The U.S. Technology Frontier

By Francesco Caselli and Wilbur John Coleman II*

In Caselli and Coleman (2000) we developed a framework that separately identifies the efficiency units embodied in unskilled labor, skilled labor, and capital in a country's aggregate production function. Applying that framework to cross-country data, we showed that countries where unskilled labor is relatively abundant are those with the most efficient unskilled workers, while countries where skilled labor and capital are abundant are the most efficient users of these inputs. We interpreted these findings as evidence of appropriate-technology adoption: in each country firms choose from a menu of technologies; different technologies imply different combinations of values for the efficiency units embodied in the three factors of production; in each country the technology is chosen that makes the most of the most abundant factors.

In this paper we apply the same framework to time-series data from the United States over the period 1963–1992. We find that throughout this period the efficiencies of skilled labor and capital have risen. The efficiency of unskilled labor has risen in tandem with those of the other factors in the early part of the sample, but surprisingly, it has been falling since sometime in the 1970's (the exact turning point depends somewhat on some parametric assumptions). In analogy with the cross-country evidence, these changes are closely associated with changes in the relative abundance of skilled labor and capital, which increased rather dramatically. In this sense, the recent history of technologies in use by U.S. firms may mimic the choice of technol-

ogies around the world today: as skills and capital become more abundant, technologies are chosen that maximize the efficiency of these inputs. As we discuss below, however, in the U.S. context the converse story (relative labor supplies adjusting to exogenous changes in technology) is also consistent with the data.

Besides its relevance to models of technology adoption, this evidence also sheds new light on the widely documented recent increase in the skilled wage premium in the United States. Lawrence F. Katz and Kevin M. Murphy (1992) and David H. Autor et al. (1998) used the relative wage and the relative labor supply series to show that the efficiency of unskilled labor relative to skilled labor must have declined over time. Our framework allows us to go further and show that, indeed, the *absolute* efficiency of unskilled labor has fallen (after 1970), while the efficiency of skilled labor and capital have increased. A similar result was obtained with different techniques by Marta Ruiz Arranz (2001).

I. The Framework

The framework is the one in Caselli and Coleman (2000), to which we refer the reader for further details and motivation. We start by adopting the constant-elasticity-of-substitution production function of Per Krusell et al. (2000):

$$(1) \quad Y_t = \{(A_t^u L_t^u)^\sigma + [(A_t^s L_t^s)^\rho + (A_t^k K_t)^\rho]^{\sigma/\rho}\}^{1/\sigma}$$

where σ, $\rho < 1$. In equation (1) Y_t is GDP per worker in period t, L_t^u, L_t^s, and K_t are per-worker inputs of unskilled labor, skilled labor, and capital, and A_t^u, A_t^s, and A_t^k are the period-t efficiency levels of unskilled labor, skilled labor, and capital. The elasticity of substitution between skilled and unskilled labor, and between capital and unskilled labor, is $1/(1 - \sigma)$. The elasticity of substitution between skilled labor and capital is $1/(1 - \rho)$. The parameters σ

and ρ are assumed to be constant across time, while the efficiency levels A_t^{u}, A_t^{s}, and A_t^{k} can vary over time.

Assume that production of output takes place in perfectly competitive markets. Then the marginal productivity of capital must equal r_t, which is the real interest rate plus the rate of depreciation on physical capital:

$$(2) \quad r_t = \{(A_t^{\mathrm{u}}L_t^{\mathrm{u}})^\sigma + [(A_t^{\mathrm{s}}L_t^{\mathrm{s}})^\rho$$
$$+ (A_t^{\mathrm{k}}K_t)^\rho]^{\sigma/\rho}\}^{(1/\sigma)-1}[(A_t^{\mathrm{s}}L_t^{\mathrm{s}})^\rho$$
$$+ (A_t^{\mathrm{k}}K_t)^\rho]^{(\sigma/\rho)-1}(A_t^{\mathrm{k}}K_t)^{\rho-1}A_t^{\mathrm{k}}.$$

Furthermore, from the condition that each of the two wage rates, w_t^{s} and w_t^{u}, equals the marginal productivity of the corresponding labor aggregate we get

$$(3)$$

$$\frac{w_t^{\mathrm{s}}}{w_t^{\mathrm{u}}} = \frac{((A_t^{\mathrm{s}}L_t^{\mathrm{s}})^\rho + (A_t^{\mathrm{k}}K_t)^\rho)^{(\sigma/\rho)-1}(A_t^{\mathrm{s}}L_t^{\mathrm{s}})^{\rho-1}A_t^{\mathrm{s}}}{(A_t^{\mathrm{u}}L_t^{\mathrm{u}})^{\sigma-1}A_t^{\mathrm{u}}}.$$

Given data on labor endowments, output, and factor prices for a given period, and a choice of σ and ρ, equations (1), (2) and (3) constitute a system of three equations in the three unknowns A_t^{u}, A_t^{s}, and A_t^{k}.[1] Essentially, then, for a given specification of the production function, along with observations for output (GDP), the inputs into production (unskilled labor, skilled labor,

