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PRODUCT DEMAND, COST OF PRODUCTION,
SPILLOVERS, AND THE SOCIAL RATE OF RETURN TO R&D

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ABSTRACT

The purpose of this paper is to develop and estimate a model of production with endogenous technological change. Technological change arises from R&D capital accumulation decisions. These decisions respond to market and government incentives and generate R&D capital spillovers.

A spillover network of senders and receivers is estimated. The network shows that each receiving industry is affected by a distinct set of R&D sources and each sending industry affects a unique set of receivers. For the receivers, spillovers generally expand product markets, lower product prices, increase production costs and input demands. For the sources, significant R&D spillovers cause the social rates of return to R&D capital to be substantially above the private returns.

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1. INTRODUCTION*

Investing in research and development (R&D) leads to the development of new products and the introduction of new or modified production processes. However, knowledge transmission occurs at relatively low cost, so that R&D investors may not be able to completely appropriate the returns from their investment. This public good characteristic of knowledge implies that externalities or spillovers are associated with R&D capital accumulation.

Theoretical work on industrial innovation has recognized the existence and importance of R&D capital spillovers. Spence (1984) showed that industry R&D investment increases with spillovers. However, because of appropriability difficulties individual firms reduce their R&D activities. Katz (1986) showed that the magnitude of spillovers and the nature of R&D sharing are important in the determination of industry output production and R&D activities. Moreover, he established that spillovers and cooperative research agreements generate distinct effects on social welfare.

Recently, within the context of growth theory, Romer (1990) developed a model with product market power and R&D spillovers. R&D capital accumulation (which is the endogenous source of technological change) in conjunction with spillovers cause product market size to expand and thereby increase the output growth rate. In addition, R&D spillovers generate a divergence between social and private returns to R&D capital. Aghion and Howitt (1990) show that R&D capital and spillovers affect output growth through the enhancement of market power for some producers, while other producers suffer an erosion of their monopoly profit.

The theories of industrial innovation and secular growth both emphasize the role of R&D capital as a source of endogenous technological change and the spillovers that emanate from R&D investment. R&D spillovers are a form of externality that arise from the nonrivalrous, but at least partially excludable character of R&D capital formation (see Griliches [1979] and Romer [1990] for discussions on this point). Also, in a number of studies done over the past decade, the demand for R&D capital has been modeled as an endogenous input, which is determined simultaneously with other production decisions (see Nadiri and Schankerman [1981], Mohnen, Nadiri and Prucha [1986], Bernstein [1988] and Bernstein and Nadiri [1988, 1989]). The empirical results confirm that the demand for R&D capital responds to changes in output and input prices, including the service price or rental rate of R&D capital itself. In addition, the empirical findings establish that R&D capital is a nonrivalrous input. Once R&D capital stock exists, it can be used freely by many producers throughout the economy.

There are a number of distinctive features of R&D spillovers. First, spillovers emanate from investment in R&D. The causality runs from R&D capital to R&D spillovers which, in turn, influence output supply and input demand decisions. Second, R&D spillovers generally affect both product demand and production characteristics. Thus there are pecuniary and technological externalities associated with spillovers. Firms can find that both their product price and production cost are affected by the R&D capital accumulation of other firms in the economy. Third, spillovers are intertemporal externalities because the transmission of R&D spillovers

arises from R&D capital stocks. R&D capital stocks exist because current expenditures on R&D give rise to a stream of future benefits. These future benefits do not solely accrue to those agents who incurred the past expenditures but also to other agents in the economy. Thus the existence of R&D spillovers implies that past R&D decisions of one firm can affect the current product price and production cost of other firms.[1]

The purpose of this paper is to develop and estimate a model of production in which R&D spillovers influence both product demand and production characteristics. Producers maximize the expected present value of the flow of funds by selecting output supply and input demands, including R&D capital. The demand for R&D capital, which is the source of endogenous technological change, is determined in accordance with the rules of intertemporal profit maximization and is therefore influenced by market incentives and government policy. Producers exhibit product market power and so are able to influence product prices through output and R&D capital decisions. R&D capital accumulation improves product quality; therefore producers can charge higher prices for their products.

In the model, R&D spillovers arise from the R&D capital stocks. These spillovers affect product prices and costs of production or, in other words, the profitability of recipient producers. Spillovers also influence input demands and output supplies. In this paper the effects of R&D spillovers on product price, cost and the structure of production are estimated. An important implication from spillovers influencing product price and production cost is that borrowed R&D capital can generate both positive and negative effects on profitability. At current prices

producers can find that product demand has fallen as a result of R&D investment (in other words, the development of new products or product characteristics) undertaken by other firms in the economy. R&D spillovers can erode the size of product markets and market power.[2]

In the empirical literature various ways have been adopted to measure R&D spillovers. The pool of R&D spillovers or of borrowed R&D has been defined as the sum of R&D expenditures (see Griliches [1964], Evenson and Kislev [1973], and Levin and Reiss [1984, 1988]), the sum of R&D capital stocks (see Bernstein [1988], and Bernstein and Nadiri [1989]), and the patent weighted sum of R&D expenditures (see Scherer [1982, 1984], Griliches and Lichtenberg [1984], and Jaffe [1986]). In all these studies the pool of borrowed R&D was defined as a single variable. Thus each spillover source was aggregated into a single pool of borrowed R&D capital. Due to the scalar definition of borrowed R&D, the emphasis of the literature has centered on the effects of R&D spillovers on the profitability and production structure of recipient producers.

As an alternative to the scalar notion of spillover, Bernstein and Nadiri (1988) introduced the vectorization of borrowed R&D capital. In this paper each producer is treated as a distinct spillover source so that from the estimation results a spillover network (or matrix) of senders and receivers is derived. R&D spillovers also create a divergence between the social and private rates of return to R&D capital. The social rate of return equals the private rate plus the change in profit due to R&D spillovers. In this paper, the social and private rates of return to R&D capital are estimated. Moreover, because a spillover network is derived,

the wedge between the social and private returns is decomposed among the spillover-receiving producers.

The remainder of this paper is organized as follows: In section two the model of production and spillovers is developed. Section three contains a discussion of the data and estimation results. In the fourth section the spillover network is derived along with the effects of spillovers on product prices, production costs, output supplies and factor demands. Section five pertains to the calculation and decomposition of the social and private rates of return to R&D capital. In the last section the results are summarized and conclusions are drawn.

