extended to 1987 (though it begins in 1958 instead of 1947), and the number of manufacturing industries is expanded from 19 to 48. This study will also focus particular attention on the resurgence of productivity growth in manufacturing during the 1980s. This is documented in Table 1, where the periodization is chosen to conform to the years for which input-output tables are available. In manufacturing, total factor productivity (TFP) growth, defined as the price-weighted sum of changes in input-output coefficients, fell from 1.1 percent per year in the 1958-67 period to 0.10 percent in 1967-77 but then strongly rebounded to 0.80 percent per year in the 1977-87 period. Utilities was the only other major sector which showed a similar pattern in TFP growth over the three periods.

Was the recovery of productivity growth in manufacturing a consequence of greater spillovers among sectors? Were there changes in linkage structure which contributed to greater spillovers? Were there greater spillovers between manufacturing and non-manufacturing sectors? These are some of the issues to be investigated in this paper. I also look further at the spillovers of R&D and technical change that occur among industries in the economy.

The remainder of the paper is organized into five parts. The next section (Section 2) provides a brief review of some of the pertinent literature on interindustry spillover effects. Section 3 develops the basic accounting framework. Section 4 provides the regression results on the spillover effects of R&D and sectoral technical change. Section 5 analyzes the factors responsible for the recovery of TFP growth in manufacturing in the 1977-87 period. Concluding remarks are presented in the last section.

2. Review of Previous Literature

R&D spillovers refer to the direct knowledge gains of customers from the R&D of the supplying industry (see Griliches, 1979).[1] There have been several approaches to measuring R&D spillovers. Brown and Conrad (1967) base their measure of borrowed R&D on input-output trade flows (both purchases and sales) between industries. Terleckyj (1974, 1980) provides measures of the amount of R&D embodied in customer inputs on the basis of interindustry material and capital purchases made by one industry from supplying industries. Scherer (1982), relying on Federal Trade Commission line of business data, uses product (in contradistinction to process) R&D, aimed at improving output quality, as a measure of R&D spillovers.

Another approach is to measure the "technological closeness" between industries. For example, if two industries use similar processes (even though their products are very different or they are not directly connected by interindustry flows), one industry may benefit from new discoveries by the other industry. Such an approach is found in Jaffe (1986) who uses patent data to measure technological closeness between industries.

Bernstein and Nadiri (1989) use as a measure of intra-industry R&D spillovers total R&D at the two-digit SIC level and apply this measure to individual firm data within the industry. Mairesse and Mohnen (1990) report similar results by comparing R&D coefficients based on firm R&D with those based on industry R&D. If there are intra-industry externality effects of firm R&D, then the coefficients of industry R&D should be higher than those of firm R&D. However, their results do not show that this is consistently the case.

There have been a host of studies which have followed one of these approaches in estimating the spillover effects of R&D (see Mohnen (1990, 1992), Nadiri (1991), and Griliches (1992) for reviews of the literature). In contrast, the literature on direct productivity spillovers is sparser. Some of the earlier literature on the subject is quite suggestive. For the German economy, Oppenlander and Schulz (1981) calculate that only about a third of new products are derived from new technology (i.e., process innovation). The remainder are "market innovations", which are used to open up new markets for the products. Pavitt (1984) estimates that out of 2,000 innovations introduced in the United Kingdom, only about 40 percent were developed in the sector using the innovation. The remaining innovations were borrowed from new technologies developed in other sectors.

The work of Nelson and Winters (1982) illustrates another approach. In their evolutionary model, spillovers in technology among firms may occur as firms search or sample from their environment to develop new production techniques. Moreover, Rosenberg (1982) and Rosenberg and Frischtak (1984) suggest the existence of clusters of innovations in industries that occupy a strategic position in the economy in terms of both forward and backward linkages. They speculate that there are certain intraindustry flows of new equipment and materials that have generated a vastly disproportionate level of technological change and productivity growth in the economy.

A paper by Bartelsman, Cabbalero, and Lyons (1991) is also highly suggestive. Using regression analysis, they relate the growth in an industry's output to a weighted average of the growth in the total outputs of supplying industries, where the weights are proportional to the industry's inputs coefficients. They conclude that the linkage between an industry and its suppliers appears the dominant factor in accounting for long-term growth-oriented externalities. However, they do not directly relate an industry's own productivity growth to either the R&D of its suppliers or to its suppliers' rate of productivity growth.

Wolff and Nadiri (1993) provide one of the first direct investigations of productivity spillovers. They use as their measure of embodied technical change a weighted average of the TFP growth of supplying industries, where the weights are given by the technical input-output coefficients of an industry. This formulation assumes that the knowledge gained from a supplying industry is in direct proportion to the importance of that industry in a sector's input structure. I intend to follow this approach here.

