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Rates of Return on Physical and R&D Capital and Structure of the Production Process: Cross Section and Time Series Evidence

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ABSTRACT

R&D investment is an outcome of a corporate plan and is influenced by the existing technology, by prices, by product demand characteristics, and by the legacy of past capital stock decisions. In this paper we focus on the determinants and interaction of labor, physical capital and R&D.

In particular, we investigate three major issues. The first relates to the nature of the factor substitution possibilities between the three inputs in response to changes in input prices and estimate the own and cross price elasticities of the factors of production. The second problem pertains to the magnitude by which output expansion (or what may be considered the same thing, product demand growth) increases labor, physical, and R&D capital. Finally, we address the extent to which adjustment costs affect factor demands, and measure the magnitude of these costs for physical and R&D capital.

1. Introduction*

It is by now a well established empirical result that research and development (R&D) is a significant element in productivity growth (see Nadiri [1980], Griliches [1980], Terleckyj [1974], and Mansfield [1968]). However, R&D investment is itself an outcome of a corporate plan. This investment is influenced by the existing technology, by prices, by product demand characteristics, and by the legacy of past capital accumulation decisions. In this paper we want to investigate the influences on R&D investment, and how these effects elicit an interaction with the other factors of production. In particular, we focus on the determinants and interaction of labor, physical and R&D capital.

There are essentially three major problems which are dealt with in this paper. The first relates to the nature of the factor substitution possibilities between the three inputs. Specifically, we want to know how labor and physical capital respond to changes in the factor price of R&D capital, and how, in turn, R&D capital is affected by changes in its own price, as well as the wage rate and rental rate on physical capital. The second problem pertains to the output expansion possibilities. In particular, we investigate the magnitude by which output expansion (or what may be considered the same thing, product demand growth) increases labor, physical, and R&D capital.

The last general problem relates directly to the dynamics of the model. Certain factors of production are costly to adjust, and therefore it takes time for the firm to adopt its long run factor requirement. It is these costs of adjustment which render the model dynamic. Generally, it is acknowledged that increases in the level of physical capital involve adjustment costs, so that it is quasi-fixed, while labor may be considered a variable input (sometimes labor is disaggregated into skilled and unskilled, the latter is variable and the former is quasi-fixed). In the present context R&D capital is also modeled as a quasi-fixed factor, because of the significant development costs incurred in this investment process. We estimate the extent to which adjustment costs affect factor demands, and measure the magnitude of these costs for physical and R&D capital.

An important but unresolved issue addressed relates to the substantial difference between the rates of return on physical and R&D capital reported in the literature. Previous empirical work (see Griliches [1980], Minasian [1969], and Mansfield [1965]) has found, and left unexplained, the result that the marginal value of R&D (measured for example by the marginal product) exceeds both the marginal value of physical capital, and the interest rate. In this paper, we show that these conclusions are the outcome of the existence of adjustment costs. The marginal value of R&D is greater than the opportunity cost of funds (i.e. the interest rate) because the former must be sufficiently large to cover the marginal costs of adjustment. Moreover, the reason that the marginal value of R&D exceeds the value for physical capital is due to the fact that the marginal adjustment costs associated with R&D are greater than the costs for physical capital. This implies that the deviation between the marginal value of R&D

and the interest rate is greater than the difference between the marginal value of physical capital and the interest rate.

Sections 2 and 3 of the paper detail the theoretical model and its specification for estimation. The data, industry characteristics and estimates are discussed in sections 4 and 5. The results concerning factor substitution, output expansion and costs of adjustment are analyzed in sections 6, 7, and 8. A summary of our findings is contained in the last section.

2. The Theoretical Model

Consider the production process of a firm which can be described by

$$(1) \quad y(t) = F\left(K_p(t-1),\ K_r(t-1),\ L(t),\ \Delta K_p(t),\ \Delta K_r(t)\right)$$

where $y(t)$ is output in period t, F is the twice continuously differentiable concave production function, $K_p(t-1)$ is the physical capital input at the beginning of period t, $K_r(t-1)$ is the R&D or knowledge capital input at the beginning of period t, $L(t)$ is the labor input in period t, $\Delta K_p(t) = K_p(t) - K_p(t-1)$, $\Delta K_r(t) = K_r(t) - K_r(t-1)$. The marginal products are positive and diminishing, $F_i > 0$, $F_{ii} < 0$ for $i=p,r,\ell$ and adjustment costs associated with $\Delta K_p(t)$ and $\Delta K_r(t)$ are internal with $F_j < 0$, $F_{jj} < 0$ $j=e,d$. Following Treadway [1971], [1974], Mortenson [1973], Meese [1980], and Morrison and Berndt [1981] we assume that the quasi-fixed factors $\left(K_p(t)\right.$ and $\left.K_r(t)\right)$ are subject to increasing internal costs of adjustment. In other words, as purchases of additional units of each quasi-fixed input occur, the quantity of foregone output rises. This implies that the average cost of investment increases in response to physical and knowledge capital accumulation.

The two quasi-fixed factors accumulate by

$$(2) \quad K_i(t) = I_i(t) + (1-\delta_i)\, K_i(t-1), \qquad i=p,r$$

where $I_i(t)$ is gross investment in period t and δ_i is the fixed depreciation rate. The work of Pakes and Schankerman [1978] has shown that knowledge capital depreciates like physical capital. Moreover, they found that the depreciation rate on the former is the higher of the two rates.

We assume that the firm is a price taker in all markets, so that the flow of funds can be written as

$$(3) \quad V(t) = p(t)y(t) - w(t)L(t) - p_p(t)I_p(t) - p_r(t)I_r(t),$$

where V(t) is the flow of funds, p(t) is the product price, w(t) is the wage, $p_p(t)$ is the P&E investment price and $p_r(t)$ is the R&D investment price in period t.