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[1] This system of equations has a closed-form solution. The solution is

$$A^{\mathrm{u}} = \frac{Y}{L^{\mathrm{u}}}(1 - S)^{1/\sigma}$$

$$A^{\mathrm{s}} = \frac{Y}{L^{\mathrm{s}}}\left[1 - \frac{r(K/Y)}{S}\right]^{1/\rho}S^{1/\sigma}$$

$$A^{\mathrm{k}} = \left[\frac{r(K/Y)^{1-\rho}}{S}\right]^{1/\rho}S^{1/\sigma}$$

where

$$S = \frac{\dfrac{w^{\mathrm{s}}L^{\mathrm{s}}}{w^{\mathrm{u}}L^{\mathrm{u}}} + \dfrac{rK}{Y}}{\dfrac{w^{\mathrm{s}}L^{\mathrm{s}}}{w^{\mathrm{u}}L^{\mathrm{u}}} + 1}.$$
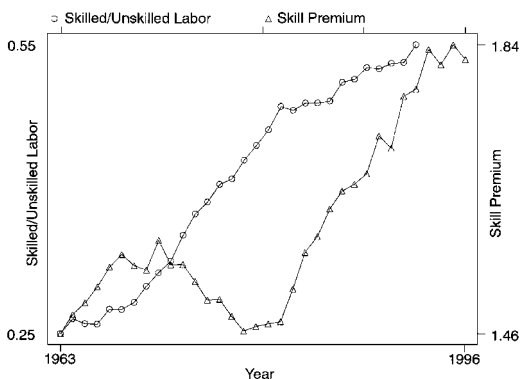

FIGURE 1. TIME PATHS OF THE LOG COLLEGE WAGE PREMIUM AND LOG RELATIVE SUPPLIES OF SKILLED AND UNSKILLED LABOR

and capital), and prices (the skilled wage premium and the real interest rate), we determine the efficiency of each input such that a model with perfectly competitive markets is consistent with all these observations. Solving this system for each period in our sample allows one to examine the time-series behavior of the relative efficiencies of unskilled labor, skilled labor, and capital.

II. The Data and Results

Data for Y_t and K_t are obtained from the Bureau of Economic Analysis web page.[2] Data for L_t^{u} and L_t^{s} are taken from Krusell et al. (2000). L^{s} refers to labor supply of individuals with at least a college degree, while L^{u} contains the rest of the labor force. Data for $w^{\mathrm{s}}/w^{\mathrm{u}}$ are from Katz and Autor (1999). As in Caselli and Coleman (2000) we set r_t to its historical average value of 0.12. For σ and ρ we use the values estimated in Caselli and Coleman (2000) (i.e., $\sigma = \rho = 0.25$). As we discuss below, our key results are quite robust to alternative choices of functional-form specification, values of r_t (including time-varying), and choices of σ and ρ.

Figure 1 shows the well-known time paths of the (log) college wage premium and of the (log) relative supplies of skilled and unskilled labor. The former rises from 1963 to 1971, falls from

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[2] URL: ⟨http://www.bea.doc.gov/⟩. GDP is in billions of chained 1996 dollars. Capital is nonresidential private fixed assets in billions of chained 1996 dollars.
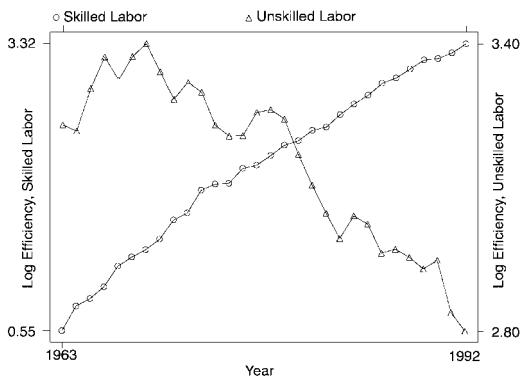
FIGURE 2. EFFICIENCY LEVELS OF SKILLED
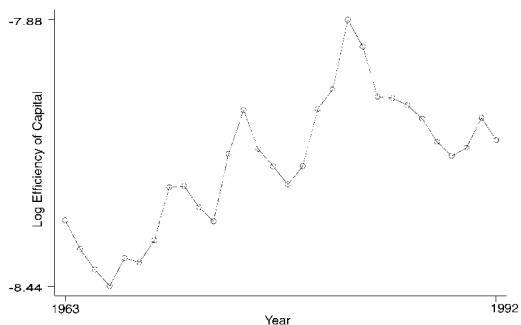AND UNSKILLED LABOR, 1963–1992

FIGURE 4. LOG EFFICIENCY OF SKILLED
VERSUS UNSKILLED LABOR

Note: Years are indicated by two-digit numbers (e.g., 63 = 1963).

FIGURE 3. EFFICIENCY LEVEL OF CAPITAL, 1963–1992

1971 to 1980, and rises from 1980 to 1992. The latter rises throughout the sample period.

Figures 2–4 summarize the results of computing efficiency levels for unskilled labor, skilled labor, and capital with the methodology and data described above. As shown in Figures 2 and 3, the efficiency of skilled workers and capital rises throughout this period. However, the efficiency of unskilled workers rises from 1963 until around 1969 and then begins to decline, so that by the end of the sample the efficiency of unskilled workers is much less than at the beginning.