3. Accounting Framework and Model

My model is based on an input-output accounting framework. Let

X_t = (column) vector of gross output by sector at time t.

Y_t = (column) vector of final demand by sector at time t.

A_t = square matrix of inter-industry technical coefficients, a_{ij}, at time t.

L_t = (row) vector of labor coefficients at time t, ℓ_{it}, showing employment per unit of output.

K_t = square matrix of capital stock coefficients, k_{ij}, at time t, showing the capital of each type required per unit of output.

P_t = (row) vector of prices at time t, showing the price per unit of output of each industry.

Unless otherwise indicated, all variables are in real terms. In addition, let us define the following scalars:

w_t = the annual wage rate.

i_t = the rate of profit on the capital stock at time t.

Following Leontief (1953), I define the rate of TFP growth for sector j in period T, $TFPGRT_{jT}$ or π_{jT}, by

$$(1) \qquad TFPGRT_{jT} \equiv \pi_{jT} = -(\Sigma_i\ \bar{p}_{iT}\ \Delta a_{ijT} + \bar{w}_T\ \Delta \ell_{jT} + \bar{i}_T\ \Delta k_{jT})\ /\ p_{jt0}$$

where Δ refers to the change over period T, $\bar{p}_{iT}$ is the average price over period T, $\bar{w}_T$ is the average wage over period T, $\bar{i}_T$ is the average rate of profit over period T, and p_{jt0} is sector j's price at the beginning of the period (t0).

R&D intensity is introduced into the model as follows. Let

$$(2) \qquad RDGDP_{jt} \equiv r_{jt} = RD_{jt}\ /\ GDP_{jt},$$

which shows the amount of R&D expenditure (RD) in constant dollars per constant dollar of GDP in sector j.

Forward spillovers from R&D are estimated on the basis of trade flows between sectors. I use two different formulations of R&D spillovers. The first assumes that the amount of information gained from supplier i's R&D is proportional to its importance in sector j's input structure (that is, the magnitude of a_{ij}) and to sector i's R&D intensity:

(3) $\mathrm{RDIND}_{jt} \equiv \Sigma_i \, a^o_{ijt} \cdot \mathrm{RD}_{it} / \mathrm{GDP}_{jt}$

where A^o is identical to the A matrix except that the diagonal is set to zero to prevent double-counting of R&D expenditures. For period T, the average values of a^0_{ij} and r_j over the period are used.

The second approach assumes that the amount of R&D that spills over from sector i to sector j is proportional to the amount of output sector i sells to j. This approach is used by Terleckyj (1974, 1980). Define the sales coefficient, b_{ijt}, as:

(4) $b^0_{ijt} \equiv a^0_{ijt} x_{jt} / x_{it}$

which shows the percentage of sector i's output that is sold to sector j. Then, the alternative measure of indirect R&D (RDINDA) is given by:[2]

(5) $\mathrm{RDINDA}_{jt} = (\Sigma_i \, b^0_{ijt} \, \mathrm{RD}_{it}) / \mathrm{GDP}_{jt}$

A similar approach is used by Scherer (1982), except that his measure of indirect R&D is distributed proportionately to the number of patents issued by sector i which falls in sector j's industrial classification.[3]

It is also possible to construct estimates of direct productivity spillovers in analogous fashion to R&D spillovers. This is given by:

(6) $\mathrm{TFPIND}_{jt} \equiv \Sigma_i \, a^o_{ijt} \cdot \pi_{it}$,

which is a measure of sector j's indirect knowledge gain from technological change in its supplying sectors. In this case, it is assumed that the information gained from supplier i's TFP is proportional to its importance in sector j's input structure. An alternative measure is given by:

$$(6) \quad TFPINDA_{jt} = \Sigma_i \, b^0_{ijt} \cdot \pi_{it}$$

where it is assumed that the knowledge gain in sector j from sector i's TFP growth is proportional to the percentage of i's output sold to sector j.

4. Data Sources and Regression Results

The basic data are 85-sector U.S. input-output tables for years 1958, 1967, 1977, and 1987.[4] Labor coefficients for 1958 were obtained from Peter Petri of the Brandeis Economic Research Center; those for 1967 were calculated from U.S. Bureau of Labor Statistics (1979); and those for 1977 were directly available in Yuskavage (1985). Sectoral employment for 1987 were estimated by first calculating the growth rates of employment by input-output industry on the basis of the Bureau of Labor Statistics' Historical Output and Employment Data Series (obtained on computer diskette) and then applying these growth rates to the 1977 input-output sectoral employment totals to update to 1987.[5]

Capital stock by input-output industry for 1967 and 1977 was calculated directly from the net stocks of plant and equipment by input-output industry provided on computer tape by the U.S. Bureau of Industry Economics (the BIE Capital Stocks Data Base as of January 31, 1983). These series ran through 1981 for manufacturing industries and through 1980 for the other sectors. They were updated to 1987 on the basis of the growth rate of constant dollar net stock of fixed capital between 1980 (or 1981) and 1987 calculated from the National Income and Product Accounts (NIPA).[6]