In order for the firm to maximize its expected present value of the flow of funds, it must minimize the expected discounted value of its costs. Thus at time t the firm chooses a plan which minimizes

$$(4) \quad J(t) = E_t \sum_{\psi=t}^{\infty} \alpha(t,\psi)\ [w(\psi)L(\psi) + p_p(\psi)I_p(\psi) + p_r(\psi)I(\psi)]$$

where E_t is the conditional expectation operator and $\alpha(t,\psi)$ is the discount factor applied at date t for cost incurred at date ψ. The program for the firm can be summarized in the following manner. The firm minimizes the expected discounted costs by selecting the labor requirements, and investment in R&D and physical capital subject to the production technology, capital accumulation conditions, and expectations regarding prices and the quantity of output. The conditional expectation operator is taken over all future values of the wage rate, the prices of R&D and physical capital investment and output.

The optimizing program can be solved by inverting the production function to obtain the labor requirments function,

$$(5) \quad L(t) = G\big(K_p(t-1),\ K_r(t-1),\ \Delta K_p(t),\ \Delta K_r(t),\ y(t)\big)$$

with $G_i < 0$ $i=p,r$, $G_j > 0$ $j=e,d$ and $G_y > 0$. By substituting (2) and (5) into (4), we can observe that the firm's intertemporal expected cost minimization problem involves the optimal selection of knowledge and physical capital. The first order conditions are,

$$(6.1) \quad E_t[w(t)G_e + p_p(t) + \alpha(t,t+1)\big(w(t+1)\ (G_p - G_e) - p_p(t+1)\ (1-\delta_p)\big)] = 0$$

$$(6.2) \quad E_t[w(t)G_d + p_r(t) + \alpha(t,t+1)\big(w(t+1)\ (G_r - G_d) - p_r(t+1)\ (1-\delta_r)\big)] = 0.$$

These equations illustrate that the net change in expected discounted costs, from purchasing an additional unit of a stock at date t, is zero. The net change consists of the marginal adjustment costs plus the purchase price, minus the future savings in adjustment costs, purchase costs, and variable (i.e. labor) costs from having larger stocks of physical capital and R&D in the present.

3. Model Specification

The estimating equations consist of the inverted production function, as well as the first order conditions (6.1) and (6.2). Since (6.1) and (6.2) are derived relations, in order to render the model estimable, we only have to specify the labor requirments function and the nature of the error terms. The former is assumed to be

$$(7)\quad L(t)/y(t) = \alpha_o + \alpha_y\, y(t) + \sum_{i=p}^{r} \alpha_i \left(K_i(t)/y(t)\right) + \frac{1}{2}\alpha_{yy}\, y^2(t) + \frac{1}{2}\sum_{i=p}^{r} \alpha_{ii} \left(K_i(t)/y(t)\right)^2 + \frac{1}{2}\alpha_{ee}\, (\Delta K_p(t)/y(t))^2 + \frac{1}{2}\alpha_{dd} \left(\Delta K_r(t)/y(t)\right)^2 + \sum_{i=p}^{r} \alpha_{yi}\, K_i(t-1) + \alpha_{pr}\, K_p(t-1)\, K_r(t-1)/y^2(t)$$

We have selected a linear-quadratic labor-output requirements function, which is a second order approximation to any arbitrary labor-output function. Note that we have not imposed any restrictions on the degree of returns to scale. In addition, because there is only a single variable factor of production, equation (7) is equivalent to specifying the average variable cost function for the firm. Lastly, incorporated into (7) is the reasonable condition that marginal costs of adjustment are zero at $\Delta K_p(t) = \Delta K_r(t) = 0$. This has the effect of making the adjustment costs internal, but separable from the output production process.[1]

Given equation (7), the first order conditions (6.1) and (6.2) become,

$$(8.1)\quad w(t)[\alpha_{ee}\,\Delta\left(K_p(t)/y(t)\right)]$$
$$+\,p_p(t) + E_t\,\alpha(t,t+1)\,[w(t+1)\,(\alpha_p + \alpha_{pp}\left(K_p(t)/y(t)\right)$$
$$-\,\alpha_{ee}\left(\Delta K_p(t+1)/y(t)\right) + \alpha_{yp}\,y(t+1) + \alpha_{pr}\left(K_r(t)/y(t)\right)$$
$$-\,p_p(t+1)\,(1-\delta_p)] = 0$$

$$(8.2)\quad w(t)[\alpha_{dd}\left(\Delta K_r(t)/y(t)\right)]$$
$$+\,p_r(t) + E_t\alpha(t,t+1)\,[w(t+1)\,(\alpha_r + \alpha_{rr}\left(K_r(t)/y(t)\right)$$
$$-\,\alpha_{dd}\left(\Delta K_r(t+1)/y(t)\right) + \alpha_{yr}\,y(t+1) + \alpha_{pr}\left(K_p(t)/y(t)\right)$$
$$-\,p_r(t+1)\,(1-\delta_r)] = 0$$

Our basic model consists of equations (7), (8.1) and (8.2). We can observe that equations (8.1) and (8.2) are simultaneous, and that the overall system is nonlinear in the variables.

To obtain parameter values for equation set (7), (8.1), and (8.2), we must consider the nature of the error terms in each of these equations. The first order conditions describe the expected effects on costs from adding physical and R&D capital stocks. Moreover, these expectations are conditional on all information available to the firm at the date the investment decisions are made. Thus the errors in (8.1) and (8.2) represent unanticipated information (i.e. surprises) which become available at date t, and therefore their conditional expected values are zero. The error associated with the labor requirements function represents technological shocks which illustrate the randomness in the production process.[2] The conditional expectation of the labor requirements function is viewed as holding on a conditioning set of instrumental variables which only contain lagged variables. In this context, it is possible to employ the results of Hansen and Singleton [1982] and Hansen [1982] who developed a generalized method of moments estimator. Moreover, as shown by Pindyck and Rotemberg [1982(a)], when the error terms are conditionally homoscedastic, the estimator is equivalent to the nonlinear three-stage estimator as developed by Jorgenson and Laffont [1974] and Amemiya [1977].

