Elasticities of Substitution Among Inputs:
Comparison of Human Capital and Skilled Labor Models

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Abstract

This paper presents new estimates of the elasticities of substitution among inputs for the U.S. for 1947-1989 using a nested CES production function. It develops a new simple linear estimation method based on the marginal productivities, and data on rates of return over time. Two models are compared: one is a nested CES function containing physical capital and newly developed estimates of the stock of human capital in one nest, with this combined factor of total capital substituting with raw labor, and the other is a similar nested CES but with human capital measured as the number of higher-skilled workers vs. the number of lower-skilled workers by education level. Empirical results show that the elasticity of substitution between human capital (or high-skilled labor) and physical capital is a low 0.0 to 0.3, and between total capital and raw labor a higher average of .43. So the capital-skill complementarity hypothesis is confirmed for the first time for the U.S. 1947-89 using both formulations. This suggests that sustained investment in new human capital formation is necessary as physical capital formation occurs if diminishing returns to physical capital are to be avoided and productivity growth sustained.

I   Introduction

It is well known that one of the most important sources of national wealth in most countries is human resources. Human capital, narrowly defined as education, contributes to economic growth by improving the quality of raw labor and hence raising productivity. The importance of human capital has been further developed recently within a so-called "endogenous growth model" in the context of transitional dynamics first initiated by Romer (1986) and Lucus (1988).

Although human capital plays a key role in economic growth, it is a necessary but not a sufficient condition. This implies that human capital must be combined with investment in physical capital. A natural question is whether human capital and physical capital are complements or substitutes. Knowledge of the elasticities of substitution among factors helps to resolve this point. If physical capital and human capital (or higher-skilled labor) are complementary to each other, an increase in the relative amounts of investment in physical capital through, for example, the investment tax credit or cuts in government expenditure on education will result in diminishing returns to physical capital. Moreover, if physical capital and raw labor (or lower-skilled labor) are close substitutes, a policy focused on promoting only physical capital investment may facilitate substitution and aggravate unemployment problems among the least skilled.

The purpose of this paper is to examine the elasticities of substitution among inputs based on the assumptions of the heterogeneity of labor and of total capital, permitting capital-skill complementarity and using U.S. time-series data for the period of 1947-1989. After developing a simple linear estimation method derived from the marginal productivity approach for estimating the NCES production function, two models are compared: one is a model with total capital

consisting of physical and human capital stocks together with raw labor, and the other is a similar NCES model but with the numbers of higher-skilled workers and lower-skilled workers. We first review the literature in section II and develop linear equations for estimating the NCES production function in section III. Section IV presents empirical results of the elasticity of substitution using NCES production functions. Finally, the conclusions are summarized in section V.

II   The Review of Literature

After the pioneering work by Arrow, Chenery, Minhas, and Solow (1961), numerous studies have attempted to estimate the elasticity of substitution between labor and physical capital using the constant elasticity of substitution (hereafter CES) production function. Most studies, however, show that the estimates of the elasticity of substitution using U.S. cross-section data in manufacturing industries is not significantly different from unity as is assumed in the Cobb-Douglas production function. Using time series data, Lucus (1969), however, concludes that "whereas unity appears to be a central value in the U.S. cross-sectional tests, the time-series estimates are centered in the range from 0.3 to 0.5." (p. 251)

Although the CES production function is less restrictive than the Cobb-Douglas form, it still assumes the elasticities of substitution are the same for all pairs of inputs. In order to see the differing elasticity of substitution among inputs, most literature uses the two-level or nested CES (henceforth NCES) production function suggested by Sato (1967) or the more flexible translog production function proposed by Christensen, Jorgenson, and Lau (1971).

Other studies have attempted to examine labor-labor substitution, human capital-raw-labor substitution, or capital-skill complementarity using

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international or U.S. cross-section data. Griliches (1969, 1970), who first advanced the so-called capital-skill complementarity hypothesis, confirmed that skill or education is more complementary to physical capital than to unskilled or raw labor based on factor demand equations using U.S. cross-sectional data.

Using cross-sectional earnings and employment data from twelve countries, Bowles (1970) argues for the separability hypothesis among the labor force by education levels using a model with no capital variable. He then concludes that the elasticities of substitution among different labor inputs are very high and hence there is no educational barrier to economic growth in developing countries. However, by including a capital variable and expanding the number of countries to eighteen countries, Psacharopoulos and Hinchliffe (1972) favor instead Griliches' complementarity hypothesis. They show that highly educated workers are more complementary to physical capital since "physical capital accumulation shifts the demand schedule for highly educated labor to the right, resulting in larger wage differentials for any given distribution of educated labor." (p. 791)

Berndt and Christensen (1974) divide the labor force into production and nonproduction workers in U.S. manufacturing, and then estimate the elasticities of substitution among inputs using the translog production function. They also accept the complementarity hypothesis against the separability hypothesis, by showing that nonproduction workers (presumably more highly educated ones) and capital are complements, while production workers and capital are substitutes.

Fallon and Layard (1975) estimate a two-level CES production function with international cross-section data. They confirm capital-skill complementarity at the levels of both the economy and industries. Grant (1979), as cited in Hamermesh and Grant (1979) based on a translog cost function, shows similar

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results confirming the complementarity hypothesis. Most studies are consistent with Griliches' (1969) early results.

More recently, several studies have investigated the elasticities of substitution among inputs using the nested CES production function. Broer and Jansen (1989) estimate long-run elasticities of substitution among inputs using a three-level CES production function with Dutch annual data (1961-80). Although the capital stock data for the Netherlands is limited, they report that the elasticity of substitution between physical capital and highly educated labor (i.e., labor with higher education) is very low (0.01), while the elasticity of substitution of physical capital for less educated labor (i.e., labor with either primary or secondary education) is very high (1.31).