Sectoral price indices for years 1958 and 1967 were provided by the Brandeis Economic Research Center and those for 1977 from the Bureau of Economic Analysis worksheets. Deflators for 1987 were calculated from the Bureau of Labor Statistics' Historical Output Data Series (obtained on computer diskette) on the basis of the current and constant dollar series.[7]

Five sectors -- research and development, business travel and office supplies, scrap and used goods, and inventory valuation adjustment -- appeared in some years but not in others (the earlier years for the first three sectors and the later years for the last two sectors). In order to make the accounting framework consistent over the four years of analysis, I eliminated these sectors from both gross and final output. This was accomplished by distributing the inputs used by these sectors proportional to either the endogenous sectors which purchased the output of these five sectors or to final output.[8]

Data on the ratio of R&D expenditures to GDP were obtained from the National Science Foundation, Research and Development in Industry, various years, for 32 manufacturing industries covering the period 1958 to 1987. I was able to allocate these figures to 48 manufacturing industries in the input-output data.[9] All told, productivity growth estimates could be made for 68 input-output industries.[10]

Regression Results. I use two specifications to estimate the direct return to R&D, as well as the spillover effects of R&D and technological change:

$$(7a) \quad TFPGRT_{jT} = b_0 + b_1\, RDGDP_{jT} + b_2\, RDIND_{jT} + \Sigma_k\, c_k\, D_{kT} + \epsilon_{jT}$$

$$(7b) \quad TFPGRT_{jT} = b_0 + b_1\, RDGDP_{jT} + b_2\, TFPIND_{jT} + \Sigma_k\, c_k\, D_{kT} + \epsilon_{jT}$$

where b_0, b_1, b_2, b_3, and c_k are coefficients and ϵ_{jT} is a stochastic error term. In both cases, the sample is a pooled cross-section time-series data set consisting of 68 industries and 3 time periods (1958-67, 1967-77, and 1977-87). From Mansfield (1980) and Griliches (1980), the coefficient b_1 is interpreted as the rate of return of R&D, under the assumption that the (average) rate of return to R&D is equalized across sectors. Time dummies D_{kT}

(for the periods 1967-77 and 1977-87) are introduced to allow for period-specific effects on productivity growth not attributable to R&D. We assume that the ϵ_{jt} are independently distributed but may not be identically distributed. The regression results reported in Tables 3 and 4 below use the White procedure for a heteroscedasticity-consistent covariance matrix.[11]

Though, because of data limitations, a contemporaneous input-output framework is used to analyze the relations among R&D, technical change, and intersectoral linkages, it should be stressed that these three relations are necessarily dynamic and may occur with considerable lags. Moreover, the use of synchronic time periods -- in this case, 1958-67, 1967-77, and 1977-87 -- allows us to capture long-term effects of R&D on productivity.

Regression results on R&D and technology spillovers are shown in Table 3. R&D intensity is significantly related to sectoral TFP growth at the one percent significance level in three out of the five specifications and at the five percent level in the other two. The estimated direct return to R&D ranges from 10.1 to 12.6 percent. These estimates are a bit on the low side compared to previous work on the subject (see Nadiri, 1991, or Mohnen, 1992, for example, for a review of previous estimates). There are two possible reasons. First, my TFP growth figures are based on gross output and three inputs -- intermediate inputs, labor and capital -- instead of value added and two inputs -- labor and capital -- so that my estimates of sectoral TFP growth are about half those based on value added.[12] Second, because of data limitations, I do not net out the inputs used in the R&D activity of each industry in order to avoid double-counting, as suggested by Schankerman (1981). This will cause a downward bias in the estimated return to R&D.

When RDIND is included with RDGDP in the equation, the return to embodied R&D is estimated to be 43 percent (specification 2). This estimate is about average compared to previous work on the subject (again see Nadiri, 1991, or Mohnen, 1992). The coefficient estimate is significant at the 10 percent level. By adding together the coefficients of RDGDP and RDIND, we obtain estimates of the total or social rate of return to R&D of 53 percent.

When TFPIND is included with RDGDP in the estimating equation (specification 3), the spillover effects of technical change are found to be very strong. The coefficient of TFPIND has a value of 1.3 and is significant at the one percent level. To interpret the coefficient value, note from equation (6) that TFPIND is a weighted average of the TFP growth of supplying sectors, with the value of intermediate inputs as weights, multiplied by the ratio of the total value of intermediate inputs to total output. This ratio averages 0.433 over the four sample years. As a result, a one percentage point increase in the TFP growth of supplying sectors would be associated with a 0.57 (0.433 x 1.30) percentage point increase in the sector's own TFP growth.