2. THE MODEL OF INTERINDUSTRY SPILLOVERS

Cost of production is affected by the R&D capital of producers throughout the economy. Thus traditional cost functions must be amended to incorporate the externality associated with R&D capital accumulation. The representative variable cost function can be written as

(1) $\quad c^v = C^v(\omega_t, \ y_t, \ K_t, \ \Delta K_t, \ S_t)$

where c^v is the normalized (by the nth variable factor price) variable cost, C^v is the twice continuously differentiable variable cost function, ω is the n-1 dimensional vector of relative variable factor prices, y is the output quantity, K is the m dimensional vector of capital inputs, which includes own R&D capital (K_r), ΔK is the m dimensional vector of net

investment ($\Delta K_{it} - |K_{it} - K_{it-1}|$, $i - 1, \ldots, m$), S is the ℓ dimensional vector of R&D capital associated with all producers other than the representative one.[3]

R&D capital affects variable cost in three ways.[4] First, a larger own R&D capital input means lower variable cost if R&D is process-oriented since a larger knowledge base is used to combine the variable factors of production ($\partial c^v / \partial K_r < 0$). However, if R&D is product-oriented then quality improvements are costly to undertake ($\partial c^v / \partial K_r > 0$). Second, investment in R&D implies that producers incur adjustment costs as they divert variable inputs from output production to R&D investment ($\partial c^v / \partial \Delta K_r > 0$, see Mohnen, Nadiri and Prucha [1986]). Third, there are spillovers associated with increases in R&D capital of other producers in the economy, which leads to cost reductions for the representative producer ($\partial c^v / \partial S_j < 0$, $j - 1, \ldots, \ell$).[5]

The specific form of the (net of adjustment cost) variable cost and adjustment cost functions are given by

$$(2.1) \quad \ln c_t^v = \beta_0 + \sum_{i=1}^{n-1} \beta_i \ln \omega_{it} + \beta_y \ln y_t + \sum_{k=1}^{m} \beta_k \ln K_{kt}$$
$$+ \sum_{i=1}^{n-1} \beta_{iy} \ln \omega_{it} \ln y_t + \sum_{i=1}^{n-1} \sum_{k=1}^{m} \beta_{ik} \ln \omega_{it} \ln K_{kt}$$
$$+ \sum_{k=1}^{m} \beta_{yk} \ln y_t \ln K_{kt} + \sum_{k=1}^{m} \sum_{q=1, q \neq k}^{m} \beta_{kq} \ln K_{kt} \ln K_{qt}$$
$$+ (\sum_{i=1}^{n-1} \beta_{is} \ln \omega_{it} + \beta_{ys} \ln y_t + \sum_{k=1}^{m} \beta_{ks} \ln K_{kt}) \sum_{j=1}^{\ell} \beta_j \ln S_{jt}$$

$$(2.2) \quad c_t^a = 0.5 \sum_{k=1}^{m} \sum_{q=1}^{m} \mu_{kq} \Delta K_{kt} \Delta K_{qt}$$

where c^v is now normalized (net of adjustment cost) variable cost, c^a is normalized adjustment cost, and $\mu_{kq} - \mu_{qk}$ (equations (2.1) and (2.2) can be

combined with just a renormalization of the μ_{kq} parameters). The functional form for variable cost is restricted translogarithmic in terms of the non-spillover variables (see Schankerman and Nadiri [1986]). The functional form for adjustment cost implies that marginal adjustment costs are zero when net investment is zero (see Morrison and Berndt [1981] and Mohnen, Nadiri and Prucha [1986]). With respect to the spillover variables, the functional form is nonlinear in the spillover parameters and linear in the logarithms of the spillover variables. The parameter nonlinearity arises from the interaction between the spillovers, factor prices, capital inputs and output quantity. Moreover, the interaction enables the spillovers to exert differential effects on output and each of the inputs. This result emerges from the β_{is}, β_{ys} and β_{ks} parameters in equation set (2). The vectorization of borrowed R&D implies that each spillover source can generate a distinct effect on variable cost, output supply and factor demands. These differential source effects are manifested by the β_j parameters in equation set (2). The terms borrowed and spilled are used interchangeably. The borrowing or spillover processes are not modeled explicitly in this paper.

The pool of borrowed R&D capital that affects variable cost is given by the term $|\sum_{j=1}^{\ell}\beta_j \ln S_j|$. The sources comprising the spillover pool affecting variable cost are determined within the estimation of the model and simultaneously with the effects on spillover recipients. These sources are characterized by the estimation of the β_j parameters. If β_j = 0 then the jth producer is not a source of spillover through production cost to the representative industry.

The accumulation of the capital stocks occurs by the following processes,

(3) $K_t = I_t + (I_m - \delta)K_{t-1}, \quad K_0 > 0$

where I_t is vector of gross investment, I_m is the m dimensional identity matrix and δ is the m dimensional diagonal identity matrix of depreciation rates such that $0 \leq \delta_i \leq 1 \quad i=1,\ldots,m$.[6]

Product demand is influenced by R&D spillovers. The representative inverse product demand function is

(4) $p_t = D(y_t, K_{rt}, z_t, S_t)$

where p is the relative product price, D is the twice continuously differentiable inverse product demand function, and z is a vector of exogenous variables which affect product demand.[7] Product demand is affected by the vector of R&D spillovers and own R&D capital. R&D capital quantities represent product quality indicators. Moreover, product quality changes arise from current and past R&D investment decisions and not solely from contemporaneous expenditures for product improvements. Product quality improvements arising from own R&D capital imply that product price increases $(\partial p/\partial K_r > 0)$. However, spillovers that affect product demand can either generate positive or negative price effects. R&D capital is not arbitrarily separated into process R&D that only affects production cost and product R&D that only affects product demand.

R&D capital affects both cost and demand. It is the parameterization of the variable cost and inverse product demand functions that permits the determination of the product and process influences of R&D capital.

The specific form of the inverse product demand function is

$$(5) \quad \ln p_t = \alpha_0 + \alpha_y \ln y_t + \alpha_r \ln K_{rt} + \sum_{i=1}^{h} \alpha_i \ln z_{it} + \alpha_{yr} \ln y_t \ln K_{rt}$$
$$+ \sum_{i=1}^{h} \alpha_{yi} \ln y_t \ln z_{it} + \sum_{i=1}^{h} \alpha_{ri} \ln K_{rt} \ln z_{it}$$
$$+ (\alpha_{ys} \ln y_t + \alpha_{rs} \ln K_{rt}) \sum_{j=1}^{\ell} \alpha_j \ln S_{jt}.$$

The inverse product demand function is nonlinear in the spillover parameters and linear in the logarithms of the spillover variables.[8]

R&D spillovers affect output and R&D capital through the α_{ys} and α_{rs} parameters. Each spillover source generates a distinct effect on product price through the α_j parameters. Indeed the pool of borrowed R&D capital affecting product demand is given by $|\sum_{j=1}^{\ell} \alpha_j \ln S_j|$. As is the case for spillovers affecting production cost, the pool of borrowed R&D affecting product demand is determined within the estimation of the model and simultaneously with the effects on spillover recipients.

Production decisions are governed by the maximization of the expected present value of the flow of funds. Thus

$$(6) \quad \max_{(y_s, v_s, K_s)_{s=t}^{\infty}} \quad E(t)\alpha(t,s)[D(y_s, K_{rs}, z_s, S_s)y_s$$
$$- C^v(\omega_s, y_s, K_s, K_s - K_{s-1}, S_s) - q_s^T(K_s - (I_m - \delta)K_{s-1})]$$

where v is the vector of variable factor quantities, $\alpha(t,s)$ is the discount factor and q is the vector of normalized (by the nth variable

factor price) capital purchase prices. Expectations are conditional on existing information and are formed over future relative variable factor prices and capital purchase prices.