Ritzen (1989) estimates the elasticities of substitution among different types of labor by education level with and without a capital stock using U.S. time-series data (1947-1985). His estimates are based on nonlinear factor demand equations derived from a two-level CES production function with a cost minimization assumption at each level. He reports that the elasticity of substitution of physical capital and unskilled labor is relatively high (0.49), while that of the combined factor (i.e., physical capital and unskilled labor) and higher skilled labor is very low (0.05). However, these estimates are based on some parameters being fixed *a priori*. Since simultaneous demand equations for estimation are highly nonlinear, it is very difficult to get results without fixing some of the parameters.

Compared to Fallon and Layard (1975), Broer and Janson (1989) and Ritzen (1989) use a different nesting pattern. That is, Fallon and Layard use physical capital and skilled labor as a combined factor at the first level, and the combined factor and unskilled labor at the second level, while Ritzen and Broer

et al. use physical capital and unskilled labor as a combined factor at the first level, and the combined factor and higher skilled labor at the second level. One problem in the latter approach is the difficulty involved in testing the capital-skill complementarity hypothesis when the combined factor is physical capital and unskilled labor. For the concept of "total capital" (i.e., physical capital and human capital (or skilled labor)), the former approach is more appropriate.

A new and different approach has been attempted by McMahon (1989) and Jung (1990). They use human capital stocks rather than the number of workers at different education levels, and also employ a different nesting pattern in order to examine capital-skill complementarity. The combined factor, physical capital and human capital (instead of the number of highly educated workers) is used at the first level, and the combined factor which now is total capital and raw labor (i.e., simply the number of persons employed) at the second level. However, the most striking feature of their estimation method is the attempt to estimate the two-level CES production function directly in log nonlinear form with no input price data as is normally done with log-linear Cobb-Douglas functions. They report some results confirming the capital-skill complementarity hypothesis. Although this method does not require such assumptions as perfect competition and cost minimization, it has in common with most other approaches the possible econometric problems of simultaneity (endogenous explanatory variables) and multicollinearity.

As mentioned before, the NCES production function can be estimated using either cost minimization step by step at each level by a linear method, or simultaneously by nonlinear methods. One advantage of the cost minimization approach is that it uses additional information that then makes it possible to estimate all the parameters in the NCES production function theoretically.

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However, this cost minimization approach based on either a linear or a nonlinear method still makes it very difficult to obtain reasonable parameters empirically since this method considers the imputed prices and implicit outputs. As Ritzen (1989) indicates, to find appropriate starting values requires a huge amount of trial and error. For the linear method, in order to estimate higher level parameters, we have to obtain some reasonable distribution parameters from the constant term, which makes it very difficult to get such parameters since the constant term often depends upon the units of measurement of the variables or simply addition of other variables such as lagged dependent and time trend variables. For the nonlinear case estimated either directly or indirectly, the parameters are so sensitive to initial values that a slight change in initial values sometimes gives large changes in the results. For example, by changing the initial values slightly, capital-skill complementarity sometimes turns to be capital-skill separability. In consequence, if we are interested simply in the elasticities of substitution among inputs, a relatively simple linear method derived from the marginal productivity conditions in the NCES production function produces much more stable and reliable results.[1]

III **Theoretical Model Development**

Consider three factors of production, physical capital (K), human capital (H), and raw labor (L). Although several nesting patterns are possible, from the viewpoint of the "capital-skill complementary hypothesis" and "total capital," the natural nesting pattern of a NCES function is

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[1]Note that using this marginal productivity approach, we can, of course, estimate all the parameters in the NCES production function *via* tedious trial and error.

$$Y = F[Q, L],$$ (1)

$$Q = G[K, H],$$

or,

$$Y = F[G(K, H), L],$$ (1′)

where F and G are assumed to have nice properties of a production function with constant return to scale.

More specifically,

$$Y = \gamma \left[\alpha Q^{-\rho} + (1-\alpha) L^{-\rho}\right]^{-\frac{1}{\rho}}$$ (2)

$$Q = \left[\beta K^{-\delta} + (1-\beta) H^{-\delta}\right]^{-\frac{1}{\delta}},$$

or

$$Y = \gamma \left[\alpha \left[\beta K^{-\delta} + (1-\beta) H^{-\delta}\right]^{\frac{\rho}{\delta}} + (1-\alpha) L^{-\rho}\right]^{-\frac{1}{\rho}},$$ (2′)

where $\gamma > 0$, $0 < \alpha$, $\beta < 1$, and $\rho, \delta > -1$.

Y denotes the total output, and Q is defined as total capital output produced by a combined factor of physical capital and human capital. From the definition of the CES production function, the elasticities of substitution at the first level (θ) and at the second level (σ) are:

$$\theta = \frac{1}{1+\delta},$$ (3) $$\sigma = \frac{1}{1+\rho}.$$ (4)

The capital-skill complementarity hypothesis states that the elasticity of substitution at the first level is expected to be less than that at the second level, i.e., $\theta < \sigma$.

From this production function, marginal products of each input become

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$$MP_K = \gamma^{-\rho}\alpha\beta\left(\frac{Y_t}{Q_t}\right)^{1+\rho}\left(\frac{Q_t}{K_t}\right)^{1+\delta} \tag{5}$$

$$MP_H = \gamma^{-\rho}\alpha(1-\beta)\left(\frac{Y_t}{Q_t}\right)^{1+\rho}\left(\frac{Q_t}{H_t}\right)^{1+\delta} \tag{6}$$

$$MP_L = \gamma^{-\rho}(1-\alpha)\left(\frac{Y_t}{L_t}\right)^{1+\sigma}. \tag{7}$$

Let us assume competitive markets. Then by equating each marginal product to its price, i.e., to the rental price of physical capital (r), the rental price of human capital (s), and the real wage rate (w_0) with no schooling, respectively, we can estimate the elasticities of substitution. By dividing equation (5) by equation (6), the basic equation for estimation of the substitution at the first level is:

$$\frac{r_t}{s_t} = \left(\frac{\beta}{1-\beta}\right)\left(\frac{K_t}{H_t}\right)^{-(1+\delta)}, \tag{8}$$

or taking logarithms and rearranging:

$$\log\left(\frac{H_t}{K_t}\right) = \log\left(\frac{1-\beta}{\beta}\right)^{\theta} + \theta\log\left(\frac{r_t}{s_t}\right). \tag{8'}$$

The elasticity of substitution between physical capital and human capital at the first level is the coefficient of $\log(r_t/s_t)$.

