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Analyzing skilled and unskilled labor efficiencies in the US

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ABSTRACT

In this paper, I analyze the time paths of the efficiencies of skilled and unskilled labor in a production framework where skilled and unskilled labor are imperfect substitutes. Their implications for economic growth and wage inequality in the US between 1950 and 2005 present two main findings. First, although skilled labor efficiency has a strong upward trend, I find no evidence of acceleration in its growth rate to support the common view that there has been an acceleration in the new skilled-biased technologies. Second, beginning around 1970, there has been a decline in the absolute level of the efficiency of unskilled labor, implying that the decline has played a significant role in the overall productivity slowdown and the substantial widening in the US wage structure.

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1. Introduction

This paper investigates how skilled and unskilled labor efficiencies have evolved since 1950. Toward this end, I extend the standard two-factor production function to a four-factor production function with capital structure, capital equipment, skilled labor, and unskilled labor, where these factors are imperfect substitute with each other. Assuming that markets are competitive and parameters of the model are known, I derive time series of capital equipment, skilled, and unskilled labor efficiencies from the data.

The paper is motivated by two important facts. First, previous studies that investigate the sources of US economic growth decompose changes in output into changes in factors of production and change in overall efficiency (total factor productivity). These studies also assume that skilled and unskilled labor are perfect substitutes (see, e.g., Jones, 2002; Ha and Howitt, 2007). Considering a more general production framework in which inputs are imperfect substitutes and decomposing overall efficiency into capital, skilled, and unskilled efficiencies provides a better understanding of the sources of US growth. Second, over the last 50 years in the US, there have been dramatic changes in the relative supply of skills and the skill premium, defined as the ratio of the skilled labor wage to the unskilled labor wage. As shown in Fig. 1, despite the rapid increase in the relative supply of skills, there has been a substantial increase in the skill premium over this period. Another aspect of Fig. 1 is that the skill premium has trended sharply upward since the early 1980s. This pattern underlines the common view that

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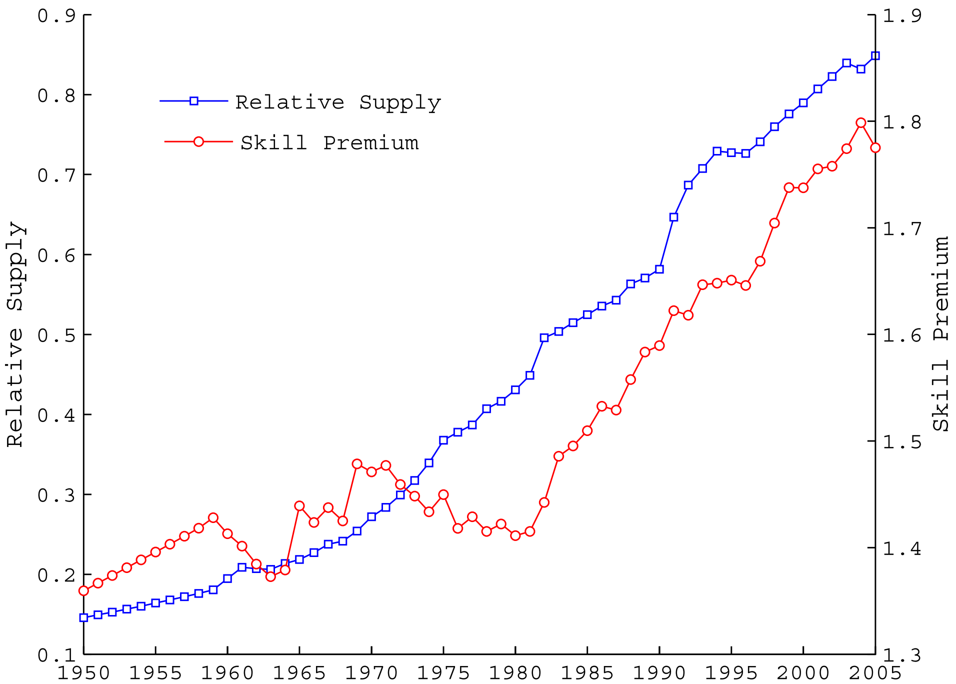

Fig. 1. Relative supply of skills vs. skill premium. *Notes:* The skilled labor class consists of college or college-plus workers and half of the workers with some college; and the unskilled labor class consists of high school dropouts, high school graduates, and half of the workers with some college. The relative supply of skills is defined as ratio of total hours worked by skilled labor to that by unskilled labor.

new technologies have been skill-biased and there has been an acceleration in skill-biased technical change.[1] One may wonder how the efficiencies of skilled and unskilled labor have changed over this period.