Specifications 4 and 5 show similar results when the alternative forms, RDINDA and TFPINDA, are used. Results for RDINDA are very similar to those for RDIND. However, TFPINDA has much lower coefficient values than TFPIND and the variable is not statistically significant. The results rather strongly suggest that the strength of direct spillovers of productivity, such as from the computer industry to the insurance industry, depends on the relative importance of computers in the technology of the insurance industry, rather than the share of computers sold by the computer industry to the insurance sector.

The time dummy variables (DUM6777 and DUM7787) are not significant, despite the apparent slowdown in productivity growth between 1958-67 and 1967-77. The R^2 statistic ranges from 0.06 to 0.10, which is typical for this type of cross-industry regression. Specification 3, which includes TFPIND, has the best fit, as measured by the standard error of the regression and the adjusted R^2 statistic.

5. **Sources of Productivity Recovery in Manufacturing in 1977-87**

The last part of the paper investigates sources of the resurgence of TFP growth in manufacturing in the 1977-87 period. On the basis of the framework used in this analysis, there may have been three contributing factors to the recovery. First, R&D intensity (RDGDP) may have increased during the 1977-87 period. Second, the R&D embodied in inputs (RDIND) may have risen in the last period, either because the R&D intensity of the supplying industries rose or because industries purchased a higher share of their inputs from R&D-intensive industries. Third, technical change embodied in inputs (TFPIND) may have risen in the last period, either because the TFP growth rate of the supplying industries rose or because industries purchased a higher share of their inputs from industries with higher rates of productivity growth.

Table 3 shows the mean value of each of the key variables for periods 1958-67, 1967-77, and 1977-87. The evidence does indicate a recovery of R&D intensity in manufacturing in the third period. Average R&D intensity declined from 2.7 percent in 1958-67 to 2.4 percent in 1967-77 and then rebounded to 2.9 percent in 1977-87. However, there was no recovery in embodied R&D in the latest period. Average R&D embodied in manufacturing inputs (RDIND) fell from 0.64 percent in the first period to 0.53 percent in the second and remained at almost the same level in the third. The pattern was similar for RDIND in non-manufacturing. The pattern was different for TFP embodied in inputs. Average TFPIND in manufacturing fell precipitously from 0.44 percent in 1958-67 to 0.10 percent in 1967-77 and then rose to 0.20 in 1977-87, which was still less than half of its 1958-67 level. For non-manufacturing, TFPIND fell from 0.25 percent in the first period to 0.11 percent in the second and then declined further to -0.04 percent in the third.

Further analysis allows us to decompose changes in embodied R&D into two effects: changes in the R&D intensity of supplying sectors (supply effect) and a change in the interindustry coefficient matrix (linkage effect). From (3), the change in RDIND between periods T0 and T1 is given by:

$$(8) \quad \Delta(\mathrm{RDIND}_j) \equiv \mathrm{RDIND}_{jT1} - \mathrm{RDIND}_{jT0} = \Sigma_i\, \bar{a}^o_{ij} \cdot \Delta r_i + \Sigma_i\, \Delta a^o_{ij} \cdot \bar{r}_i$$

where $\bar{a}^o_{ij}$ is the average value of coefficient aij in periods T0 and T1, $\bar{r}_i$ is the average value of R&D intensity in periods T0 and T1, Δr_i is the change in R&D intensity between periods T0 and T1, and Δa^o_{ij} is the change in coefficient aij between periods T0 and T1· Likewise,

$$(9) \quad \Delta(\mathrm{TFPIND}_j) \equiv \mathrm{TFPIND}_{jT1} - \mathrm{TFPIND}_{jT0} = \Sigma_i\, \bar{a}^o_{ij} \cdot \Delta\pi_i + \Sigma_i\, \Delta a^o_{ij} \cdot \bar{\pi}_i \ .$$

Results of the decomposition are shown in Table 4. Between the 1958-67 and the 1967-77 periods, almost all the reduction in R&D embodied in inputs used by the manufacturing industries (RDIND) is due to a shift in their input structure away from R&D-intensive industries and towards industries which spent less on R&D. The linkage effect alone accounts for a 10 percentage point reduction in RDIND out of a total 11 point reduction. In the non-manufacturing sectors, the reduction in RDIND of 5 percentage points comes about equally from a reduction in the R&D intensity of their supplying industries and a shift in inputs towards less R&D-intensive industries.

Between the 1967-77 and 1977-87 periods, manufacturing industries continued to shift their input structure away from R&D intensive industries. However, the R&D intensity of their supplying industries also increased between the two periods. The supply effect essentially cancels out the linkage effect, resulting in almost no net change in RDIND within manufacturing. In non-manufacturing, the input structure again shows a modest shift away from the more R&D-intensive sectors, and the R&D intensity of their supplying sectors also declines slightly, resulting in a modest overall decrease in RDIND between these two periods.