Similarly, taking logarithms and rearranging, equation (7) becomes

$$\log\left(\frac{Y_t}{L_t}\right) = \log\left[\gamma^{\left(\frac{\rho}{1+\rho}\right)}(1-\alpha)^{-\left(\frac{1}{1+\rho}\right)}\right] + \left(\frac{1}{1+\rho}\right)\log(w_{0t}), \tag{9}$$

or,

$$\log\left(\frac{Y_t}{L_t}\right) = \log\left[\gamma^{1-\sigma}(1-\alpha)^{-\sigma}\right] + \sigma\log(w_{0t}). \tag{9'}$$

The elasticity of substitution between total capital and raw labor at the second level is the coefficient of $\log(w_{0t})$.

We can modify two basic equations (8′) and (9′) by considering an adjustment hypothesis of the Koyck type and neutral technological progress.

First consider that factor inputs do not adjust to their desired level instantaneously. If the factor ratios in the LHS of (8′) and (9′) are desired levels (*), partial cost adjustment mechanisms at both levels can be written as

$$\frac{(H/K)_t}{(H/K)_{t-1}} = \left[\frac{(H/K)_t^*}{(H/K)_{t-1}}\right]^\zeta \tag{10}$$

and

$$\frac{(Y/L)_t}{(Y/L)_{t-1}} = \left[\frac{(Y/L)_t^*}{(Y/L)_{t-1}}\right]^\xi, \tag{11}$$

where ζ and ξ are the adjustment parameter at the first level and the second level, respectively, ranging from zero to one.

Introducing neutral technical progress, the NCES function (3.10) is rewritten as follows:

$$Y = \gamma\left[\alpha\left[\beta K^{-\delta} + (1-\beta)H^{-\delta}\right]^{\frac{\rho}{\delta}} + (1-\alpha)L^{-\rho}\right]^{-\frac{\nu}{\rho}}e^{\lambda t}, \tag{5′}$$

where λ is the rate of neutral technological change.

All these points are considered in the empirical estimation.

IV   Empirical Results

A Model with Human Capital and Raw Labor and Neutral Technical Progress

The following are alternative specifications used to estimate the elasticity of substitution. For the first level of the Nested-CES:

$$\log(H_t/K_t) = b + \theta\log(r_t/s_t) + u_t \tag{B1}$$

$$\log(H_t/K_t) = b + \xi\theta\log(r_t/s_t) + (1-\xi)\log(H_{t-1}/K_{t-1}) + u_t \tag{B2}$$

For the second level,

$$\log(Y_t/L_t) = b + \sigma\log(w_{0t}) + u_t \tag{B3}$$

$$\log(Y_t/L_t) = b + \zeta\sigma\log(w_{0t}) + (1-\zeta)\log(Y_{t-1}/L_{t-1}) + u_t \tag{B4}$$

$$\log(Y_t/L_t) = b + \zeta\sigma\log(w_{0t}) + (1-\zeta)\log(Y_{t-1}/L_{t-1})$$
$$+ (1-\sigma)\lambda t + u_t \tag{B5}$$

In all models, b is a constant term, and the error terms are assumed to be

$$u_t = \sum_{i=1}^{p} \phi_i u_{t-i} + e_t, \text{ with } e_t \sim \text{ i.i.d. } N(0,\sigma_e^2).$$

Non-Neutral Technical Progress

In the above models, we considered only disembodied neutral technical progress, referring technical advances mainly due to, for example, improvement in organization and operation of inputs. This type of progress is not directly associated with technical change embodied in the production factor itself.

Embodied technical progress, on the other hand, is also important in actual production processes, with technical advances embodied in certain production inputs, especially in human capital through education and in physical capital. This type of technical progress may be due to, for example, advances in

technology through investment in R&D. Therefore, as a rate of technical progress, we utilize the exponential growth rate of the U.S. knowledge-capital stock formed through investment in R&D rather than using arbitrary and fixed rates.

Although it is not clear which input technical progress should be embodied in, Bartel and Lichtenberg (1987) argue that educated labor has a comparative advantage in implementing new technology. Following this argument, we assume that some technical progress is embodied in human capital (or skilled labor) at a rate related to the growth rate of the R&D stocks. Then both with and without neutral disembodied technical progress, the following equations are estimated at the first level:[2]

$$\log(e^{\alpha_{t-i}}H_t/K_t) = b + \theta\log(r_t/s_t) + u_t \tag{B1'}$$

$$\log(e^{\alpha_{t-i}}H_t/K_t) = b + \xi\theta\log(r_t/s_t) + (1-\xi)\log(e^{\alpha_{t-i-1}}H_{t-1}/K_{t-1}) + u_t \tag{B2'}$$

As before, b is a constant term, and the error terms are assumed to be:

$$u_t = \sum_{i=1}^{p} \phi_i u_{t-i} + e_t, \text{ with } e_t \sim \text{i.i.d. } N(0,\sigma_e^2). \tag{12'}$$

In the above models, $\alpha_{t-i}[=\alpha(t-i)]$ is the growth rate of the R&D stock with an i-year lag, and $e^{\alpha(t-i)}$ represents the rate of embodied technical progress. Embodied technical progress is assumed to be lagged because it may take time before investment in R&D capital becomes effectively embedded in the human capital or higher skilled labor and hence affects output. Since theory does not dictate the lag structure, it must be determined empirically.

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[2]Note that despite the inclusion of embodied technical progress, the second level estimating equations in both models are exactly the same as before.