The specific equilibrium conditions defined by (6) can be found by using equations (2), (3), and (5), applying Shephard's Lemma (see Diewert [1974]) and carrying out the maximization. The equilibrium conditions are,

(7.1) $\omega_{is} v_{is}/c_s^v = \beta_i + \beta_{iy}\ln y_s + \sum_{k=1}^{m}\beta_{ik}\ln K_{ks}$

$\qquad + \beta_{is}\sum_{j=1}^{\ell}\beta_j\ln S_{js} \quad i=1,\ldots,n-1; \quad s=t,\ldots,\infty$

(7.2) $p_s y_s/c_s^v = (1 + \alpha_y + \alpha_{yr}\ln K_{rs} + \sum_{i=1}^{h}\alpha_{yi}\ln z_{is} + \alpha_y\sum_{j=1}^{\ell}\alpha_j\ln S_{js})^{-1}$

$\qquad (\beta_y + \sum_{i=1}^{n-1}\beta_{iy}\ln\omega_{is} + \sum_{k=1}^{m}\beta_{yk}\ln K_{ks}$

$\qquad + \beta_{ys}\sum_{j=1}^{\ell}\beta_j\ln S_{js}) \qquad\qquad s=t,\ldots,\infty$

(7.3) $\omega_{ks}^{\bullet} K_{ks}/c_s^v + \beta_k + \sum_{i=1}^{n-1}\beta_{ik}\ln\omega_{is} + \beta_{yk}\ln y_s + \sum_{q=1,q\neq k}^{m}\beta_{kq}\ln K_{qs}$

$\qquad + \sum_{q=1}^{m}\mu_{kq}(\Delta K_{qs} - (1+\rho_s)^{-1}\Delta K_{qs+1}^{\bullet})K_{ks}/c_s^v$

$\qquad + \beta_{ks}\sum_{j=1}^{\ell}\beta_j\ln S_{js} = 0 \qquad k\neq r, k=1,\ldots,m; \quad s=t,\ldots,\infty$

(7.4) $\omega_{rs}^{\bullet} K_{rs}/c_s^v + \beta_r + \sum_{i=1}^{n-1}\beta_{ir}\ln\omega_{is} + \beta_{yr}\ln y_s + \sum_{q=1,q\neq r}^{m}\beta_{rq}\ln K_{qs}$

$\qquad +\sum_{q=1}^{m}\mu_{rq}(\Delta K_{qs} - (1+\rho_s)^{-1}\Delta K_{qs+1}^{\bullet})K_{rs}/c_s^v + \beta_{rs}\sum_{j=1}^{\ell}\beta_j\ln S_{js}$

$\qquad - (p_s y_s/c_s^v)[\alpha_r + \alpha_{yr}\ln y_s + \sum_{i=1}^{h}\alpha_{ri}\ln z_{is}$

$\qquad + \alpha_{rs}\sum_{j=1}^{\ell}\alpha_j\ln S_{js}] = 0 \qquad\qquad s=t,\ldots,\infty,$

where the relative rental rates on the capital inputs are $\omega_{ks}^{\bullet} = q_{ks}[(1 - (1+\rho_s)^{-1}(1-\delta_k)q_{ks+1}^{\bullet}/q_{ks}]$ $k=1,\ldots,m$, ρ_s is the discount rate such that

$\alpha(s,s+1) = (1+\rho_s)^{-1}$, the superscript e denotes the conditional expectation of a variable.

Equation set (7.1) denotes the equilibrium conditions for the variable factors of production. In equilibrium the ith variable factor cost share is directly affected by the pool of borrowed R&D that influences production cost through the β_{is} parameters.[9]

The equilibrium condition for output is given by equation (7.2). In equilibrium the revenue to cost ratio is influenced by spillovers that affect both product price and production cost. Spillovers altering product price affect the revenue to cost ratio through the inverse price elasticity of product demand, as α_{ys} delimits how the spillover pool changes the inverse price elasticity. In addition, spillovers affecting production cost influence the revenue to cost ratio through the variable cost flexibility.[10] This effect is manifested through β_{ys}.

Equation set (7.3) characterizes the equilibrium conditions for the non-R&D capital inputs. In equilibrium the marginal cost of a non-R&D capital input, which consists of the user cost and the marginal adjustment cost, is offset by the expected marginal benefit, which consists of the variable cost reduction in period s and the future adjustment cost reduction from having a larger capital input. Clearly, adjustment costs create the intertemporal links. These costs generate the trade-off between marginal cost increases in period s and marginal cost decreases in period s+1. In addition, R&D spillovers affecting production cost influence the equilibrium conditions for non-R&D capital inputs directly through the β_{ks}, $k \neq r$, $k=1,\ldots,m$ parameters.

Equation (7.4) shows the equilibrium condition for the R&D capital input. This condition is different from the other capital input equations. R&D capital not only affects variable cost but also product price. Thus the marginal benefit associated with R&D capital consists of increases in marginal revenue, net of changes in variable cost as well as variable adjustment cost reductions. The revenue component arises from the α_r, α_{yr}, α_{rs} parameters. In addition, the R&D capital equilibrium condition is affected by both sets of spillovers through the β_{rs} and α_{rs} parameters .

The equilibrium conditions along with the variable cost and inverse product demand functions point out how spillovers influence the array of production decisions, including the intertemporal trade-offs associated with R&D and non-R&D capital inputs.

3. THE DATA AND ESTIMATION RESULTS

Data was obtained for six industries for the period 1957-1986. The six industries are chemical and allied products (SIC 28), fabricated metal prducts (SIC 34), nonelectrical machinery (SIC 35), electrical products (SIC 36), transportation equipment (SIC 37), and scientific instruments (SIC 38). These industries account for 92% of manufacturing R&D expenditures on average over the sample period.

The data on the quantities of output, labor, physical capital and intermediate inputs as well as the data on price indices were obtained from the Bureau of Labor Statistics (see Gullickson and Harper [1986] for a detailed description of the data).

For each industry the output quantity is measured as the value of gross output divided by the output price index. There are two variable factors, labor and intermediate inputs. The wage rate is defined as the labor price index normalized to one at 1982. The labor input quantity is measured as the labor cost divided by the labor price index. The price of intermediate inputs is derived from a Tornqvist index (normalized at 1982) of the prices of materials, energy, and purchased services. The quantity of intermediate inputs is measured as the total cost of materials, energy, and purchased services divided by the price index of intermediate inputs.

There are two quasi-fixed factors, physical capital and R&D capital. Physical capital is defined as the sum of structures and equipment capital stocks. The deflator of physical capital is derived as a Tornqvist index of the acquisition price indices of structures and equipment, respectively. The rental rate of physical capital is defined as $w_p = p_p(\rho + \delta_p) (1 - \iota_p - u_c z)$ where p_p is the physical capital deflator, ρ is the discount rate, which is taken to be the rate on Treasury bonds of ten-year maturity, δ_p is the physical capital depreciation rate, ι_p is the investment tax credit, u_c is the corporate income tax rate, and z is the present value of capital consumption allowances.

R&D capital is defined as the accumulation of deflated R&D expenditures.[11] The R&D expenditures were obtained from the National Science Foundation (1987 and earlier issues). The deflator of R&D capital is constructed by linking Mansfield's (1985) constructed deflator series forward with the GNP deflator and backward with Schankerman's (1979) constructed R&D deflator series. Initial deflated R&D expenditures are

grossed up by the average annual growth rate of physical capital for the period 1948-1956 in order to obtain initial R&D capital stock. Given the initial stock, R&D capital is developed according to the perpetual inventory formula using declining balance depreciation. The depreciation rate is taken to be 10 percent. This rate is similar to the ones used in other studies (Mohnen, Nadiri, Prucha [1986] used 10 percent and Jaffe [1986] used 15 percent). Little is known about R&D capital depreciation, but Hulten and Wykoff (1981) found that for assets which are used in R&D activities depreciation ranged from 10% to 20%.[12] The rental rate on R&D capital is defined as $w_r = p_r(\rho + \delta_r)(1 - \iota_r - u_c)$ where p_r is the R&D price deflator, δ_r is the R&D capital depreciation rate equal to 0.1 and ι_r is the incremental R&D tax credit.