4. The Data and Industry Characteristics

The sample consists of a set of firms grouped into four two-digit SIC industry classifications. Within SIC 20 (foods) there are five firms, there are nine firms within SIC 28 (chemicals), for SIC 33 (primary metals) we have seven firms, and finally for SIC 35 (nonelectrical machinery) there are fourteen firms. The word "industry" in this paper refers to a specific set of firms in each classification. The selection of firms was dictated by the availability of consistent time series data on R&D and physical capital (or plant and equipment) expenditures. The time period ranges from 1959-1966. Thus we have a sample of time series and cross section data which were pooled in order to provide a richer set of information in which to estimate the model under consideration.

The list of variables and their construction are: Plant and equipment (P&E) capital input (K_p) is the measure of net stock generated by the declining balance depreciation formula

$$K_p(t) = I_p(t) + (1-\delta_p)\ K_p(t-1)$$

where $I_p(t)$ equals actual expenditures on P&E deflated by its price. Investment in P&E was obtained from the Standard & Poors tapes. The investment deflator (p_p) is obtained from the President's Economic Report, 1980. The depreciation rate for each firm was calculated by summing over time depreciation allowances divided by the gross plant and equipment and then dividing this sum by the number of time periods. The R&D capital input (K_r) was obtained from a similar procedure,

$$K_r(t) = I_r(t) + (1-\delta_r)\ K_r(t-1).$$

Investment in R&D (I_r) and its associated price (p_r) were obtained from Standard & Poors data series, and we arbitrarily chose $\delta_r = .1$ to measure the depreciation rate for the stock of knowledge. The labor input (L) is defined as the labor expense, from the Standard & Poors tape, divided by the wage rate (w). The latter variable was obtained from the Bureau of Labor Statistics. Output (y) is defined as sales, obtained from the Standard & Poors data, divided by the producer price index (p). The price variable comes from the Bureau of Labor Statistics. Finally, the one period discount rate $(\alpha(t,t+1) = 1/(1+r(t)))$ is measured as the corporate bond rate (Aaa). This variable was obtained from the President's Economic Report, 1980.

Table 1 presents the means and standard deviations of the main variables for each industry used in the model between 1959 and 1966. Defining variable intensities in terms of output, we see an interesting set of cross industry patterns emerging. The food industry has the lowest intensity in all three input variables, while the chemical industry has the highest. Although primary metals and chemicals exhibit the same physical capital to output ratio, the standard deviation for the latter is substantially smaller. Primary metals exhibits a physical capital intensity which is slightly more than twice that for nonelectrical machinery. Moreover, the R&D intensity for the latter industry is slightly below double that for primary metals. Since the labor intensities (and their standard deviations) are the same it will be of interest to compare the results obtained for each of these two industries.

The physical capital intensity illustrates that there are two classes of "industries", the "highs" (chemicals and primary metals) and the "lows" (food and nonelectrical machinery). However, the R&D intensity variable shows that there is roughly an equal spread among the four industries. The R&D intensity of primary metals is approximately twice that for foods. Nonelectrical machinery is nearly double the value of primary metals, while chemicals is almost twice the magnitude for nonelectrical machinery. Finally, the labor intensity illustrates that three out of the four industries exhibit the same magnitude, while foods is substantially smaller.

5. The Estimates

In this section we describe the empirical estimates obtained from equations (7), (8.1) and (8.2). First, we pooled all four industries to obtain the aggregate results presented in Table 2. In estimating the pooled data we introduced industry dummy variables in the zero and first order terms. Therefore, the constants in the derived equations ((8.1) and (8.2)) are also industry specific. Overall the fit is good, as the R^2's are high in all three equations. Most of the estimates are significant, and all have the correct sign. In particular, as output increases, according to the first and second order parameters, labor intensity (or average variable costs) increases ($\alpha_y > 0$, $\alpha_{yy} > 0$). Holding output fixed, the first order terms show that as physical and R&D capital intensity rise the labor intensity falls ($\alpha_p < 0$, $\alpha_r < 0$). The second order conditions are satisfied as $\alpha_{pp} > 0$, $\alpha_{rr} > 0$ and $\alpha_{pp}\,\alpha_{rr} - \alpha_{pr}^2 > 0$. Finally the cost of adjustment coefficients are positive ($\alpha_{ee} > 0$, $\alpha_{dd} > 0$) and the physical capital parameter is significant. Thus physical capital is in fact a quasi-fixed factor of production. The troublesome aspect is that the adjustment parameter for R&D is insignificant.[3] This result can arise for essentially two reasons; either on average for the four industries, and over the period 1959-1966, R&D capital is a variable factor of production, or else there are more industry-specific variations than have been presently allowed for in the model. In other words, not only are the zero and first order parameters different across industries, but the second order coefficients also vary. Adopting this second view, we estimate the model for each industry.

Tables 3-6 illustrate the estimates for foods, chemicals, primary metals and nonelectrical machinery. In all of the industries the model fits the data quite well, most of the variables are significant, all of them have the correct sign, and, in particular, the second order conditions are satisfied.[4] The cost of adjustment estimate of physical capital is significantly different from zero at the 99% level of confidence for three out of the four industries. Only for the food industry is the coefficient marginally insignificant at the 90% level of confidence.

Since the R&D cost of adjustment estimate was insignificant in the industry-pooled model, it is of interest to see if the industry-specific estimates are different from the former. This test is one way of determining whether or not there was sufficient allowance for industry variation in the industry-pooled model. These results are presented in Table 7. Clearly, the industry-specific estimates of the cost of adjustment parameter are significantly different from the industry-pooled magnitude. In three out of the four industries the estimate of α_{dd} is significantly different from the industry-pooled estimate at the 99% level of confidence, while in the last industry (nonelectrical machinery) the test is marginally rejected at the 90% level. However, in this latter industry, although the coefficient is small, it is significantly different from zero at the 99% level of confidence. Hence R&D capital is a quasi-fixed factor of production, which implies that there are signifiant costs to develop knowledge.