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Measurement of Variables

The description of variables used in the regression equations and data
sources are as follows:

Y = potential real output as developed by Gordon (1990, pp. Al-A3), instead of
actual output, since this study considers longer run growth process rather
than cyclical fluctuations.

K = the net physical capital stock from the U.S. Department of Commerce (1989)
Survey of Current Business for the period 1947-88. The capital stock for
1989 was estimated using the previous 5-year growth rates.

H = total human capital stock formed by primary, secondary, and higher
education of labor force, age 16 years and over. The stock of human
capital is measured in terms of cost of education based on formal
schooling following Schultz (1971) and McMahon (1974, 1991)[3]. In
estimating the human capital stock, three factors are multiplied: the
annual real cost per student, average schooling completed by the
population, and the number of persons in the labor force. The major data
sources are the U.S. Department of Education (1989), *Digest of Education
Statistics and Biennial Survey of Education*; U.S. Bureau of the Census
(1990), *Historical Statistics of the United States, Colonial Times to
1970*, *Statistical Abstract of the United States*, *and Current Population
Reports* (Series P-20) for enrollment rate by education level, school
expenditures, tuition and fees, and average schooling completed by
population. These human capital stock estimates are shown and compared to

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[3]For the basic data used for Y, K, H, L, and A see McMahon (1991,
Appendix A) and for detailed construction of the human capital stock see the Data
Appendix to this article available from the authors on request. The latter is
also explained in Kwag (1991).

Jorgenson and Fraumeni's broader estimates that include non-market returns in McMahon (1991, pp. A1-A3).[4]

L = total civilian labor force, age 16 years and over, from U.S. Council of Economic Advisors (1990), *Economic Report of the President*. The labor force and annual earnings by educational levels were calculated using data from U.S. Bureau of the Census (1990), *Current Population Reports* (Series P-60) and U.S. Council of Economic Advisors (1990, pp. 320, 330), *Economic Report of the President*.

w_0 = annual average earnings of workers with 0-7 years education, as a measure of the price of raw labor, and w = earnings higher education levels, from the U.S. Council of Economic Advisors (1990).

r = Moody's Aaa real corporate bond rate as a proxy for the rental price of physical capital from U.S. Council of Economic Advisors (1990), *Economic Report of the President*.

s = rate of return to human capital conceived of here as the rental price of human capital calculated by the following formula: $s = (w-w_0)/c$, where c denotes annual educational investment per person. Since c includes institutional expenditures as well as foregone earnings, and w is before taxes, s can be considered to be the social rate of return to human

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[4]Recently Jorgenson and Fraumeni (1989, p. 42) developed estimates of the new human wealth stock in the United States during the 1948-84 based on current market wages. Their estimates based on benefit from education are much larger than those based on cost of education, which may make it difficult to use their estimates empirically because they include nonmonetary benefits of schooling.

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Figure 1

Social Rates of Return to Human Capital

Comparison of Micro and Macro Data

□ All Level(S)   + Secondary   ◇ College
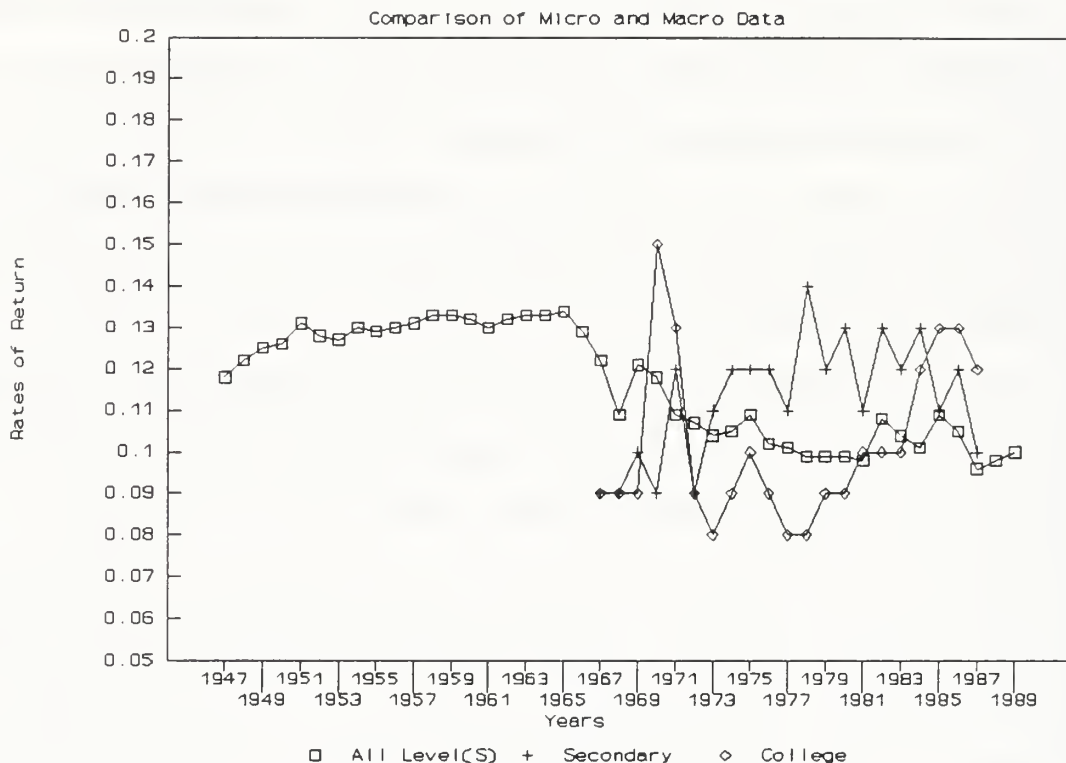
capital. A similar method was used by Fallon and Layard (1975) and is identical to benefit-cost analysis. As shown in Figure 1, using this method for the entire 1947-89 period, the rate of return was calculated on the average to be 11.65 percent (minimum = 9.62 and maximum = 13.34). These estimates based on macro data are remarkably similar to those shown in Figure 1 for 1967-1988 and for secondary and college levels separately based on microeconomic data done by McMahon (1991), who calculates the social rates of return to human capital by education level and by sex directly by solving the pure internal rate of return formula. During that period, our s produces an average of 10.59 percent, while the latter

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averages 11.5 percent. In the absence of adequate data for educational cost, the rate of return to human capital as a price of human capital can also be calculated using the following simple method: $s = (w-w_0)/w_0$. This method overestimates the rate of return to human capital because it considers only foregone earnings in calculating educational cost. However, these two kinds of rate of return calculations yield virtually the same regression results.