The exogenous variable affecting product demand for any one industry is defined as real gross domestic product (GDP) net of the industry output divided by population. This variable captures the effect of real income for those agents who demand the product.

The estimation model consists of the variable cost function (equation (2.1)), the inverse product demand function (equation (5)) and the output and input equilibrium conditions (equations (7.1) - (7.4)). There are six equations to be estimated for each of the six industries. The endogenous variables are product price, variable cost, labor cost share, output quantity, physical capital, and R&D capital inputs. Optimizing errors are added to equations (2.1), (5), (7.1) and (7.2). The errors associated with equations (7.3) and (7.4) upon removal of the conditional expectations operator represent unanticipated information which become

available after the time that the capital decisions are made. Thus the conditional expected value of the error is zero at the time of the capital decisions. It is also assumed that the errors have zero mean and positive definite symmetric covariance matrix.

The estimation model consists of equations which contain expected future values of variables (see equations (7.3) and (7.4)). In order to estimate these Euler equations, Hansen and Singleton (1982) developed a generalized method of moments estimator, which has been shown by Pindyck and Rotemberg (1982) when the errors are homoskedastic, to be equivalent to the nonlinear three stage least squares estimator (see Jorgenson and Laffont [1974]). This estimator involves the selection of instruments. Lagged values of relative factor prices, relative product price, variable cost, output, physical and R&D capital, and real net GDP per capita are the instruments selected. The estimator is consistent and efficient (for the set of instruments that are used).

The estimation results are shown in appendix Table A1. In order to identify the parameters, without loss of generality the restriction $\beta_{rs} = \alpha_{rs} = 1$ is imposed. The set of spillover sources for each receiving industry is determined in the following manner. First, all spillover sources are entered into the model which is then estimated. The spillover sources that generate a negative impact effect on variable cost are retained.[14] The model is again estimated with the remaining spillovers. The process is repeated until all spillover sources generate variable cost reductions. To guarantee that the acceptance of a spillover source is not biased by the order in which sources are rejected, the model is estimated

a number of times with the different spillover sources considered in various combinations. For each industry the accepted spillover sources always converged to the ones outlined by the parameters in Table A1. In addition, the parameters associated with any set of spillovers must be consistent with the restrictions on the variable cost function or more generally the second order conditions of the maximization problem defined by (6).

The acceptance condition for spillover sources is quite general. First, it is consistent with the assumption of free disposability in production. If spillovers are cost increasing then producers have the option of eliminating them from their production process. Producers can costlessly dispose of spillovers. Second, the criterion is based upon variable cost and not total cost. Spillovers that increase total cost are not rejected. Fixed costs associated with R&D capital can increase with spillovers. In order to absorb the spillovers, additional R&D investment may have to be undertaken, thereby increasing total cost. Third, the acceptance condition does not restrict spillovers that affect product price. R&D spillovers can either increase or decrease product price and thereby generate positive or negative revenue effects, given the size of product markets.

The estimation results from Table A1 imply that the estimated magnitudes of the endogenous variables are positive and the variable cost function is concave with respect to variable factor prices, and convex in physical capital and adjustment cost is convex in physical and R&D investment. In addition, variable profit (revenue minus variable cost) is

concave in output and R&D capital. These conditions are satisfied at each point in the sample and for each industry.

The results show that the standard errors of the estimates are generally small relative to the estimates. The standard errors of each of the equations is also small. The square of the correlation coefficients between the actual and predicted values of the endogenous variables are generally high and residual plots did not point out any significant serial correlation. The estimated model seems to fit the data quite well and satisfies the integrability conditions.

The dynamic features of the model are associated with the capital adjustment parameters, μ_{pp}, μ_{rr} and μ_{pr}. The wedge between the expected marginal benefit due to capital expansion and the respective rental rate arises from the significance of the adjustment cost parameters. In general, from Table A1, the adjustment parameters are statistically significant for each industry. Besides the own adjustment cost parameters (μ_{ii}, i = p,r), which are all positive as required, there is also the cross adjustment parameter μ_{pr}. In five of six industries (electrical products is the exception) the cross parameter is significant and positive. Thus an increase in net investment for physical (R&D) capital stock increases adjustment cost for the R&D (physical) capital stock.

Contemporaneous marginal adjustment cost is equal to the difference between the expected marginal benefit and rental rate for each capital input. If marginal adjustment cost is zero, then the expected marginal benefit per dollar of the ith capital service equals the respective rental rate. Table 1 shows the marginal adjustment cost per dollar of capital

TABLE 1: Marginal Adjustment Cost Per Dollar of Capital Service
(mean values)

Industry	Physical Capital	R&D Capital
Chemical Products	$0.27	$0.31
Fabricated Metal	$0.87	$0.25
Nonelectrical Machinery	$0.39	$0.24
Electrical Products	$0.26	$0.18
Transportation Equipment	$0.25	$0.07
Scientific Instruments	$0.33	$0.46

service for each type of capital. For a dollar spent on additional

physical capital, industries incur adjustment costs ranging from $0.25 to

$0.87. Transportation equipment is at the low end of the range while

fabricated metal is at the high end. The range among the industries of

marginal adjustment cost per dollar of R&D capital service is greater than

for physical capital. The range for R&D capital is from $0.07 to $0.46,

with transportation equipment at the low end and scientific instruments is

at the high end. Table 1 shows that each industry must incur significant

adjustment costs when either R&D or physical capital stocks are increased.

These adjustment costs imply that there is an intertemporal trade-off in

the decision to accumulate both physical and R&D capital inputs (see

equations (7.3) and (7.4)). Thus both types of capital inputs are,

indeed, quasi-fixed factors.

4. R&D SPILLOVERS, PRICE, COST, AND PRODUCTION

There is a different set of spillover sources for each recipient

industry. Table 2 shows the spillover network. This table is derived by

considering the β_j, α_j j = 28, 34, 35, 36, 37, 38 parameter estimates from

Table A1. As can be seen from Table 2, each industry is a receiver of R&D

spillovers and five of six industries are spillover sources (fabricated

metal is not a spillover source). In addition, four of the industries are

affected by a single source, one industry is affected by two sources and

one industry is affected by three sources. However, even in the case of

multiple sources, for each receiving industry the spillover parameters are

TABLE 2: Spillover Network

Receiver Industry	Sender Industry
28 Chemical Products	38 Scientific Instruments
34 Fabricated Metal	37 Transportation Equipment
35 Nonelectrical Machinery	28 Chemical Products
	37 Transportation Equipment
36 Electrical Products	38 Scientific Instruments
37 Transportation Equipment	35 Nonelectrical Machinery
38 Scientific Instruments	28 Chemical Products
	36 Electrical Products
	37 Transportation Equipment

equal across source industries. For each receiving industry, the interindustry spillover sources tend to be concentrated in a few industries. Thus using aggregate R&D expenditures, or aggregate R&D capital, or producer weighted sums of these variables appears to be too broad a measure of R&D spillovers. When allowance is made to account for individual spillover sources, there is a narrow range of source industries for each receiving industry. In addition, each source only affects a few industries. There are not more than three industries affected by any one source. Thus for each spillover sender or receiver the network is relatively narrow. However, since the collection of senders and receivers is not symmetric, the network involves all of the industries.