6. Price Elasticities of Factor Demands

There are two sets of price elasticities which are relevant to the present model. The first group relates to the situation when both quasi-fixed factors have adjusted to their long run magnitudes. Under these circumstances $\Delta K_p(t) = \Delta K_r(t) = 0$, and all prices, output and the interest rate have adjusted to their stationary values. Consequently equations (8.1) and (8.2) become

$$(9)\quad \alpha_{ii}K_i/y + \alpha_i + \omega_i + \alpha_{yi} + \alpha_{pr}K_j/y = 0 \qquad i=p,r \quad i\neq j,$$

where $\omega_i = p_i\ (r + \delta_i)/w$ $i=p,r$ is the wage normalized rental price for the ith quasi-fixed factor. From equation set (9) which is a simulataneous system, equation (7) (with $\Delta K_p(t) = \Delta K_r(t) = 0$) and using the estimates from Tables 3 to 6, all the long run price elasticities can be computed. These results are presented in Table 8.

We can observe from this table that for the various industries there is a great deal of similarity with respect to the signs and magnitudes of the factor price elasticties. The own price elasticities of both quasi-fixed factors are negative and similar in value to each other, and across the four industries. Roughly an increase of 1% in the rental price of one of the quasi-fixed factors leads to a .5% decrease in its demand. Next we see that physical and knowledge capital are complements in each industry. However, the degree of complementarity is not symmetric across industries. In foods and chemicals, changes in the R&D rental price exerts greater downward pressure on the demand for physical capital, relative to a change in the physical capital rental rate on the demand for R&D capital. The converse is true for primary metals and nonelectrical machinery products. Our interest in emphasizing the role of R&D as an endogenous input decision, which entails substantial development costs, has enabled us to show that there are significant own and cross price elasticity effects. These are usually neglected in treatments of R&D.[5]

Changes in the wage rate illustrate that both quasi-fixed factors are substitutes for labor, with the degree of substitution roughly the same order of magnitude for P&E and R&D capital. Only in the food industry, with the physical capital intensity of output more than twice as high as the R&D intensity and with the lowest labor-output ratio, is physical capital a significantly greater substitute for labor compared to R&D.

Finally, we can observe that for each industry, and for each factor demand, changes in the wage rate elicit (in absolute value) the greatest response. This, of course, occurs because physical and R&D capital are complements, while each type of capital is a substitute for labor. Therefore, the results point out the importance of unit labor costs in the production process, and how changes in these costs cause significant modifications in the factor magnitudes, both in absolute and relative terms.

It is often difficult to relate particular estimates to other research, because of differences in model specification and data. However, if we look at the cost of adjustment models using aggregate data with at least two quasi-fixed factors where labor and physical capital were decomposed (e.g. into skilled and unskilled for labor), the own price elasticity of physical capital tends to be around -.5 (see, for example, Morrison and Berndt [1981] and Pindyck and Rotemberg [1982(b)]. This result is similar to our findings at the industry level.[6] In other models where there is a single quasi-fixed factor or where labor and physical capital were not decomposed, the elasticity was approximately -.2 (besides the previously cited two papers see Epstein and Denny [1983]).

We have already noted that there are few studies which have investigated the price effects on R&D, and especially in the cost of adjustment framework. Finally with respect to the own price elasticity of labor demand, the estimates seem to vary (see Hamermesh [1976] for a survey of the pre-cost of adjustment literature). What appears to be consistent, though, is that the wage elasticity of labor demand is greater in absolute value to the own price elasticity of physical capital.[7]

Up to this juncture, we have calculated the factor price elasticities when both quasi-fixed factors have adjusted to their long-run magnitudes. Now let us suppose only one of the quasi-fixed factors has adjusted. This second set of experiments recognizes that there may be differential speeds of adjustment in the quasi-fixed factors. These elasticities may be termed intermediate-run.[8]

The intermediate-run elasticities are presented in Table 9. The most striking conclusions are that the intermediate-run own price elasticities for each type of capital are similar to the long-run magnitudes, and the own and cross wage elasticities are significantly smaller (in absolute value) compared to the long-run. The first conclusion strengthens the fact that factor prices influence R&D, as well as P&E capital. In particular, even if physical capital has not adjusted to its long-run level, a 1% increase in the R&D rental price decreases its demand by .5%. The same is true for physcial capital. The second conclusion appears to arise from the fact that in the long-run both quasi-fixed factors are substitutes for labor. In the intermediate-run only one of these inputs is able to adjust to the higher wage, so the degree of substitution for labor is smaller, and consequently the intermediate-run own price elasticity of labor demand is smaller in absolute value.

7. Output Elasticities and the Returns to Scale

Since output is exogenous, we can calculate short, intermediate and long-run output elasticities of factor demands. Table 10 contains these elasticities. With respect to labor, we can observe that for each industry there is a decline in output elasticity from the short to the long-run. In the short-run only labor is variable. Hence in response to an increase in demand for its product the firm must produce the additional output by increasing more than proportionately its demand for labor. As R&D and physical capital adjust, given the higher level of product demand, the firm increases its demand for the quasi-fixed factors and reduces the use of the variable factor of production. This result occurs because as each quasi-fixed factor increases, the demand for labor decreases. This is just another way of stating that P&E and R&D capital are substitutes for labor. Therefore in each industry we find that overshooting occurs for labor.

This finding is consistent with Morrison and Berndt [1981], where unskilled labor is a variable factor of production whose short-run output elasticity is 1.349, and because they impose constant returns to scale, the long-run elasticity is 1. The long-run output elasticity is roughly consistent with those surveyed in Hamermesh [1976], and in Pindyck and Rotemberg [1982(a), 1982(b)], although our short run elasticities are quite different. Another result from the model is that the output elasticity of labor is affected when at least one of the quasi-fixed factors (but not necessarily both) adjusts to its long run level. In other words, for each industry there is virtually no difference between the intermediate and long-run output elasticities of labor. All that is needed to dissipate labor overshooting is the adjustment of at least one of the quasi-fixed factors.