α = the growth rate of R&D stock. This rate is calculated for 1947-49 from Kendrick's (1976) estimates of the R&D stock and for 1950-89 from Wasserman's (1991) estimates. Wasserman calculates the R&D stock using the following formula:

$$R_t = IR_t + (1 - d)R_{t-1} \tag{13}$$

$$IR_t = (1+g)IR_{t-1}, \tag{14}$$

where R = R&D stock, IR = investment in R&D, d = the depreciation rate, and g = the growth rate of investment. The depreciation rates are taken to be 10 percent geometric depreciation for applied research, zero for basic research, 8.7 percent for private R&D, and 7.7 percent for federal and university based applied research.

Estimation Results

The estimates of the elasticities of substitution are presented in the following tables. As in most time-series analysis, this study also confronts the problem of serially correlated residuals. The presence of serial correlation implies that the regression coefficients using the least squares estimation method are not efficient, and their estimated variances are biased. In addition, if lagged dependent variables appear on the right-hand side of the regression

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equation as in the most regressions presented in this section, the application of uncorrected OLS will not yield consistent estimates of the parameters.[5] Therefore, most results reported here correct for first and second-order serial correlation using the SHAZAM program (White *et al.*, 1990) with options of ML (maximum likelihood method), GS (grid search) in the presence of autocorrelation.[6]

The following tables show the results estimated from the NCES production function. Table 1 shows the elasticity estimates of the model with human capital and raw labor using the NCES production function, while Table 2 presents the results from the model with technical progress embodied in human capital. As a proxy for the embodied technical rate of change, the annual exponential growth rates of the R&D stock with a two-year lag were used.[7]

In the human capital model, Table 1, the specifications of B1 and B2 give the first level elasticity of substitution between physical and human capital at the first level of the nested CES, while Models B3, B4, and B5 give the second level elasticity of substitution between total capital and raw labor. Models B1, B4, and B5 are estimated with a correction for second-order autocorrelation, and

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[5]The usual Durbin-Watson d statistic in detecting autocorrelation is inappropriate in the presence of the lagged dependent variables in the regression since it was derived on the assumption of a nonstochastic explanatory variable. The alternative test statistics for a regression including lagged dependent variables is Durbin's h statistic, which is asymptotically normally distributed. Therefore, if h > 1.645, we reject the null hypothesis at the 5 percent level of significance in favor of the hypothesis of a positive first-order autocorrelation. For more detail, see, for example, Johnston (1984).

[6]The DLAG (lagged dependent variable) option was used when a model has a lagged dependent variable in the right-hand side of the equation in order to calculate Durbin's h statistics. In the SHAZAM program, note that the ML option is valid only for first and second order autocorrelation.

[7]Estimates of the model with no lag in the growth rates of the R&D stock produced results were very similar to those reported here.

in Model B2 there is a correction for third-order autocorrelation. Model B2 requires no correction since Durbin's h statistic shows no autocorrelation. In the models with technical progress embodied in human capital, there is a correction for second-order autocorrelation in both B1' and B2' in Table 2.

Model B1 shows that in spite of the correction for second-order autocorrelation, the Durbin-Watson d statistic falls in the indeterminate range. Moreover, although the elasticity estimate is insignificant and virtually zero, this simple specification shows a zero or negative elasticity of substitution, implying that the substitution between human and physical capital is extremely low. By introducing a partial cost adjustment mechanism (i.e., inclusion of a lagged dependent variable), Model B2 shows no autocorrelation (Durbin's h statistic = 0.568).

In general, the elasticity estimates at both levels seem to be relatively low. Consistent with this is the lack of responsiveness to the relative rates of return as indicated by the insignificance of the coefficients of these price ratios and the significance of delayed effects via the lagged dependent variables. The first level elasticity of substitution between human and physical capital in model B2 is 0.303, while the second level elasticity estimates ranges from 0.284 to 0.478, depending on model specifications. At any rate, these results seem to weakly confirm the so-called "capital-skill complementarity" hypothesis on the whole. That is, physical capital is more complementary to human capital over time than to raw labor. From Model B2, the partial adjustment coefficient at the first level (ξ), which is calculated as 1 minus the coefficient of the lagged dependent variable, is 0.024. This implies that only 2.4 percent of the gaps between the desired and the actual are eliminated in a

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Table 1

**Elasticities of Substitution-NCES Production Function
Human Capital and Raw Labor Model
the U.S. Economy, 1947-1989**

Independent Variables	Alternative Specifications				
	B1	B2	B3	B4	B5
Constant	-0.426 (-2.044)	0.019 (1.790)	-8.028 (-10.962)	-0.339 (-1.476)	-0.738 (-1.297)
$\log(r/s)t$	-0.002 (-0.300)	0.007 (1.105)			
$\log(H/K)t-1$		0.976 (32.992)			
$\log(w0)t$			0.478 (5.634)	0.016 (0.842)	0.037 (1.124)
$\log(YP/L)t-1$				0.943 (55.161)	0.890 (12.143)
Time(t)					0.001 (0.743)
Adj. R^2	0.973	0.982	0.990	0.998	0.998
D.W.	1.414	1.794	1.533	1.991	1.939
Durbin h		0.568			
θ	-0.002	0.303			
ξ		0.024			
σ			0.478	0.284	0.336
ζ				0.057	0.110
λ					0.001

Note: t-statistics are in parentheses. These models were estimated with correction for second-order autocorrelation for B1, B4 and B5 and with correction for third-order autocorrelation for B3. Model B2 required no correction.