Spillovers influence production decisions by first altering product price and production cost for any receiving industry. To see these initial effects hold output and the capital inputs fixed and differentiate equations (2) and (5) with respect to the spillover variables,

(8.1) $\quad (\partial \ln p_t / \partial \ln S_{jt})\big|_{y_t, K_t} = (\alpha_{ys} \ln y_t + \ln K_{rt})\alpha_j \qquad j = 1, \ldots, \ell$

(8.2) $\quad (\partial \ln c_t^v / \partial \ln S_{jt})\big|_{y_t, K_t} = (\beta_{1s} \ln \omega_{1t} + \beta_{ys} \ln y_t + \beta_{ps} \ln K_{pt}$
$$+ \ln K_{rt})\beta_j \qquad j = 1, \ldots, \ell.$$

Equation (8.1) shows the product price effect associated with R&D spillovers and equation (8.2) shows the cost-reducing effect associated with spillovers. An increase in product price, given output, physical and R&D capital inputs, as a result of R&D spillovers means that revenue increases for the recipient industry. The converse is true for decreases in product price.

The product price and cost reduction effects are presented in Table 3. Four of the six industries, namely fabricated metal, nonelectrical machinery, electrical products, and transportation equipment are recipients of negative price effects. Thus at existing output and R&D capital levels, R&D spillovers cause product prices to fall. These negative elasticities vary significantly across industries; the range is from -0.05% to -0.16%. Chemical products and scientific instruments are the two industries where R&D spillovers increase their product price. The magnitude is from 0.03% for scientific instruments to 0.05% for chemical products. For all the industries, the effects of spillovers that influence product price are very stable over the sample period.

The cost reductions, for each industry, are also stable over the sample. A 1% increase in R&D spillovers causes a range of variable cost reductions from 0.05% to 0.24%. The major beneficiary of spillover-generated cost reductions is fabricated metal, while chemical products receive the smallest reduction in their cost. From Table 3 by substracting cost reductions from the price effects (since cost reductions increase profit), the effect of R&D spillovers on the profitability of each recipient industry can be determined (given output, physical and R&D capital inputs). Spillovers increase variable profit for each industry except chemical products, where the cost-reduction and price increase offset each other.[15] The increases in 1985 are 0.086% for fabricated metal, 0.061% for nonelectrical machinery, 0.054% for electrical products, 0.062% transportation equipment, and 0.050% for scientific instruments. When R&D spillovers cause variable profit to grow, not only is the effect stable over time, but also quite similar across industries.

TABLE 3: The Effect of R&D Spillover on Product Price and Variable Cost

Receiver Industry	Year	Product Price	Cost Reduction
28 Chemical Products*	1965	0.045	-0.045
	1975	0.047	-0.047
	1985	0.048	-0.048
34 Fabricated Metal	1965	-0.158	-0.215
	1975	-0.154	-0.233
	1985	-0.156	-0.242
35 Nonelectrical Machinery	1965	-0.059	-0.115
	1975	-0.056	-0.115
	1985	-0.058	-0.119
36 Electrical Products	1965	-0.061	-0.113
	1975	-0.064	-0.117
	1985	-0.065	-0.119
37 Transportation Equipment	1965	-0.045	-0.107
	1975	-0.046	-0.109
	1985	-0.048	-0.110
38 Scientific Instruments	1965	0.024	-0.067
	1975	0.025	-0.072
	1985	0.027	-0.077

*The null hypothesis that $\alpha_j + \beta_j = 0$ is not rejected.

The significance of adjustment costs associated with both physical and R&D capital implies that industries are in short-run equilibrium. In the short run producers treat capital inputs as fixed factors and the equilibrium relates to product price, variable cost, variable input and output quantities.

The effects of R&D spillovers on equilibrium are given by

$$(9.1) \quad \partial \ln y_t / \partial \ln S_{jt} = [s_{yt}(\eta_{jt} - \epsilon_{jt}) + \beta_{ys}\beta_j(1 + \epsilon_{yt})^{-1} - \alpha_{ys}\alpha_j\eta_{yt}(1+\epsilon_{yt})^{-2}]$$
$$/s_{yt}(1 + \epsilon_{yt} - \eta_{yt}) \qquad\qquad j=1,\dots,5$$

$$(9.2) \quad \partial \ln p_t / \partial \ln S_{jt} = \epsilon_{jt} + \epsilon_{yt}(\partial \ln y_t / \partial \ln S_{jt}) \qquad\qquad j=1,\dots,5$$

$$(9.3) \quad \partial \ln c_t^v / \partial \ln S_{jt} = \eta_{jt} + \eta_{yt}(\partial \ln y_t / \partial \ln S_{jt}) \qquad\qquad j=1,\dots,5$$

$$(9.4) \quad \partial \ln v_{1t} / \partial \ln S_{jt} = e_{1jt} + (\beta_{1y} + s_{1t}\eta_{yt})s_{1t}^{-1} (\partial \ln y_t / \partial \ln S_{jt}) \qquad j=1,\dots,5$$

where $s_{yt} = p_t y_t / c_t^v$, η_{jt} is the right side of (8.2) (or the cost reduction), ϵ_{jt} is the right side of (8.1) (or the price effect), ϵ_{yt} is the inverse price elasticity of product demand, η_{yt} is the cost flexibility (or the output elasticity of variable cost), e_{1jt} is the spillover elasticity on conditional (output fixed) labor demand and s_{1t} is the labor cost share.[16] There are three terms in the numerator of equation (9.1). The first term shows the direct effect of spillovers on output supply through changes in product price and variable cost, the second term shows the indirect effect through variable cost and the last term shows the indirect spillover effect through product price. Equations (9.2), (9.3), and (9.4) point out that spillovers affect product price, variable cost, and variable factor demands directly and also indirectly through changes in output supply.

Table 4 shows the spillover elasticities of output supply, product price, variable cost, labor and intermediate input demands. An increase in R&D spillovers in each industry causes output to expand and thereby product price to fall. Indeed, even for the two industries where R&D spillovers increase product price, given output and the capital inputs (namely chemical products and scientific instruments), the output expansion effect arising from the spillovers is sufficiently strong to cause product prices to fall. In addition, the sum of the output and price elasticities shows the effect on revenue as R&D spillovers increase. For each industry, R&D spillovers generate revenue growth. Thus, R&D spillovers cause the size of the product markets to expand.

Once output expands from the spillovers, then variable production cost increases. Thus, the effect of the growth in output outweighs the initial cost-reduction due to the spillovers. Moreover, in each industry the demands for labor and intermediate inputs increase as a result of R&D spillovers. Technological change, represented by R&D spillovers, causes product markets to grow and this expansion leads to increases in labor and intermediate inputs.