The output elasticities of the physical and R&D capital stocks are quite similar both for the different industries and for the intermediate and long-runs. It is also interesting to compare Tables 8 and 9 to 10. We see that output increases (or product demand growth) exert a larger effect on input demands compared to any individual price change (in absolute value). This suggests, in particular, that policies which spur product demand growth may cause more R&D and physical capital investment to be initiated than policies (such as specific tax allowances) which lower the rental rates.

Although we have not restricted the technologies to exhibit constant returns to scale, we can observe, from the long run output elasticities, that the returns to scale is not significantly different from unity.[9] In fact we can compute the returns to scale for each industry. In order to undertake this calculation, consider any general specification of the technology,

$$(10) \quad T(\ell n\ L, \ell n\ K_p, \ell n\ K_r, \ell n\ y) = 1,$$

where T is the transformation function defined over the natural logarithms of the inputs and output. The definition of returns to scale, which is the proportional increase in output resulting from the common proportional increase in all inputs, means that we need

$$(11) \quad T_L d\ell n\ L + T_p d\ell n\ K_p + T_r d\ell n\ K_r + T_y d\ell n\ y = 0.$$

Assuming $d\ell n\ L = d\ell n\ K_p = d\ell n\ K_r = d\ell n\ v$ then (11) becomes

$$(12) \quad \frac{d\ell n\ y}{d\ell n\ v} = -\ [T_L + T_p + T_r]/T_y$$

which is the measure of returns to scale.

We can represent the technology from (10) in terms of a labor requirements function defined over the natural logarithms of the inputs and output. Since the firm minimizes costs, and because there is a single variable factor of production, the labor requirements function is equivalent to the variable cost function. Let,

$$(13) \quad \ell n\ L = H(\ell n\ K_p,\ \ell n\ K_r,\ \ell n\ y)$$

and then the right side of (12) becomes

$$(14) \quad \frac{d\ell n\ y}{d\ell n\ v} = [1 - (H_p + H_r)]/H_y.$$

Equation (14) permits us to compute the returns to scale in terms of the specified labor requirements function, upon which our estimates are based.

The results are presented in Table 11. For each industry, we show the three short run elasticities for labor demand, which are necessary for the calculation (which correspond to H_y, H_p and H_r in equation (14)). The first row repeats the output elasticity found in the first row of Table 10. The second and third rows represent respectively short run elasticity of labor demand with respect to the physical and R&D capital inputs. If we were to picture these elasticities they would represent the curvature of the isoquant between labor and one of the quasi-fixed factors, holding the other capital input and output fixed. There are some interesting features of these measures. First, as expected, they are all negative, so labor and the quasi-fixed factors are short run substitutes. Second, in each case labor and physical capital are stronger substitutes in the short run than labor and R&D capital. Although in the nonelectrical machinery industry, there is only a minor difference. The only other study we are aware of which has looked at elasticities between factor demands is Nadiri-Bitros [1980]. They found, for the largest firms in their sample, a ranking of the degrees of substitution which is similar to ours, with $e^S_{\ell p} = -.3430$ and $e^S_{\ell r} = -.0386$. Indeed the physical capital elasticity of labor demand is strikingly close to the average of our industry measures, but our elasticity for R&D capital is substantially greater in absolute value.

The third result from Table 11 is that for the industry with the lowest factor intensities of output (SIC 20, foods) and the industry with the highest intensities (SIC 28, chemicals) the P&E elasticity is nearly twice as large as the R&D elasticity. It seems that it is not the absolute magnitude of the input intensities which matters, but rather the relative difference beween the capital intensities of output. This can be seen from the fact that the greatest difference between the physical and R&D capital intensities of output is found in SIC 33 (primary metals). Table 11 shows that this industry exhibits the greatest difference in quasi-fixed factor short run elasticities of labor. Moreover, the industry with the smallest difference in the capital input intenstities of output is SIC 35 (nonelectrical machinery), and here we observe very little difference in the degree of substitution between physical capital and R&D for labor.

The final row in Table 11 illustrates the returns to scale. Each industry does not significantly depart from constant returns to scale, but there is some evidence of slightly decreasing returns to scale in the food industry.

8. Costs of Adjustment and Rates of Return

The model that has been estimated for the different industries is dynamic because of the presence of internal adjustment costs. This implies that, for the quasi-fixed factors at each time period, there is a wedge between the rental price and the marginal value for each type of capital. This wedge is represented by the marginal costs of adjustment. Hence the importance of adjustment costs can be understood by comparing the marginal costs of adjustment to the rental price. This ratio may be thought of as a "coefficient of variability." If the ratio is zero then the input is perfectly variable, because marginal adjustment costs are zero, and the rental price equals the marginal value. Moreover, the higher the ratio the lower the degree of variability.

For physical capital we compute,

(15) $\alpha_{ee}\ [w(t)\ \Delta K_p(t)/y(t)\ p_p(t)\ \left(r(t) + \delta_p\right)]$

and for R&D capital the ratio is

(16) $\alpha_{dd}\ [w(t)\ \Delta K_r(t)/y(t)\ p_r(t)\ \left(r(t) + \delta_r\right)]$.

The results are presented in Table 12. The first point to notice is that there is no consistent pattern across industries; for two (SIC 20 and 33) physical capital is relatively less variable than R&D, while the converse is true for the other two industries. Second, for foods, which exhibits the lowest input intensities of output, and for chemicals, which exhibits the highest (see Table 1), we find the smallest difference (in absolute value) between the ratios; .044 for SIC 20 and .058 for SIC 28. Moreover, the physical and R&D capital ratios for chemicals are more than double that for foods, although the physical capital ratio is higher for the latter, and lower for the former.

The third conclusion is that there is a great deal of variation across industries for each set of ratios. For both physical and knowledge capital the relative difference between the largest and smallest magnitude represents more 200%. In addition, the industry with the most variability for physical capital (nonelectrical machinery) illustrates that almost 50% of its rental rate for knowledge capital consists of marginal adjustment costs.

There are no equivalent numbers to compare for R&D, but with respect to physical capital Pindyck and Rotemberg [1982(b)] found for U.S. manufacturing, that equipment had a ratio of .23 and structures .34. These magnitudes seem to be in line with our findings for physical capital, across the four different industries.