Table 2

Elasticities of Substitution-NCES Production Function
Technical Progress Embodied in Human Capital
the U.S. Economy, 1947–1989

Independent Variables	Alternative Specifications				
	B1'	B2'	B3	B4	B5
Constant	-0.413 (-1.722)	0.005 (0.364)	-8.028 (-10.962)	-0.339 (-1.476)	-0.738 (-1.297)
$\log(r/s)_t$	-0.013 (-1.485)	0.018 (2.324)			
$\log(H/K)_{t-1}$		0.878 (22.039)			
$\log(w_0)_t$			0.478 (5.634)	0.016 (0.842)	0.037 (1.124)
$\log(YP/L)_{t-1}$				0.943 (55.161)	0.890 (12.143)
Time(t)					0.001 (0.743)
Adj. R^2	0.951	0.967	0.990	0.998	0.998
D.W.	1.799	1.932	1.533	1.991	1.939
θ	-0.013	0.149			
ξ		0.122			
σ			0.478	0.284	0.336
ζ				0.057	0.110
λ					0.001

Note: t-statistics are in parentheses. Model B1' and B2' in the first level were estimated with correction for second-order autocorrelation. Models B3, B4, and B5 in the second level are reproduced from Table 3.2.2 for reference since these results are the same before.

year. The speed of adjustment seems to be relatively very slow in part because of thestructural rigidities. From Models B4 and B5, the adjustment coefficient at the second level (ζ) averages 0.08, which is slightly larger than the first level. Model B5 shows that Hicks-neutral technological change (λ) in the whole economy occurred through disembodied technical progress at rate of 0.1 percent per year. Table 2 shows the new estimates of the elasticity of substitution assuming now that technical progress is embodied in human capital at a rate determined by the level of investment in human capital times the lagged growth rate of the R&D stock. The simple specification B1 still produces negative elasticity estimates as before. However, Model B2' which allows for a lagged adjustment yields very good results. The first level elasticity of substitution in this model (0.149) is lower than the elasticities where there is no embodied technical progress (0.303) discussed earlier. Therefore, with embodied technical progress in human capital and in higher skilled labor, the capital-skill complemetarity hypothesis is strongly reaffirmed. Comparing the adjustment coefficient at the first level, the coefficient in the model with embodied technological progress (0.122) is much larger than that in the model with no embodied progress (0.024).

B Model with Higher-Skilled and Lower-Skilled Labor

Similarly, we can derive two basic equations using higher-skilled labor and lower-skilled labor instead of human capital and raw labor with the same nesting pattern. The NCES production function with higher-skilled labor (L_3) and lower-skilled labor (L_{12}) is defined as follows:

$$Y_t = \gamma \left[\alpha \left[\beta K_t^{-\delta} + (1-\beta) L_{3t}^{-\delta} \right]^{\frac{\rho}{\delta}} + (1-\alpha) L_{12t}^{-\rho} \right]^{-\frac{1}{\rho}}. \tag{15}$$

The following linear equations derived from the marginal productivity conditions as before are estimated. For the first level,

$$\log(L_{3t}/K_t) = A + \theta \log(r_t/w_{3t}) + u_t \tag{C1}$$

$$\log(L_{3t}/K_t) = A + \xi\theta\log(r_t/w_{3t}) + (1-\xi)\log(L_{3t-1}/K_{t-1}) + u_t \tag{C2}$$

For the second level,

$$\log(Y_t/L_{12t}) = A + \sigma\log(w_{12t}) + u_t \tag{C3}$$

$$\log(Y_t/L_{12t}) = A + \zeta\sigma\log(w_{12t}) + (1-\zeta)\log(Y_{t-1}/L_{12t-1}) + u_t \tag{C4}$$

$$\log(Y_t/L_{12t}) = A + \zeta\sigma\log(w_{12t}) + (1-\zeta)\log(Y_{t-1}/L_{12t-1})$$
$$+ (1-\sigma)\lambda t + u_t \tag{C5}$$

Assuming embodied technical progress in higher-skilled labor, the following equations are also estimated in the first level as before:

$$\log(e^{\alpha_{t-i}}L_{3t}/K_t) = A + \theta\log(r_t/w_{3t}) + u_t \tag{C1'}$$

$$\log(e^{\alpha_{t-i}}L_{3t}/K_t) = A + \xi\theta\log(r_t/w_{3t}) + (1-\xi)\log(e^{\alpha_{t-i-1}}L_{3t-1}/K_{t-1}) + u_t \tag{C2'}$$

where, α_{t-i} [$=\alpha(t-i)$] is the growth rate of the R&D stock with a i-year lag, and $e^{\alpha(t-i)}$ represents the rate of embodied technical progress.

In all models, A is a constant term, and the error terms are assumed to

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$$u_t = \sum_{i=1}^{p} \phi_i u_{t-i} + e_t, \text{ with } e_t \sim \text{i.i.d. } N(0, \sigma_e^2). \tag{16}$$

Description of Variables

L_{12} = the number in the labor force with primary and secondary education $[L_{12} = L_1 + L_2*(w_2/w_1)]$ following the simple aggregation method of workers suggested by Bowles (1970).

L_3 = the number in the labor force with higher education.

w = overall annual average earnings of labor force employed (Le). This is calculated as follows: $w = (Le_1*w_1 + Le_2*w_2 + Le_3*w_3)/Le$, where Le is the number in the labor force who are employed and Le_i denotes employment with education level i.

w_{12} = average annual earnings of workers with primary and secondary education. This is calculated as follows: $w_{12} = (Le_1*w_1 + Le_2*w_2)/Le_{12}$, where Le_i denotes the labor force employed with each corresponding education level.

w_3 = annual average earnings with higher education.

Other variables are already defined and described in the human capital model.