5. RATES OF RETURN TO CAPITAL

Rates of return to physical and R&D capital differ because of adjustment costs and spillovers. Private rates of return can differ among the two types of capital because expected marginal benefits are equated to rental rates and marginal adjustment costs. Differences in marginal

TABLE 4: Spillover Elasticities

Receiving Industry	Year	Output	Price	Cost	Labor	Intermediate
28 Chemical Products	1965	0.204	-0.018	0.186	0.200	0.177
	1975	0.243	-0.014	0.230	0.249	0.220
	1985	0.284	-0.010	0.278	0.304	0.267
34 Fabricated Metal	1965	0.128	-0.170	-0.078	-0.066	-0.086
	1975	0.266	-0.184	0.046	0.073	0.029
	1985	0.314	-0.194	0.083	0.116	0.064
35 Nonelectrical Machinery	1965	0.755	-0.623	0.124	0.296	0.124
	1975	0.786	-0.674	0.100	0.298	0.100
	1985	1.383	-1.185	0.191	0.568	0.192
36 Electrical Products	1965	0.207	-0.131	0.076	0.032	0.119
	1975	0.234	-0.143	0.092	0.043	0.141
	1985	0.250	-0.149	0.101	0.043	0.148
37 Transportation Equipment	1965	0.238	-0.110	0.128	0.236	0.056
	1975	0.220	-0.087	0.133	0.246	0.071
	1985	0.222	-0.078	0.147	0.259	0.083
38 Scientific Instruments	1965	0.421	-0.133	0.287	0.182	0.403
	1975	0.388	-0.122	0.266	0.160	0.363
	1985	0.380	-0.121	0.259	0.145	0.348

adjustment costs between physical and R&D capital create differences in their private returns. R&D spillovers define externalities which affect product price and production cost, as a consequence, social rates of return to R&D can differ from their private returns. There are no externalities associated with physical capital and hence its social rate of return is equated to its private rate.

The before tax net of depreciation private rates of return to the capital stocks are derived from equations (7.3) and (7.4) by re-arranging terms in each equation and using the definition of rental rates

(10) $\rho_{kt} = \rho_t + \sum_{q=p}^{r} \mu_{kq} \Delta K_{qt}(1+\rho_t)/q_{kt}$ $k = p, r$

where ρ_{kt} represents the remaining terms in equations (7.3) or (7.4). In equilibrium, the private rate of return on the kth capital equals the discount rate plus the capitalized value of marginal adjustment cost per dollar of the kth capital. The private rate of return to R&D capital, as defined in this paper, is the rate of return accruing to an industry.[17]

In order to calculate the social rates of return to R&D capital a welfare function must be specified because R&D spillovers affect product demand, as well as cost of production. However, the present task is more limited in scope. The purpose here is to calculate the difference between social and private rates of return when both rates are evaluated at the equilibrium levels of output supply and input demands. To undertake the calculation, consider a situation where the R&D spillovers are internalized by the industries. In this case the joint industry expected discounted flow of funds is given by

(11) $\Phi_t = \sum_{j=1}^{\ell} \sum_{s=t}^{\infty} E^j(t)\alpha(t,s)[D^j(y_s^j, K_{rs}^j, z_s^j, S_s^j)y_s^j$

$- C^{vj}(\omega_s^j, y_s^j, K_s^j, K_s^j - K_{s-1}^j, S_s^j)$

$- q_s^{jT}(K_s^j - (I_m - \delta)K_{s-1}^j)]$

where Φ is defined at the equilibrium levels of output supply and input demands. Now since the R&D spillovers have been internalized, there are additional profits to be earned from each of the different R&D capital stocks. The additional profit implies additional return and the extra return is the increase in Φ from R&D spillovers. Thus, using equations (2) and (5),

(12) $\partial\Phi_t/\partial K_{rt}^j = \sum_{s=1, s\neq j}^{\ell}[(\alpha_{yt}^s \ln y_t^s + \ln K_{rt}^s)\alpha_j^s s_{yt}^s - (\beta_{ls}^s \ln\omega_{lt}^s + \beta_{ys}^s \ln y_t^s$

$\beta_{ps}^s \ln K_{pt}^s + \ln K_{rt}^s)\beta_j^s]c_t^{vs}/K_{rt}^j$ $j = 1,\ldots,\ell$

The additional return on each R&D capital stock equals the net product price and cost-reduction effects arising from the R&D spillovers. This means that the social rates of return on the R&D capital stocks, evaluated in equilibrium, are defined as

(13) $\gamma_{rt}^j = \rho_{rt}^j + (1+\rho_s)(\partial\Phi_t/\partial K_{rt}^j)/q_{rt}^j$ $j = 1,\ldots, \ell$

These social rates of return, denoted as γ_r^j, are essentially sectoral rates of return to the R&D capital stocks, while ρ_r^j are industrial rates of return. From equation (13) spillover-generated increases in product

price and cost reductions cause the gap to widen between the rates of return to R&D capital.

Table 5 shows the contributions to the social rates of return arising from the spillovers associated with the R&D capital of each industry. For each source industry, the effects are decomposed by spillover recipient. Chemical products affects the variable profit, through product price and variable cost, of nonelectrical machinery, and scientific instruments. Table 5 shows that the spillovers from chemical products generate price reductions in nonelectrical machinery and price increases in scientific instruments. However, the cost reduction caused by chemical products on nonelectrical machinery is greater (in absolute value) than the decrease in price. Thus the net return to R&D capital, from the spillovers on nonelectrical machinery, is positive and in 1985 is 0.156. The return to R&D capital in 1985 from scientific instruments is 0.090.

The fabricated metal industry does not generate spillovers. Nonelectrical machinery induces spillovers on transporation equipment. In 1985 the net return on R&D capital, from the product price and cost reductions, is 0.155. Electrical products also affects only one industry, scientific instruments. In 1985 the return to R&D capital of electrical products from scientific instruments is 0.045.

The spillovers from transportation equipment affect fabricated metal, nonelectrical machinery and scientific instruments. As a result of the spillovers, product prices decrease for fabricated metal and nonelectrical machinery, but the net returns to the R&D capital of transportation equipment from the two industries are positive and in 1985 are 0.039 and

TABLE 5: R&D Spillover Returns

Sending Industry	Spillover Type	Year	Receiving Industries					
			28	34	35	36	37	38
28 Chemical Products	Product Price	1965			-0.246			0.024
		1975			-0.207			0.025
		1985			-0.225			0.030
	Variable Cost	1965			0.385			0.050
		1975			0.331			0.050
		1985			0.381			0.060
34 Fabricated Metal	Product Price							
	Variable Cost							
35 Nonelect. Machinery	Product Price	1965					-0.314	
		1975					-0.219	
		1985					-0.200	
	Variable Cost	1965					0.545	
		1975					0.381	
		1985					0.355	
36 Electrical Products	Product Price	1965						0.010
		1975						0.011
		1985						0.015
	Variable Cost	1965						0.021
		1975						0.023
		1985						0.030
37 Transport. Equipment	Product Price	1965		-0.136	-0.053			0.005
		1975		-0.110	-0.053			0.006
		1985		-0.123	-0.070			0.010
	Variable Cost	1965		0.156	0.082			0.011
		1975		0.141	0.085			0.013
		1985		0.162	0.119			0.019
38 Scient. Instruments	Product Price	1965	0.545			-0.755		
		1975	0.402			-0.435		
		1985	0.262			-0.355		
	Variable Cost	1965	0.332			1.010		
		1975	0.265			0.595		
		1985	0.185			0.492		

0.049 respectively. The return from scientific instruments in 1985 is
0.029.

The spillovers from scientific instruments affect chemical products
and electrical products. These spillovers decrease the product price for
electrical products but the cost reduction effect is such that the net
return is positive and in 1985 is 0.137 from electrical products. The
return from chemical products in 1985 is 0.447.

The general conclusions that emerge are that three of the five
sending industries affect multiple industries. Three of the sources
industries cause product price reductions for spillover recipients.
However, the R&D capital for each source industry generates a positive net
contribution to the social rate of return from each of its spillover
recipients. Lastly, chemical products, nonelectrical machinery and
scientific instruments are the main spillover source industries.