In contrast, almost all the change in embodied technical change (TFPIND) is explained by changes in the TFP growth of supplying sectors. The sharp decline in TFPIND in manufacturing industries of 0.33 percentage points between 1958-67 and 1967-77 is almost entirely due to the slowdown in productivity growth of its supplying industries. The same is true for the non-manufacturing sector over this period. Likewise, the increase in TFPIND over the last two periods is almost completely due to the recovery in TFP growth of the input industries. The continued decline in TFPIND in non-manufacturing is again largely due to a continued decline of TFP growth of the industries selling to non-manufacturing sectors.

The final part of the analysis presents a decomposition of the change in TFP growth between periods into components. The first three columns of Table 5 show the contribution of each variable, defined as the coefficient value multiplied by the average value of the variable, to TFP growth by period. Tabulations are done separately for specification 2 (which includes RDIND) and specification 3 (which includes TFPIND) and for manufacturing and non-manufacturing. On the basis of specification 2, R&D intensity (RDGDP) and embodied R&D (RDIND) make about equal contributions to manufacturing TFP growth in the 1958-67 period, 0.27 percentage points. The residual (the unexplained portion) is 0.34 percentage points.

Between the 1958-67 and the 1967-77 periods, the contribution of RDGDP declines slightly, from 0.27 to 0.24 percentage points, as does that of RDIND, from 0.27 to 0.23. The fourth column shows the sources of the productivity slowdown between these two periods, computed as the difference in the contributions of each component in the 1967-77 and the 1958-67 periods. The modest decreases in RDGDP and RDIND account for 3 percent (-0.03/-0.94) and 5 percent (-0.05/-0.94), respectively, of the slowdown in TFP growth between these two period. With this specification, over 90 percent of the productivity slowdown is not explained by these variables.

Between the 1967-77 and 1977-87 periods, the contribution of RDGDP shows a modest increase, from 0.24 to 0.29 percentage points, while that of embodied R&D shows no change. Of the rather substantial upsurge of TFP growth in manufacturing of 0.70 percentage points per year between these two periods, the gain in RDGDP accounts for 7 percent. However, over 90 percent of the change in TFP growth is again left unexplained (that is, is accounted for by the change in the contributions of the time dummies and the residual).

In the non-manufacturing sector, the contribution of embodied R&D (RDIND) to TFP growth declines over time, from 0.11 percentage points in the 1958-67 period to 0.09 percentage points in the 1967-77 period and then to 0.08 percentage points in the 1977-87 period. The decline in the contribution of RDIND between the last two periods explains only 1 percent of the 0.85 percentage point drop in TFP growth. Moreover, while the contribution of RDIND also falls between the first two periods, TFP growth actually increases slightly. Most of the change in TFP growth in non-manufacturing is again picked up by the time dummies and the residual.

Results from specification 3 are much more telling. In the 1958-67 period, embodied technical change (TFPIND) alone accounts for over half of manufacturing TFP growth (0.57 out of 1.05 percentage points per year). Between the 1958-67 and the 1967-77 periods, the contribution of TFPIND falls from 0.57 to 0.14 percentage points. The decline in TFPIND by itself accounts for 47 percent (-0.44/-0.94) of the slowdown in TFP growth between these two periods. As with specification 2, the modest reduction in RDGDP explains another 3 percent of the slowdown in TFP growth, leaving about half not explained by these two variables.

Between the 1967-77 and 1977-87 periods, the contribution of embodied TFP growth shows a marked gain, from 0.13 to 0.26 percentage points. Of the increase of TFP growth in manufacturing of 0.70 percentage points between these two periods, the gain in TFPIND accounts for 20 percent (0.14/0.70) and that of RDGDP for 7 percent. However, most of the productivity recovery is again left unexplained.

In the non-manufacturing sector, embodied TFP growth (TFPIND) has a large effect on TFP growth in the 1958-67 period, of 0.33 percentage points, but its contribution falls off to 0.14 percentage points in the 1967-77 period and -0.06 percentage points in the 1977-87 period. The decline in the contribution of TFPIND between the last two periods amounts to 0.19 percentage points, which accounts for 22 percent of the 0.85 percentage point fall in annual TFP growth in this sector. However, while the contribution of TFPIND also falls by 0.19 percentage points between the first two periods, TFP growth increases by 0.08 percentage points.

6. **Conclusions**

I find strong evidence that industry TFP growth is significantly related to the TFP performance of supplying sectors, with an elasticity of almost 60 percent. The relation now holds for all sectors of the economy, instead of manufacturing alone, as was found in Wolff and Nadiri (1993). The difference in results is likely due to the inclusion of the 1977-87 period in the regression analysis here (and the exclusion of data for 1947-58). In fact, in the earlier paper, we had speculated that inter-sectoral technology spillovers might be heightened during the 1980s because of the paradigmatic shift from electromechanical automation to information technologies and the widespread use of computers in non-manufacturing sectors. These new results appear to confirm that speculation.