Estimation Results

Table 3 shows our empirical results estimated from the model with lower and higher skilled labor, and Table 4 shows the results from the model by considering technical progress embodied in higher-skilled labor. As a proxy for the embodied technical rate of change, the exponential growth rates of the R&D stock with a two-year lag again were used.

In the skilled labor model, the best results were obtained by correcting C1 and C2 for second-order autocorrelation and C3 for third-order autocorrelation.

Table 3

Elasticities of Substitution-NCES Production Function
Lower and Higher Skilled Labor Force Model
the U.S. Economy, 1947-1989

Independent Variables	Alternative Specifications				
	C1	C2	C3	C4	C5
Constant	1.576	0.085	-8.220	-0.381	-1.127
	(13.972)	(0.076)	(-7.981)	(-1.581)	(-1.897)
$\log(r/w_3)_t$	0.013	0.004			
	(2.307)	(0.676)			
$\log(L_3/K)_{t-1}$		0.976			
		(20.901)			
$\log(w_{12})_t$			0.482	0.028	0.047
			(4.216)	(1.340)	(1.877)
$\log(YP/L_{12})_{t-1}$				0.963	0.812
				(65.408)	(7.325)
Time(t)					0.003
					(1.371)
Adj. R^2	0.973	0.987	0.994	0.996	0.996
D.W.	1.953	1.973	2.011	1.902	1.718
Durbin h				0.103	0.868
θ	0.013	0.146			
ξ		0.024			
σ			0.482	0.769	0.248
ζ				0.037	0.188
λ					0.003

Note: t-statistics are in parentheses. The models were estimated by correcting for second-order autocorrelation in C1 and C2 and third-order autocorrelation in C3. Models C4 and C5 were estimated using the method of OLS.

Table 4

Elasticities of Substitution-NCES Production Function
Technical Progress Embodied in Higher Skilled Labor
the U.S. Economy, 1947-1989

Independent Variables	Alternative Specifications				
	C1'	C2'	C3	C4	C5
Constant	1.486 (9.544)	0.099 (0.506)	-8.220 (-7.981)	-0.381 (-1.581)	-1.127 (-1.897)
$\log(r/w_3)_t$	0.002 (0.116)	0.004 (0.412)			
$\log(L_3/K)_{t-1}$		0.972 (14.670)			
$\log(w_{12})_t$			0.482 (4.216)	0.028 (1.340)	0.047 (1.877)
$\log(YP/L_{12})_{t-1}$				0.963 (65.408)	0.812 (7.325)
Time(t)					0.003 (1.371)
Adj. R^2	0.919	0.948	0.994	0.996	0.996
D.W.	1.871	1.883	2.011	1.902	1.718
Durbin h				0.103	0.868
θ	0.002	0.136			
ξ		0.028			
σ			0.482	0.769	0.248
ζ				0.037	0.188
λ					0.003

Note: t-statistics are in parentheses. Models C1' and C2' in the first level are corrected for first-order autocorrelation. Models C3, C4, and C5 in the second level were reproduced from Table 3.2.4 for reference since these results are the same as explained before.

Models C4 and C5 were estimated using OLS since Durbin's h statistics show no autocorrelation as shown in Table 3. In models C1' and C2' in Table 4, with technical progress embodied in the higher skilled labor, a correction was made for first-order autocorrelation.

The results in Table 3 are very consistent with the "capital-skill complementarity" hypothesis. The first level elasticity of substitution between physical capital and the number of higher skilled workers in C1 without the partial adjustment again is very low (i.e., 0.013) and only slightly higher (0.146) when the lagged adjustment term is introduced. Between the combined total capital factor and lower skilled labor the range is a much higher 0.482 to 0.769 without the time trend. Comparing the human capital stock model B2 with the labor force model C2, the former shows a higher elasticity estimate (0.303) than the latter (0.146). For the adjustment coefficient at the first level, both models show the same speed of adjustment (0.24). At the second level, the speed of adjustment is very similar (i.e., 5.7% in the human capital stock model B4 and 3.7% in the labor force model C4). The neutral technical change rate is nearly the same in both models (i.e., 0.2% for the human capital model and 0.3% for the skilled labor model).

Table 4 shows the new estimates of the elasticity of substitution assuming technical progress is embodied in higher skilled labor by means of the growth rate of R&D stock as in the human capital model. The first level elasticities of substitution between physical capital and the higher skilled labor are low and virtually the same where there is a lagged adjustment in C2 and C2' (14.6% and 13.6% in Tables 3 and 4) whereas the elasticities of substitution between the combined factor of total capital and raw labor where there is a similar lagged adjustment are similarly high (.769 in C4 and C4'). Compared with the human

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capital model, the skilled labor model with or without embodied technical progress in higher-skilled labor shows that the capital-skill complemetarity hypothesis is even more strongly confirmed.

V   Conclusions

This paper estimates elasticities of substitution among human capital, physical capital, and raw labor inputs for the U.S., developing a new linearized marginal productivity approach for estimating a nested CES production function. This method gives much more simple and stable estimates of elasticities. The empirical evidence for 1947-1989 shows that the elasticity of substitution between physical capital and human capital is less than that between total capital (the combined human and physical capital factor) and raw labor. This is shown for the first time using new human capital stock estimates, and also using the number in the labor force by education level to measure the quality of labor but with the production function the same in all other respects, thereby offering new evidence for the U.S. based on both measures consistent with Griliches' (1969) original finding of capital-skill complementarity. Furthermore, the elasticities of substitution at both levels are less than unity, which is also consistent with results obtained by Lucus (1969) who estimated elasticities of substitution *via* the simple CES function for U.S. industries.

Capital-skill complementarity implies that, for sustained economic growth, investment in human capital must be emphasized along with the expansion of physical capital or diminishing returns to physical capital will set in. There is no evidence of diminishing returns to investment in human capital in the U.S., except for school leavers after grade 8 (McMahon, 1991, Figure 3), (who may be more comparable to raw labor and inferior 'goods' in the labor market over time in the U.S.). Together these two points suggest that sustained increments to

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investment in human capital formation through education of given quality may be necessary as physical capital formation occurs to offset diminishing returns and maintain productivity growth.