The importance of marginal adjustment costs can shed some light on the nature of the rate of return to R&D (and to physical capital). There has been a great deal of interest in the result that the derived marginal value of R&D (for example, as measured by the marginal product) has been substantially above the interest rate in the economy. No explanation has been provided for this conclusion, only that it seems to be an empirical result found by different researchers.

Let us step back for a moment to interpret the relationship between the marginal value and the interest rate. Consider the long run situation, when all variables do not change. In this case equations (8.1) and (8.2) become

$$(17)\quad r = -\frac{w}{p_i}\left[\alpha_i + \alpha_{ii}\frac{K_i}{y} + \alpha_{yi}\, y + \alpha_{pr}\frac{K_j}{y}\right] - \delta_i \qquad i,j=p,r \quad i\neq j.$$

Equation (17) states that the firm equates the interest rate (i.e. the opportunity cost of funds) to the marginal rate of return on each quasi-fixed factor. The latter consists of the per dollar decline in variable (i.e. labor) costs attributable to the specific type of capital net of depreciation. We can call the right side of equation (17) the net marginal value of either physical or knowledge capital.

The opportunity cost of funds is equated to the marginal rate of return on physical and R&D capital. However, in the short run the marginal rate of return consists of the net marginal value minus the marginal costs of adjustment. The net marginal value of capital must be sufficiently greater than the opportunity cost of funds to cover the marginal adjustment costs. Therefore, although the firm equates the marginal rate of return on each type of capital to the opportunity cost of funds, in each time period, the composition of the marginal rate of return differs between the long and short-run.

The implication is that it is meaningful to investigate the relationship between the net marginal value and the interest rate. As long as marginal adjustment costs are positive, the net marginal value must be greater than the long run opportunity cost of funds. Thus the explanation, for the differences between the interest rate, the net marginal value of R&D, and physical capital, is that there are marginal costs of adjustment for each type of capital, and these costs are not equal.

We compute the net marginal value for R&D and physical capital, for each of our four industries. The results are presented in the first two rows of Table 13. We see that the net marginal value for physical capital is less than the magnitude for R&D in each industry. The highest value for both physical and knowledge capital is found in the chemical industry (see Griliches [1980] for a similar result). The difference between the net marginal values in the food and primary metal industries is not very large. The net marginal value for physical capital is 86% of that for R&D in foods, and 91% in primary metals. The differences are more significant in the other two industries; with 67% in chemcials and only 30% in nonelectrical machinery. These results are consistent with those presented in Table 12. For example for nonelectrical machinery, the proportion of the marginal adjustment costs out of the rental rate for physical capital was very small in absolute terms and relative to the proportion for R&D. Thus we would expect that the net marginal value of physical capital to be substantially smaller than the value for R&D, and also not very different from the interest rate (which is .044 for the period under consideration). These conclusions are borne out in Table 13.

In the long run (when marginal adjustment costs are zero) the net marginal value for each type of capital is the marginal rate of return, and equal to the interest rate. Hence, by subtracting the interest rate from the net marginal value we can determine the marginal cost of adjustment. These figures are given by the last two rows in Table 13.

We see that the marginal costs of adjustment are consistently larger for R&D than for physical capital for each industry. The largest costs are found in the chemical industry, and the greatest difference between the costs for physical and knowledge capital is in the nonelectrical machinery products industry.

From Table 13 it can be observed that there are substantial differences between the short and long-run net marginal value of R&D. Taking the interest rate to be the long-run net marginal value for both types of capital, for chemicals the long-run net marginal value is about 22% of the value in the short run (i.e. .044/.198), for nonelectrical machinery 27%, for primary metals 44% and for foods 47%. The situation is somewhat different for physical capital. As a percentage of the long-run net marginal value, the long-run value for chemicals is 33%, for primary metals 48%, for foods 55% and for nonelectrical machinery 98%. We see that the ranking has changed, and the percentages have increased slightly for physical capital. However, in the case of machinery products, there is virtually no difference between the short and long-run net marginal value of physical capital. Consequently, our findings illustrate that the net marginal value, for both types of capital in the short run and for each industry, exceeds the interest rate, while the value for R&D is greater than the value for physical capital.

9. Conclusion

In this paper we have examined the price and output effects on factor demands, and the role of adjustment costs in a dynamic cost minimizing model relating to labor, R&D, and physical capital requirements. With respect to factor substitution possibilities, we found a consistent pattern emerging for the different industries. R&D capital is quite responsive to the different factor price changes, and generally R&D and physical capital are complements, while the quasi-fixed factors are substitutes for labor.

Output growth exerts a significant impact on factor requirements across the various industries. Indeed in absolute value terms output elasticities exceed factor price elasticities. We also found that in the short run, when the capital inputs are fixed, overshooting occurs in the demand for labor. However, because the quasi-fixed factors are substitutes for labor, as they adjust the overshooting dissipates.

Finally we have detailed the importance of adjustment costs. In fact, we found for R&D that marginal adjustment costs represent anywhere from 22% - 65% of the rental rate, while for physical capital the range is 20% to 60%. These adjustment costs enable us to explain the large differences between the marginal value of R&D and physical capital, and between the marginal values and the interest rate.

Important avenues for future research remain open. Two crucial ones relate to the problems of financing and spillovers. First, in this paper, we have assumed that all the benefits from R&D can be fully appropriated. We know, of course, in general this is not true, and that the accumulation of knowledge is affected by the R&D (both present and past) decisions of other firms. By admitting less than full appropriation, we could develop a model that would permit the estimation of spillover effects. In addition, it would then be possible to see how the private rate of return on R&D differs from both the industry-specific rate of return (when firms are pooled), and the economy-wide rate of return (when industries are pooled).

Conventional wisdom holds that R&D investment is generally financed out of internal funds to a greater degree than physical investment. In order to investigate and test this view it would be of interest to develop and estimate a model integrating the decisions on real capital accumulation and financial capital structure. A by-product of this analysis would be the testing of whether financial costs or adjustment costs exert the greater influence on R&D and physical capital investment decisions.