R&D intensity is also found to be a highly significant determinant of sector TFP growth. The estimated return to R&D is 10-13 percent. The return to embodied R&D is estimated to be 43 percent.

In an analysis of the sources of the change in TFP growth in manufacturing between 1958 and 1987, changes in direct productivity spillovers appear to play a key role. Between the 1958-67 and the 1967-77 periods, TFP growth in manufacturing falls by 0.91 percentage points per year. The contribution of productivity spillovers declines from 0.57 to 0.13 percentage points between these two periods, thereby accounting for 47 percent of the productivity slowdown. Between the 1967-77 and 1977-87 periods, TFP growth in manufacturing increases by 0.70 percentage points per year. The contribution of embodied TFP growth also shows a marked gain, from 0.13 to 0.26 percentage points, explaining 20 percent of the productivity recovery in this sector. Changes in R&D intensity and embodied R&D are relatively unimportant in explaining movements in manufacturing TFP growth over these three periods.

It is also found that the decline in productivity spillovers in manufacturing between 1958-67 and 1967-77 comes almost entirely from the slowdown in the TFP growth of supplying sectors; changes in linkage structure play almost no role. Likewise, the increase in productivity spillovers between 1967-77 and 1977-87 is almost completely due to the recovery in TFP growth of the supplying industries.

In contrast, between 1958-67 and 1967-77, the reduction in embodied R&D in manufacturing is due almost exclusively to a shift in its input structure away from the more R&D-intensive industries and towards the less R&D-intensive ones. Between 1967-77 and 1977-87, manufacturing industries continued to shift their input structure away from R&D-intensive industries. However, the R&D intensity of their supplying industries also increased, resulting in almost no net change in embodied R&D. The shift in manufacturing inputs away from R&D-intensive industries may seem surprising in light of the growing computerization within manufacturing. However, it primarily reflects the increasing relative share of services in the manufacturing input structure and the declining share of inputs from other manufacturing industries.

These results do point toward the importance of direct productivity spillovers among closely connected industries. Such agglomeration effects have been discussed by others (see, for example, Rosenberg, 1982), but this paper supplies strong additional evidence of technological change in one sector affecting TFP growth in purchasing sectors. The new results presented here strongly suggest that within manufacturing at least, a decline in TFP growth in one industry can pull down the technological growth of associated industries, leading to a cascading effect of technological change between supplying industries and their users. Likewise, recovery of TFP growth in one industry can pull up that of its customers. This result also provides support to the notion of knowledge spillovers among industries that has been resurrected in the new growth theory.

FOOTNOTES

[1] Griliches also identifies a second interpretation of spillovers -- namely, that inputs purchased from an R&D-performing industry may embody quality improvements that are not fully appropriated by the supplier. It should be emphasized at the outset that while these two notions of spillovers are quite distinct, they cannot be distinguished statistically in this work.

[2] Matrix A^0 is used again to avoid double-counting of industry j's own R&D.

[3] Wolff and Nadiri (1993) also introduced another measure of borrowed R&D, which is the amount of R&D embodied in new investment. This variable was estimated on the basis of capital flow data by industry. Unfortunately, a capital flow matrix is not yet available for 1987 to allow a similar computation.

[4] Details on the construction of the input-output tables can be found in the following publications: 1967 -- U.S. Interindustry Economics Division (1974); 1977 -- U.S. Interindustry Economics Division (1984); and 1987 -- Lawson and Teske (1994).

[5] Data on hours worked by sector, though the preferable measure of labor input to employment, are not available by sector and year and therefore could not be incorporated.

[6] The source is Musgrave (1992). Since there are fewer industries in the NIPA breakdown than in the input-output data, I applied the same percentage growth rate across all input-output industries falling within a given NIPA classification. Data on government-owned capital stock for all years were obtained from Musgrave (1992).

[7] In addition, the deflator for transferred imports was calculated from the

NIPA import deflator, that for the Rest of the World industry was calculated as the average of the NIPA import and export deflator, and the deflator for the inventory valuation adjustment was computed from the NIPA change in business inventory deflator. The source is U.S. Council of Economic Advisers (1992), Tables B-1, B-2, and B-3.

[8] The allocation of the scrap sector was handled differently in the make-use framework of the 1967, 1977, and 1987 tables. See ten Raa and Wolff (1991) for details.