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References

Arrow, K. J., Chenery, H. B., Minhas, B. S., and Solow, R. M. (1961), "Capital-Labor Substitution and Economic Efficiency," *Review of Economics and Statistics* 43, 225-250.

Bartel, A. P. and Lichtenberg, F. R. (1987), "The Comparative Advantage of Educated Workers in Implementing New Technology," *Review of Economics and Statistics* 69, 1-11.

Berndt, E. R. and Christensen, L. R. (1974), "Testing for the Existence of a Consistent Aggregate Index of Labor Inputs," *American Economic Review* 64, 391-404.

Bowles, S. (1970), "Aggregation of Labor Inputs in the Economics of Growth and Planning: Experiments with a Two-Level CES Function," *Journal of Political Economy* 78, 68-81.

Broer, D. P. and Janson, W. J. (1989), "Employment, Schooling and Productivity Growth," *De Economist 137*, 425-453.

Christensen, L. R., Jorgenson, D. W., and Lau, L. J. (1973), "Transcendental Logarithmic Production Function," *Review of Economics and Statistics* 55, 28-45.

Fallon, P. and Layard, P. (1975), "Capital-Skill Complementarity, Income Distribution, and Output Accounting," *Journal of Political Economy* 83, 279-301.

Gordon, R. J. (1990), *Macroeconomics*, Fifth edition, Scott, Foresman and Company.

Grant, J. (1979), "Labor Substitution in U.S. Manufacturing," Ph.D. Dissertation, Michigan State University.

Griliches, Z. (1969), "Capital-Skill Complementarity," *Review of Economics and Statistics* 51, 465-468.

Griliches, Z. (1970), "Notes on the Role of Education in Production Function and Growth Accounting," in *Education, Income, and Human Capital*, edited by W. L. Hansen, New York, 71-115.

Hamermesh, D. S. and Grant, J. (1979), "Econometric Studies of Labor-Labor Substitution and Their Implication for Policy," *Journal of Human Resources* 14, 518-542.

Johnston, J. (1984), *Econometric Methods*, McGraw-Hill Book Company.

Jorgenson, D. W. and Fraumeni, B. (1989),"Investment in Education," *Educational Researcher* 18, 35-44.

Jung, J. H. (1990), "Human Capital, Economic Growth, and Income Distribution: Korea and The United States," Ph.D. dissertation, University of Illinois at Urbana-Champaign.

Kendrick, John (1976), *The Formation and Stocks of Total Capital*, Columbia University Press, New York.

Kwag, C. G. (1991), "Human Capital, Economic Growth, and Income Distribution: Three Essays on Human Capital," Ph.D. dissertation, University of Illinois at Urbana-Champaign.

Lucus, R. E. Jr. (1969), "Labor-Capital Substitution in U.S. Manufacturing," in *The Taxation of Income from Capital*, edited by A. C. Harberger and M. J. Baily, Studies of Government Finance, The Brookings Institution, Washington, D.C.

Lucus, R. E. Jr. (1988),"On the Mechanics of Economic Development," *Journal of Monetary Economics* 22, 3-42.

McMahon, W. W. (1974), *Investment in Higher Education*, Lexington Books, D.C. Heath and Company.

McMahon, W. W. (1989), "Investment in Education and U.S. Productive Growth: Macrodynamic Model Estimates and Simulations,"Faculty Working Paper (in process), Bureau of Economic and Business Research, University of Illinois at Urbana-Champaign.

McMahon, W. W. (1991), "Relative Returns to Human and Physical Capital in the U.S. and Efficient Investment Strategies," *Economics of Education Review*, December 1991.

Office of Management and the Budget (1991), "Total Financial R&D Stocks," in Table 2A calculated by Strategic Economic Studies Staff, M. Wasserman, and N. Johnson, Executive Office of the President, Washington, D.C. (Background papers for the FY 1992 Budget).

Psacharopoulos, G. and Hinchliffe, K. (1972), "Further Evidence on the Elasticity of Substitution among Different Types of Educated Labor," *Journal of Political Economy* 80, 786-792.

Ritzen, J. M. M. (1989), "The Elasticities of Substitution between Labor with Different Levels of Education in the U.S.A.," Working Paper Department of Economics, University of Wisconsin at Madison.

Romer, P. M. (1986),"Increasing Returns and Long-Run Growth," *Journal of Political Economy* 94, 1002-1037.

Sato, K. (1967), "A Two-Level Constant-Elasticity-of-Substitution Production Function," *Review of Economics Studies* 34, 201-218.

Schultz, T. W. (1971), *Investment in Human Capital*, New York, The Free Press.

U.S. Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970*, Superintendent of Documents, Washington, D.C.

U.S. Bureau of the Census (1990), *Statistical Abstract of the United States*, Superintendent of Documents, Washington, D.C.

U.S. Bureau of the Census (1990), *Current Population Reports, Series P-20 and P-60*, Superintendent of Documents, Washington, D.C.

U.S. Council of Economic Advisors (1990), *Economic Report of the President*, Superintendent of Documents, Washington, D.C.

U.S. Department of Commerce (1989), *Survey of Current Business*, Superintendent of Documents, Washington, D.C.

U.S. Department of Education (1989), *Digest of Education Statistics* and *Biennial Survey of Education*, Superintendent of Documents, Washington, D.C.

Wasserman, Mark (1991), "Human Capital Stock 1990-2030 and R&D Projects," Office of Management and the Budget, Strategic Economic Analysis Group, Executive Office of the President, Washington, D.C.

White, K. J., Haun, S. A., Horsman, N. G., and Wong, S. D. (1990), *SHAZAM: Econometric Computer Program*, version 6.2, McGraw-Hill Book Company.