From Table 5, for each spillover source, adding the product price and
variable cost generated returns from the spillovers over all recipients to
the private rate of return to R&D capital equals the social rate of
return. Table 6 shows the before tax net of depreciation rates of return
to physical and R&D capital. Marginal adjustment cost per dollar of
physical capital stock is not significantly different from the magnitude
for R&D capital so that the before-tax private rates of return are quite
similar. This result appears at each point in the sample and for each
industry. However, there are significant returns to R&D spillovers. In
five of the six industries the social rate of return to R&D capital
exceeds the private rate. In 1985 the smallest percentage difference

between the social and private returns is about 20% and is exhibited by electrical products. The percentage difference is slightly less than 50% for transportation equipment in 1985. The greatest deviation between returns is observed from scientific instruments. In this case the difference is 200% in 1985. For the chemical products and nonelectrical machinery industries the social rate of return is about twice the private rate in 1985. Thus, in general, the social rates exceed the private rate, and there is also a great deal of variation across spillover source industries as to the extent of the wedge between returns. In addition, it is possible to generate significant social rates of return to R&D capital by only affecting a few receiving industries. The spillover reach does not have to be extensive for social rates to exceed private rates of return.

6. CONCLUSION

In this paper a dynamic model of production and endogenous technological change was developed and estimated. Technological change arose from the R&D capital accumulation decisions by producers. These decisions were governed by the conditions of intertemporal profit maximization and were formed simultaneously with output, input and physical capital accumulation decisions.

The accumulation of R&D capital generated spillovers because of the nonrivalrous but excludable character of R&D capital. The spillover network that was estimated showed that each receiving industry was

TABLE 6: Rates of Return

| Industry | Year | Private Rate | | Social Rate |
		Physical Capital	R&D Capital	R&D Capital
Chemical Products (28)	1965	0.234	0.254	0.467
	1975	0.198	0.205	0.404
	1985	0.202	0.218	0.464
Fabricated Metal (34)	1965	0.355	0.203	0.203
	1975	0.234	0.217	0.217
	1985	0.212	0.215	0.215
Nonelec. Machinery (35)	1965	0.175	0.188	0.420
	1975	0.216	0.224	0.386
	1985	0.236	0.246	0.401
Elec. Products (36)	1965	0.237	0.220	0.251
	1975	0.178	0.145	0.179
	1985	0.181	0.267	0.313
Transport. Equip. (37)	1965	0.232	0.201	0.267
	1975	0.224	0.180	0.262
	1985	0.257	0.234	0.350
Scient. Instrum. (38)	1965	0.188	0.194	1.323
	1975	0.242	0.286	1.113
	1985	0.281	0.281	0.865

affected by a distinct set of R&D sources and each sending industry
affected a unique set of receivers. Among the spillover recipients both
product demand and production characteristics were affected by R&D
spillovers. Spillovers caused output (or product market size) to
increase, which in turn, caused product price to fall, production cost and
input demands to increase. Among the spillover sources, although private
rates of return (net of depreciation and before tax) to physical and R&D
capital were not dissimilar, R&D spillovers caused the social returns to
be significantly greater than the private returns to R&D capital.

There are a number of further areas of research with respect to R&D
spillovers. First, R&D spillovers could be an important source of the
international transmission of knowledge. International spillovers could
increase the rate of knowledge diffusion among trading partners, such as
the U.S. and Japan. Second, R&D spillovers can be an important source of
knowledge transmission between nonmarket organizations, such as
universities and industrial organizations. R&D spillover links between
the two types of organizations could be important contributors to the
social rates of return to R&D capital in the economy.

NOTES

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1. There are other public goods which give rise to similar externalities as
R&D capital. For example, roads, bridges and airports have some of the
same type of characteristics as R&D capital.

2. Spillovers that affect product demand are like quality changes. Quality
improvements associated with some products can decrease demand for other
products. These quality changes are based on the accumulation of R&D
investment.

3. Variable factors only generate hiring costs, while the capital inputs (or
quasi-fixed factors) generate user and adjustment costs. The adjustment
costs are reflected by the net investment vector in the domain of the
variable cost function. Given output, capital inputs and spillovers, an
increase in net investment causes variable cost to rise (see Morrison and
Berndt [1981] and Mohnen, Nadiri and Prucha [1986]). Although a single
output is assumed, the model can be generalized to multiple outputs. The
subscript t represents the time period.

4. In general the normalized variable cost function is nondecreasing,

homogeneous of degree zero and concave in the variable factor prices, (the
non-normalized variable cost function is homogeneous of degree one in
variable factor prices) nondecreasing in output, nonincreasing and convex
in non-R&D capital inputs and nondecreasing and convex in non-R&D net
investments. There are few restrictions associated with output and own
R&D capital because these variables also affect product price and hence
revenue. The production process summarized by equation (1) is not
restricted to exhibit constant returns to scale.

5. The reduction of variable cost due to spillovers is a manifestation of
   free disposability in production. If spillovers increase cost then
   producers have the option of not using them in their production process as
   spillovers can be costlessly disposed.

6. It is assumed that capital services are proportional to the capital
   stocks.

7. The inverse product demand function is nonincreasing in output and
   nondecreasing in own R&D capital. Product demand is specified in terms of
   a function directly rather than derived from a utility function because
   not all customers facing the producers are consumers.

8. More general functional forms for the inverse product demand function were
   used in the estimation of the model but they failed to improve the
   results.

9. There are n-1 variable factor demand equations because the nth variable
   factor equation is linearly dependent on the first n-1 equations $(\sum_{i=1}^{n} \omega_{is} v_{is}/c_s^v = 1)$.

10. Variable cost flexibility is the output elasticity of variable cost (see

Jorgenson [1986]).

11. The R&D components of labor and intermediate inputs were substracted from their respective categories, in order that there would not be any double counting among the factors of production which include R&D expenditures.

12. Previous work showed that estimation results are not affected by depreciation rates between 8% and 12%.

13. The subscript k referring to the parameters pertaining to the capital inputs are now subscripted with p for physical capital and r for R&D capital.

14. The negative impact effect means that spillovers reduce variable cost, given output, physical and R&D capital inputs.

15. For the chemical products industry the only spillover parameters were β_{38} and α_{38} (see Table A1). Moreover, the null hypothesis that $\beta_{38} + \alpha_{38} = 0$ is not rejected. Thus by equations (8.1) and (8.2) variable cost reduction offsets product price increase.

16. The intermediate input demand effect can be derived from the spillover elasticity of labor demand since the former is the residual variable factor.

17. Equation (10) is just another way of writing the equilibrium conditions for the capital inputs. Indeed, ρ_{ks} is defined as the before tax expected marginal benefit of the kth capital, net of depreciation per dollar of the kth capital stock.