Overall, as highlighted in Figure 4, there is a strong negative correlation between the efficiency of skilled workers and capital, on the one hand, and the efficiency of unskilled workers on the other hand. This last figure is very similar to the one we obtained in Caselli and Coleman (2000). The difference is that countries have
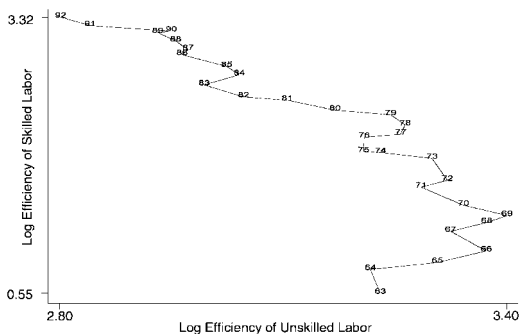
been replaced by years. As in the cross-country context, years (countries) with a relatively low ratio of L^s to L^u tend to be toward the bottom-right corner, while years (countries) with high L^s/L^u tend to be on the top-left corner.

Upon surveying the literature, Krusell et al. (2000) argue that representative "off-the shelf" estimates of σ and ρ are 0.33 and -0.67, respectively. Their own estimates are 0.4 and -0.5.[3] We checked for robustness to these alternative choices. Furthermore, we verified robustness to using a time-varying interest rate r_t, constructed by subtracting the (*ex post*) inflation rate from the one-year Treasury-bill nominal interest rate (and adding a 10-percent depreciation rate). Finally, and perhaps most importantly, we checked for robustness in the context of a simplified two-factor version of the model, without capital: this version uses only two equations, (1) and (3), to estimate only the unknowns A^s and A^u. This check is particularly important because it corresponds to the model used by Katz and Murphy (1992). All these checks confirmed that the efficiency of skilled labor in-

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[3] The values of the elasticity of substitution between skilled and unskilled labor corresponding to the various choices of σ range between 1.35 and 1.66, in line with the predominant consensus (see Autor and Katz, 1998). The elasticity of substitution between skilled labor and capital ranges much more widely, from 0.6 to 1.35, a symptom that we know much less about this parameter. It may be useful to note that, while our baseline choices of σ and ρ imply no capital–skill complementarity, the alternative two choices do.

creased in the 1960s, and decline sharply in the 1980s. Different specifications differ somewhat on whether in the 1970s it mildly decreased, mildly increased, or stayed roughly unchanged.

To see the relationship with Katz and Murphy (1992), recall that they run a regression of the log of w_t^s/w_t^u on the log of L_t^s/L_t^u and a time trend. A look at equation (3) clearly shows that the coefficient on the time trend is an estimate of the trend in the ratio A_t^s/A_t^u. Since this trend is positive, Katz and Murphy argue that it is an important part of an explanation for the behavior of the skill premium in the United States. Here we have shown that not only did the relative efficiency of skilled labor rise, but it rose more strongly that the efficiency of unskilled labor fell from 1969 to 1992.[4]

Because they are obtained by solving three equations in three unknowns, our estimated time series for A^s, A^u, and A^k do not depend on assumptions of exogeneity of the factor supplies or the factor prices. Hence, our account of the recent history of technology adoption and relative wage changes in the United States is consistent both with an interpretation in which the A's change exogenously and factor supplies adjust (as in Oded Galor and Daniel Tsiddon [1997], Jeremy Greenwood and Mehmet Yorukoglu [1997], and Caselli [1999]) and with one in which factor supplies change exogenously and firms respond by appropriately modifying technologies (as in Daron Acemoglu [1998])—or a combination of the two! In the cross-country paper we were able to identify additional patterns in the data (namely, that in the cross-section w^s/w^u is *negatively* correlated

with A^s/A^u and L^s/L^u) that induced us to emphasize the "endogenous-technology" interpretation over the "endogenous skilled-labor supply" one. However, in the U.S. time series, the overall trends in the data are consistent with either interpretation.[5]

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[4] Krusell et al. (2000), who analyze the same data under the assumption that A^s/A^u and A^k/A^u are constant, argue that the positive time trend in Katz and Murphy (1992) is picking up a large increase in the stock of equipment, which is complementary to skilled labor. Ruiz Arranz (2001), however, shows that adding various measures of the stock of equipment to the Katz and Murphy regression does not make the time trend "go away," and so a role for varying efficiency ratios is still called for by the data. She then proceeds with a structural estimation of a translog production function with separate time trends for the factor biases in technical change, a procedure that is roughly equivalent to estimating time trends for A^k, A^s, and A^u. Consistent with our finding for the later part of the sample, she finds a negative trend for the unskilled-labor bias of technical change.

[5] One may perhaps rely on the fact that in the 1970's skilled labor supply continued to increase even though the skill premium was falling to argue for the "endogenous technology" version (see Acemoglu, 1998). However, given that human-capital investments tend to be made at the beginning of life, it may be that skilled-labor supply rose in the 1970's in anticipation of high (exogenous) A's in the 1980's.

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