Notes

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1. In other words, $\partial(L(t)/y(t))/\partial\Delta K_p(t) = \partial(L(t)/y(t))/\partial\Delta K_r(t) = 0$ at $\Delta K_p(t) = \Delta K_r(t) = 0$, which is easily seen to be the case in equation (7). We have also imposed the usual assumption that the adjustment costs of the two quasi-fixed factors (in this case P&E and R&D) are independent. See Morrison and Berndt [1981] and Pindyck and Rotemberg [1982(b)].

2. Clearly, the disturbances in each of the equations could also arise through measurement and optimization errors.

3. The one-tailed test of H_0: $\alpha_{dd} = 0$, H_A: $\alpha_{dd} > 0$ at the 90% level of confidence is 1.645.

4. The second order conditions were initially imposed by the procedure described in Lau [1974]. With these estimates as initial conditions, we re-estimated the models without the imposition of the second order conditions. The convergence criteria we used was .001. In all cases convergence was achieved.

5. This point has been previously emphasized by Nadiri [1982].

6. The focus on two quasi-fixed factors and the decomposition of labor or physical capital seems appropriate in our context, since we have two quasi-fixed factors with R&D essentially being an aggregate of a particular class of labor and physical capital.
7. Comparison of cross price elasticities is even more difficult, given the diversity of the factors involved in the different models.
8. Pindyck and Rotemberg [1982(a)] calculate intermediate run elasticities when labor adjusts but physical capital does not. In the present paper we calculate these elasticities under the assumption that first R&D adjusts but P&E does not, and then for the converse case.
9. A property of constant returns to scale is that the long-run output elasticity of each factor demand is unity. Clearly from Table 10 these elasticities are close to one.

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Table 1

Main Variable Magnitudes by Industry

Main Variable	SIC*			
	20	28	33	35
Physcial Capital Stock per Unit of Output	.27 (.08)	.83 (.16)	.83 (.41)	.38 (.15)
R&D Capital Stock per Unit of Output	(.10) (.06)	.52 (.18)	.16 (.13)	.27 (.11)
Labor Services per Unit of Output	.07 (.01)	.16 (.04)	.13 (.02)	.13 (.02)
Physical Capital Stock	204.16 (106.89)	487.83 (194.88)	610.71 (583.26)	22.32 (10.48)
R&D Capital Stock	82.67 (71.34)	298.65 (131.76)	86.46 (86.18)	13.98 (3.48)

*Standard deviations in brackets

Table 2

Industry Pooled Estimates with Dummy Variables in Zero and First Order Terms

Parameter*	Estimate	t-Statistic	Parameter	Estimate	t-Statistic
α_0^{20}	.1366	2.9283	α_r^{20}	-.1647	-170.82
α_0^{28}	.2258	8.4791	α_r^{28}	-.1447	-110.92
α_0^{33}	.1141	7.3363	α_r^{33}	-.1279	-122.99
α_0^{35}	.0289	1.7019	α_r^{35}	-.1388	-169.29
α_y^{20}	.2894 E-03	2.5413	α_{yy}	.3131 E-06	2.4916
α_y^{28}	.4909 E-03	6.4900	α_{pp}	.1895 E-01	3.3051
α_y^{33}	.2658 E-03	3.6463	α_{rr}	.5498 E-02	2.8193
α_y^{35}	.1735 E-03	.7121	α_{ee}	.2001	2.1087
α_p^{20}	-.1159	-32.527	α_{dd}	.1358	1.2239
α_p^{28}	-.1170	-29.659	α_{yp}	-.2092 E-04	-4.1129
α_p^{33}	-.0964	-24.059	α_{yr}	-.4156 E-05	-3.0837
α_p^{35}	-.1280	-47.408	α_{pr}	-.5067 E-02	-3.4005

R^2 Labor Equation	.945	SEE Labor Equation	.030
R^2 P&E Equation	.994	SEE P&E Equation	.009
R^2 R&D Equation	.997	SEE R&D Equation	.002

Table 3

Food Industry Estimates

Parameter	Estimate	t-Statistic
α_0	.0612	2.3640
α_y	.8384 E-04	1.2935
α_p	-.1044	-32.590
α_r	-.1288	-55.963
α_{yy}	.8733 E-07	1.2166
α_{pp}	.0770	7.1015
α_{rr}	.0485	3.0217
α_{ee}	1.3342	1.559
α_{dd}	1.3879	1.754
α_{yp}	-.2111 E-04	-6.1508
α_{yr}	-.4203 E-05	-2.0418
α_{pr}	-.0428	-4.3744

R^2 Labor Equation	.954	SEE Labor Equation	.0135
R^2 P&E Equation	.998	SEE P&E Equation	.0037
R^2 R&D Equation	.999	SEE R&D Equation	.0020

Table 4

Chemical Industry Estimates

Parameter	Estimate	t-Statistic
α_0	.5192	16.669
α_y	.6551 E-03	11.029
α_p	-.1336	-22.704
α_r	-.1268	-28.365
α_{yy}	.1089	13.666
α_{pp}	.0236	4.5452
α_{rr}	.0214	16.747
α_{ee}	1.8271	3.8026
α_{dd}	1.6898	3.9908
α_{yp}	-.1922 E-04	-2.4974
α_{yr}	-.6651 E-05	-.9845
α_{pr}	-.5555 E-02	-2.8038

R^2 Labor Equation	.949	SEE Labor Equation	.0372
R^2 P&E Equation	.997	SEE P&E Equation	.0057
R^2 R&D Equation	.998	SEE R&D Equation	.0053