A P P E N D I X

TABLE A1: Estimation Results

Parameter	Chemical Products (28)		Fabricated Metal (34)	
	Estimate	Std. Error	Estimate	Std. Error
β_0	5.190	3.485	-10.451	2.574
β_1	1.606	0.121	0.392	0.863E-01
β_y	0.832	0.342	1.753	0.212
β_p	0.799	0.199	0.715	0.188
β_r	-1.528	0.259	0.625	0.210
β_{1y}	0.271E-01	0.237E-01	0.386E-01	0.842E-02
β_{1p}	-0.119	0.202E-01	-0.455E-01	0.473E-02
β_{1r}	-0.219E-01	0.608E-02	0.290E-02	0.200E-02
β_{yp}	-0.975E-01	0.168E-01	-0.311E-01	0.146E-01
β_{yr}	0.134	0.250E-01	-0.436E-01	0.177E-01
β_{pr}	0.389E-02	0.112E-01	-0.502E-02	0.694E-03
μ_{pp}	0.377E-05	0.452E-06	0.243E-04	0.319E-05
μ_{rr}	0.313E-05	0.582E-06	0.492E-05	0.286E-05
μ_{pr}	0.880E-06	0.104E-06	0.730E-06	0.107E-06
β_{1s}				
β_{ys}				
β_{ps}			-1.841	0.171
β_{28}				
β_{34}				
β_{35}				
β_{36}				
β_{37}			0.210E-01	0.419E-02
β_{38}	-0.445E-02	0.166E-02		
α_0	8.620	0.726	-4.822	2.398
α_y	-0.886	0.102	0.589	0.230
α_r	-1.142	0.180	0.426	0.167
α_i	-1.142	0.180	0.225	0.298
α_{yr}	0.107	0.149E-01	-0.384E-01	0.147E-01
α_{yi}	0.973E-01	0.160E-01	-0.299E-02	0.249E-01
α_{ri}	0.100E-01	0.863E-02	-0.683E-02	0.212E-02
α_{ys}			-1.248	0.147
α_{28}	.			
α_{34}				
α_{35}				
α_{36}				
α_{37}			0.261E-01	0.415E-02
α_{38}	0.445E-02	0.166E-02		

Equation	Std. Error	Correlation Sq.	Std. Error	Correlation Sq.
Inverse Demand	0.671E-01	0.982	0.366E-01	0.992
Variable Cost	0.604E-01	0.996	0.163E-01	0.999
Labor Share	0.214E-01	0.753	0.894E-02	0.909
Ouput Quantity	0.786E-01	0.966	0.118E-01	0.968
Physical Capital	0.315E-01	0.728	0.278E-01	0.529
R&D Capital	0.689E-02	0.802	0.689E-03	0.741

TABLE A1 (cont'd)

Parameter	Nonelectrical Machinery (35)		Electrical Products (36)	
	Estimate	Std. Error	Estimate	Std. Error
β_0	-6.391	3.696	-7.782	1.327
β_1	1.143	0.938E-01	0.401	0.991E-01
β_y	1.886	0.363	0.881	0.228E-01
β_p	-0.398E-02	0.721E-01	0.960	0.131
β_r	0.869	0.333	1.038	0.113
β_{ly}	0.117	0.991	-0.104	0.156E-01
β_{lp}	-0.154	0.118E-01	-0.199E-01	0.119E-01
β_{lr}	-0.344E-01	0.730E-02	0.131	0.177E-01
β_{yp}	-0.111E-01	0.445E-02		
β_{yr}	-0.768E-01	0.281E-01		
β_{pr}	0.282E-02	0.406E-02	-0.981E-01	0.117E-01
μ_{pp}	0.839E-05	0.158E-05	0.139E-05	0.464E-06
μ_{rr}	0.202E-05	0.332E-06	0.228E-05	0.380E-06
μ_{pr}	0.157E-05	0.819E-06	-0.277E-06	0.170E-06
β_{ls}				
β_{ys}	-1.338	0.164		
β_{ps}				
β_{28}	0.223E-01	0.316E-02		
β_{34}				
β_{35}				
β_{36}				
β_{37}	0.223E-01	0.316E-02		
β_{38}			-0.103E-01	0.172E-02
α_0	-1.784	2.923	1.403	0.231
α_y	0.224	0.296	-0.326	0.105
α_r	0.447	0.267	0.266	0.276E-01
α_i			-0.326	0.105
α_{yr}	-0.384E-01	0.227E-01	-0.729E-03	0.603E-02
α_{yi}	0.481E-02	0.479E-02	0.729E-03	0.603E-02
α_{ri}	-0.481E-02	0.479E-02	0.363E-01	0.134E-01
α_{ys}	-1.101	0.132		
α_{28}	0.235E-01	0.240E-02		
α_{34}				
α_{35}				
α_{36}				
α_{37}	0.235E-01	0.240E-02		
α_{38}			-0.559E-02	0.124E-02

Equation	Std. Error	Correlation Sq.	Std. Error	Correlation Sq.
Inverse Demand	0.979E-01	0.914	0.328E-01	0.990
Variable Cost	0.865E-01	0.971	0.434E-01	0.997
Labor Share	0.204E-01	0.817	0.128E-01	0.948
Output Quantity	0.228E-01	0.996	0.483E-01	0.990
Physical Capital	0.253E-01	0.854	0.265E-01	0.742
R&D Capital	0.970E-02	0.958	0.157E-01	0.812

TABLE A1 (cont'd)

Parameter	Transportation Equipment (37)* Estimate	Std. Error	Scientific Instrument (38) Estimate	Std. Error
β_0	50.645	6.620	1.426	0.671
β_1	0.549	0.221	1.420	0.613E-01
β_y	-2.908	0.643	0.182	0.932E-01
β_p	-0.525E-01	0.169	0.374	0.655E-01
β_r	-4.441	0.446	0.679	0.719E-01
β_{1y}	0.182	0.294E-01	-0.131	0.204E-01
β_{1p}	-0.978E-01	0.182E-01	0.151E-01	0.198E-01
β_{1r}	0.108	0.107E-01	0.293E-01	0.159E-01
β_{yp}	-0.242E-01	0.168E-01	0.342E-01	0.607E-02
β_{yr}	0.360	0.435E-01	0.361E-01	0.599E-02
β_{pr}	0.182E-01	0.121E-01	-0.851E-01	0.666E-02
μ_{pp}	0.461E-06	0.666E-07	0.170E-04	0.339E-05
μ_{rr}	0.161E-06	0.811E-07	0.188E-04	0.345E-05
μ_{pr}	0.366E-06	0.451E-07	0.934E-05	0.280E-05
β_{1s}				
β_{ys}				
β_{ps}				
β_{2s}			-0.754E-02	0.110E-02
β_{34}				
β_{35}	-0.915E-02	0.177E-02		
β_{36}			-0.754E-02	0.110E-02
β_{37}			-0.754E-02	0.110E-02
β_{38}				
α_0	20.641	2.491	1.108	0.101
α_y	-2.204	0.243	-0.152	0.252E-01
α_r	-2.026	0.364	0.152	0.252E-01
α_1	-2.204	0.243		
α_{yr}	0.223	0.277E-01	-0.157E-01	0.117E-02
α_{yi}	0.126	0.196E-01	0.157E-01	0.117E-02
α_{ri}	0.930E-01	0.162E-01		
α_{ys}				
α_{2s}			0.264E-02	0.622E-03
α_{34}				
α_{35}	-0.388E-02	0.331E-02		
α_{36}			0.264E-02	0.622E-03
α_{37}			0.264E-02	0.622E-03
α_{38}				

Equation	Std. Error	Correlation Sq.	Std. Error	Correlation Sq.
Inverse Demand	0.710E-01	0.980	0.394E-01	0.991
Variable Cost	0.597E-01	0.994	0.317E-01	0.999
Labor Share	0.285E-01	0.603	0.141E-01	0.934
Output Quantity	0.112	0.980	0.392E-01	0.993
Physical Capital	0.263E-01	0.631	0.114E-01	0.939
R&D Capital	0.182E-01	0.621	0.135E-01	0.920

*Dummy variables, defined on β_0, β_p, equal 1 from 1981 to 1985 and 0 otherwise to reflect the recession; β_{0d} = 0.475 (0.577E-01). β_{pd} = -0.369(0.468E-02)

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