[9] This was calculated in two steps. First company R&D from the Federal Trade Commission Line of Business Data was averaged over 1974, 1975, and 1976 and then divided by the average of industry GDP over the same three years. Second, using the National Science Foundation data, I computed the average ratio of R and D expenditures to GDP at the 32-industry level for the 1958-87 period and adjusted the first set of R&D to GDP ratios accordingly. It should be noted that although it would be preferable to use the ratio of R&D to industry sales in this analysis, the National Science Foundation provides a consistent time series only on the ratio of R&D to industry GDP. Moreover, the R&D data at this level of detail were not available prior to 1958, which prevented me from also including the 1947-58 period in the regression analysis.

[10] The sectoring followed the standard 85-order BEA classification scheme, with these exceptions: agriculture (1-4); metallic ores mining (5-6); nonmetallic minerals mining (9-10); construction (11-12); lumber and wood products (20-21); furniture and fixtures (22-23); footwear, leather, and leather products (33-34); and farm, construction, and mining machinery (44-45).

[11] It should be noted that because $TFPGRT_{jT}$ is a function of $RDGDP_{jT}$, a specification bias would be introduced by including both $RDIND_{jT}$ and $TFPIND_{jT}$

in the same specification (since $TFPIND_{jT}$ is thereby a function of $RDIND_{jT}$). I thank an anonymous referee for pointing this out.

[12] Terleckyj's 1980 paper supports this conjecture. With a two-factor TFP index, the coefficient on direct (private) R&D is 0.27; with a three-factor TFP index, the coefficient is 0.20 (Table 6.6, p. 375).

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Table 1

Total Factor Productivity Growth by Major Sector, 1958-1987[a]

(Percent per Annum)

	1958-67	1967-77	1977-87	1958-87
Agriculture	0.70	1.48	1.20	1.14
Mining	0.18	-1.02	-0.18	-0.36
Construction	0.76	-1.53	0.18	-0.23
Manufacturing	1.05	0.10	0.80	0.64
Transportation	2.18	1.77	-0.44	1.13
Communication	0.69	1.51	-1.47	0.22
Utilities	1.10	-3.33	1.59	-0.26
Wholesale and Retail Trade	0.91	1.07	1.12	1.04
Finance, Insurance, and Real Estate	0.58	2.00	-1.22	0.45
Other Services	-0.89	0.52	-1.16	-0.50
Total[b]	0.68	0.35	0.11	0.37

[a] Calculations are based on U.S. input-output data. See equation (1) for the definition of TFP growth.

[b] Total TFP growth is defined as a weighted average of sectoral rates of TFP growth, where current dollar gross domestic output (GDO) by sector is used as the weight.

Table 2
Regressions of R&D Intensity, Embodied R&D, and Embodied TFP Growth on Sectoral TFP Growth (TFPGRT): First Set[a]

Independent Variables	Specification (1)	(2)	(3)	(4)	(5)
Constant	0.004* (1.84)	0.002 (0.62)	-0.001 (0.37)	0.002 (0.67)	0.004 (1.62)
RDGDP	0.126*** (3.32)	0.101** (2.50)	0.112*** (3.00)	0.102** (2.51)	0.124*** (3.28)
RDIND		0.429* (1.76)			
TFPIND			1.300*** (2.80)		
RDINDA				0.408* (1.66)	
TFPINDA					0.146 (0.91)
DUM6777	-0.003 (1.10)	-0.003 (0.89)	0.002 (0.48)	-0.003 (0.91)	-0.003 (0.99)
DUM7787	0.000 (0.06)	0.001 (0.32)	0.004 (1.19)	0.001 (0.29)	0.000 (0.07)
R^2	0.060	0.074	0.096	0.073	0.064
$\bar{R}^2$	0.046	0.056	0.078	0.054	0.045
Std. Err. σ	0.0168	0.0167	0.0166	0.0168	0.0168
Sample Size	204	204	204	204	204

a. Estimated coefficients are shown next to the respective independent variables and the absolute value of the t-statistic is shown in parentheses. The White procedure for a heteroscedasticity-consistent covariance matrix is used in the estimation.

* Significant at the .10 level (two-tailed test).

** Significant at the .05 level (two-tailed test).

*** Significant at the .01 level (two-tailed test).

Table 3

Mean Value of TFP Growth, R&D Intensity, Embodied R&D, and Embodied TFP Growth By Period for Manufacturing and Non-Manufacturing Sectors

(percentage points)

	1958-67	1967-77	1977-87
A. TFPGRT: Annual rate of TFP Growth			
Manufacturing	1.05	0.10	0.80
Non-Manufacturing	0.52	0.60	-0.25
Total[a]	0.68	0.35	0.11
B. RDGDP: R&D as a Percent of GDP by Industry			
Manufacturing	2.67	2.41	2.87
Non-Manufacturing	0.00	0.00	0.00
Total	1.09	0.97	1.05
C. RDIND: R&D embodied in inputs			
Manufacturing	0.64	0.53	0.54
Non-Manufacturing	0.26	0.21	0.20
Total	0.41	0.34	0.32
D. TFPIND: TFP growth embodied in inputs			
Manufacturing	0.44	0.10	0.20
Non-Manufacturing	0.25	0.11	-0.04
Total	0.33	0.10	0.05

[a] Total TFP growth is defined as a weighted average of sectoral rates of TFP growth, where current dollar gross domestic output (GDO) by sector is used as the weight.