Table 5

Primary Metals Industry Estimates

Parameter	Estimate	t-Statistic
α_0	.1531	7.5820
α_y	.3455 E-03	3.1828
α_p	-.0986	-77.285
α_r	-.1433	-87.173
α_{yy}	.5350 E-06	2.8315
α_{pp}	.9829 E-02	4.5640
α_{rr}	.0227	6.1326
α_{ee}	.8968	3.1825
α_{dd}	.5271	1.8201
α_{yp}	-.1254 E-04	-5.1134
α_{yr}	-.8964 E-05	-2.9201
α_{pr}	-.9846 E-02	-3.8210

R^2 Labor Equation	.933	SEE Labor Equation	.0348
R^2 P&E Equation	.999	SEE P&E Equation	.0026
R^2 R&D Equation	.999	SEE R&D Equation	.0036

Table 6

Nonelectrical Machinery Industry Estimates

Parameter	Estimate	t-Statistic
α_0	.1136	4.8087
α_y	.2152 E-02	2.4606
α_p	-.1154	-12.694
α_r	-.1609	-51.302
α_{yy}	.3251 E-04	2.3866
α_{pp}	.0478	2.7145
α_{rr}	.0758	16.243
α_{ee}	.1018	2.2737
α_{dd}	.3106	4.2636
α_{yp}	-.2829 E-03	-2.7295
α_{yr}	-.2492 E-03	-7.2832
α_{pr}	-.0266	-4.9256

R^2 Labor Equation	.991	SEE Labor Equation	.0125
R^2 P&E Equation	.989	SEE P&E Equation	.0126
R^2 R&D Equation	.999	SEE P&E Equation	.0037

Table 7

Test of the Equality of α_{dd} Between

Industry-Pooled and Industry-Specific Estimates*

SIC 20 (Foods and Kindred Products)	t = 11.28	reject at 99%
SIC 28 (Chemicals and Allied Products)	t = 14.00	reject at 99%
SIC 33 (Primary Industrial Metals)	t = 3.51	reject at 99%
SIC 35 (Machinery, except Electrical)	t = 1.64	reject at 90%

* $\dfrac{.1358 - \hat{\alpha}^{i}_{dd}}{.111}$, $i = 20, 28, 33, 35$

Table 8

Long-Run Price Elasticities of Factor Demands*

	SIC			
Elasticity*	20	28	33	35
e^L_{pp}	-.4784	-.4325	-.4738	-.4538
e^L_{pr}	-.5566	-.1423	-.2820	-.1782
$e^L_{p\ell}$	1.0350	.5748	.7559	.6320
e^L_{rp}	-.2089	-.0924	-.3435	-.2136
e^L_{rr}	-.4965	-.4980	-.4696	-.4276
$e^L_{r\ell}$	.7054	.5904	.8131	.6411
$e^L_{\ell p}$	.2778	.2307	.1758	.2945
$e^L_{\ell r}$	.5045	.3649	.1553	.2493
$e^L_{\ell\ell}$	-.7822	-.5956	-.3311	-.5438

* e^L_{ij} means long-run factor j price elasticity of factor i, with the subscript ℓ representing labor, p means P&E capital, r stands for R&D capital, and the superscript L means the long run. All values of exogenous variables are equal to their mean.

Table 9

Intermediate-Run Price Elasticities of Factor Demands

Price Elasticities	SIC 20	SIC 28	SIC 33	SIC 35
	Elasticity Without Physical Capital Adjustment*			
e^J_{rr}	-.4908	-.5046	-.4619	-.4222
$e^J_{r\ell}$	.4908	.5046	.4619	.4222
$e^J_{\ell r}$	.2328	.2277	.1986	.2272
$e^J_{\ell\ell}$	-.2328	-.2277	-.1986	-.2272
	Elasticity Without R&D Adjustment**			
e^I_{pp}	-.4565	-.4243	-.4821	-.4674
$e^I_{p\ell}$	.4565	.4243	.4821	.4674
$e^I_{\ell p}$	.2172	.1594	.2251	.2272
$e^I_{\ell\ell}$	-.2172	-.1594	-.2251	-.2272

*Superscript J means intermediate run with P&E not adjusted to its long-run level.

**Superscript I means intermediate run with R&D not adjusted to its long-run level. All values of the exogenous variables are equal to their mean.

Table 10

Output Elasticities of Factor Demands

	SIC			
Elasticities*	20	28	33	35
$e^S_{\ell y}$	1.8125	1.3592	1.6208	1.7024
$e^J_{\ell y}$	.9459	.9544	.9436	.9519
$e^I_{\ell y}$	.9776	.9864	.9996	.9759
$e^L_{\ell y}$	.9754	1.0024	1.0074	.9668
e^J_{ry}	1.0111	1.0138	1.0169	1.0462
e^L_{ry}	1.0425	1.0229	1.0412	1.0764
e^I_{py}	1.0684	1.0426	1.0337	1.0649
e^L_{py}	1.0842	1.0473	1.0435	1.0825

*The superscripts represent S - short-run, J - intermediate-run (P&E not adjusted), I-intermediate-run (R&D not adjusted), L - long run. The values of the exogenous variables are equal to their mean.

Table 11

Short Run Elasticities of Labor Demand
and Returns to Scale

Elasticities*	SIC 20	SIC 28	SIC 33	SIC 35
$e^S_{\ell y}$	1.8125	1.3592	1.6208	1.7024
$e^S_{\ell p}$	-.4219	-.2106	-.5576	-.3680
$e^S_{\ell r}$	-.2341	-.1281	-.1290	-.3138
Returns to Scale	.9137	.9849	1.0406	.9879

*The values of the exogenous variables are equal to their mean.

Table 12

Marginal Adjustment Costs Relative to the Rental Rate

	SIC			
Quasi-Fixed Factor	20	28	33	35
Physical Capital	.268	.589	.363	.197
Knowledge Capital	.224	.647	.234	.470

Table 13

Net Marginal Values and
Marginal Adjustment Costs

	SIC			
	20	28	33	35
Net Marginal Values				
Physical Capital	.080	.133	.091	.047
Knowledge Capital	.093	.198	.100	.160
Marginal Costs of Adjustment				
Physical Capital	.036	.089	.047	.003
Knowledge Capital	.049	.154	.056	.116

r = .044 (mean value)