Table 4

Decomposition of the Change in Embodied R&D and Embodied TFP Growth Into a Supply and Linkage Effect

(percentage points)

	1967-77/1958-67			1987-77/1967-77		
	Total	Supply	Linkage	Total	Supply	Linkage
A. Δ(RDIND): R&D embodied in inputs[a]						
Manufacturing	-0.11	-0.01	-0.10	0.01	0.05	-0.04
Non-Manufacturing	-0.05	-0.03	-0.02	-0.02	-0.01	-0.01
Total	-0.07	0.05	-0.13	-0.02	-0.01	-0.01
B. Δ(TFPIND): TFP growth embodied in inputs[b]						
Manufacturing	-0.34	-0.33	-0.01	0.11	0.09	0.02
Non-Manufacturing	-0.14	-0.12	-0.02	-0.15	-0.13	-0.02
Total	-0.22	-0.20	-0.02	-0.06	-0.04	-0.01

a. From equation (8):

$$\Delta(\mathrm{RDIND}_j) = \Sigma_i\, \bar{a}^{o}_{ij}\cdot\Delta r_i \ \text{[supply effect]} + \Sigma_i\, \Delta a^{o}_{ij}\cdot\bar{r}_i \ \text{[linkage effect]}$$

b. From equation (9):

$$\Delta(\mathrm{TFPIND}_j) = \Sigma_i\, \bar{a}^{o}_{ij}\cdot\Delta\pi_i \ \text{[supply effect]} + \Sigma_i\, \Delta a^{o}_{ij}\cdot\bar{\pi}_i \ \text{[linkage effect]}$$

Table 5
Decomposition of the Change in TFP Growth between Periods Into Effects From the Change in R&D Intensity, Embodied R&D, and Embodied TFP Growth

	Contribution of Each Factor to TFP Growth by Period[a] (percent per annum)			Decomposition of the Change in TFP Growth between Periods[b] (percent per annum)	
	1958-67	1967-77	1977-87	1967-77/1958-67	1977-87/1967-77
<u>I. Specification 2 (including RDIND)</u>					
<u>A. Manufacturing</u>					
Constant	0.16	0.16	0.16	0.00	0.00
RDGDP	0.27	0.24	0.29	-0.03	0.05
RDIND	0.27	0.23	0.23	-0.05	0.00
Time Dummies	0.00	-0.26	0.09	-0.26	0.35
Residual	0.34	-0.27	0.03	-0.61	0.30
TFPGRT[c]	1.05	0.10	0.80	-0.94	0.70
<u>B. Non-Manufacturing</u>					
Constant	0.16	0.16	0.16	0.00	0.00
RDGDP	0.00	0.00	0.00	0.00	0.00
RDIND	0.11	0.09	0.08	-0.02	-0.01
Time Dummies	0.00	-0.26	0.09	-0.26	0.35
Residual	0.25	0.60	-0.59	0.36	-1.19
TFPGRT[c]	0.52	0.60	-0.25	0.08	-0.85
<u>II. Specification 3 (including TFPIND)</u>					
<u>A. Manufacturing</u>					
Constant	-0.11	-0.11	-0.11	0.00	0.00
RDGDP	0.30	0.27	0.32	-0.03	0.05
TFPIND	0.57	0.13	0.26	-0.44	0.14
Time Dummies	0.00	0.16	0.37	0.16	0.21
Residual	0.29	-0.35	-0.05	-0.64	0.30
TFPGRT[c]	1.05	0.10	0.80	-0.94	0.70
<u>B. Non-Manufacturing</u>					
Constant	-0.11	-0.11	-0.11	0.00	0.00
RDGDP	0.00	0.00	0.00	0.00	0.00
TFPIND	0.33	0.14	-0.06	-0.19	-0.19
Time Dummies	0.00	0.16	0.37	0.16	0.21
Residual	0.30	0.41	-0.46	0.11	-0.86
TFPGRT[c]	0.52	0.60	-0.25	0.08	-0.85

a. Defined as the coefficient value multiplied by the average value of the variable by period. Coefficients are from Specifications 2 or 3 in Table 2. Key: TFPGRT -- annual rate of TFP growth; RDGDP -- R&D intensity; RDIND -- R&D embodied in inputs; and TFPIND -- TFP growth embodied in inputs.

b. Defined as the difference between the coefficient value multiplied by the average value of the second period and that of the firs period.

c. TFPGRT is equal to the sum of components.