The main findings of this paper can be summarized as follows. First, I find that although skilled labor efficiency has a strong upward trend, there is no evidence of acceleration in its growth rate. Interestingly, I also find that beginning around 1970, there has been a *decline* in the absolute level of the efficiency of unskilled labor, although the magnitude of the decline is relatively less when there is a higher elasticity of substitution between skilled and unskilled labor. This is in sharp contrast to the period of 1950–1970, during which unskilled labor efficiency was generally rising. Finally, I find that the time paths of the capital equipment efficiency depend on the elasticity of substitution between capital equipment and skilled labor.

This paper is related to the accounting literature that investigates the sources of growth in the US economy.[2] The paper contributes to this literature by decomposing changes in overall efficiency into changes in efficiencies of capital (equipment), skilled labor, and unskilled labor.[3] In backing out the actual levels of efficiencies from the data, this paper follows Caselli and Coleman (2002) who, applying a different production framework to time series data from the US over 1963–1992, find that throughout this period efficiency of skilled labor and capital have risen, while the efficiency of the unskilled labor has fallen since the early 1970s.[4] This paper differs from theirs in two important aspects. First, it uses a more general production function in which there are two different types of capital (structure and equipment) as opposed to the single aggregate capital input in Caselli and Coleman (2002). Using a single aggregate capital input, they implicitly assume that capital structure and equipment are perfect substitutes, which is inconsistent with the data.[5] The time paths of capital equipment and skilled labor efficiencies obtained from this general production function also differ from those in Caselli and Coleman (2002).[6] Second, this paper con-

[1] The literature on this subject is vast. Important contributions are Bound and Johnson (1992), Katz and Murphy (1992), and Acemoglu (1998). See Acemoglu (2002) for a more comprehensive review of the literature.

[2] See Solow (1957), Jones (2002), and Jorgenson (2005), among many others.

[3] Growth in the efficiency of skilled labor is the largest contributor to output per hour growth in this decomposition, accounting for between about 30% and 120% of growth (depending on the exact value of parameters in the model, the definition of skilled labor, and the time period considered in the exercise), while changes in the efficiency of unskilled labor accounts for between about −90% and 50% of growth (see Sections 3 and 4).

[4] Under a different production framework, Caselli and Coleman (2006) use the same methodology to study *cross-country* differences in skilled and unskilled labor efficiencies when skilled and unskilled labor are imperfect substitutes. They show that higher-income countries use skilled labor more efficiently than lower-income countries, but they use unskilled labor relatively less efficiently. This paper shows that the efficiency of unskilled labor is not monotonically declining with an increase in the income level using the US *time-series*.

[5] The production framework used in this paper is similar to that in Krusell et al. (2000), who argue that this general production function is more consistent with the US data. Furthermore, in analyzing the effect of investment-specific technical change on productivity, Greenwood et al. (1997) find that a Cobb–Douglas production function with two different capital inputs (equipment and structure) fits the US data better.

[6] For example, when capital is complementary to skilled labor in this general framework, I find that skilled labor efficiency has grown more slowly (in particular, since the mid 1980s) than that in Caselli and Coleman (2002). However, I also find that capital equipment efficiency has grown much faster than the efficiency of (aggregate) capital in Caselli and Coleman (2002). See Section 4.3 for more details.

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ducts extensive accounting exercises in order to investigate how the evolutions of efficiencies have affected economic growth and wage inequality in the US.

The present study is also related to the wage inequality literature that typically addresses the determinants of the dramatic changes in the US skill premium (see Katz and Murphy, 1992; Krusell et al., 2000; Autor et al., 2008, among many others). These studies address the roles of different types of technical changes on the skill premium by estimating an econometric specification. In this paper, on the other hand, I derive the time series behavior of skilled and unskilled labor efficiencies directly from the data, using a few assumptions widely accepted in the literature.

The rest of this paper is organized as follows. Section 2 introduces the benchmark production framework that underlies the analysis. Section 3 presents the quantitative analysis in which the main features of the data are explained and the main results are presented. Section 4 studies robustness of results and compares them to those in the previous studies. Finally, Section 5 offers some concluding remarks.

2. Modeling production

I consider a production function which is Cobb–Douglas over capital structure (K_b), and a nested constant-elasticity of substitution (CES) function of capital equipment (K_e), skilled labor (L_s), and unskilled labor (L_u) as in Krusell et al. (2000):

$$Y_t = K_{bt}^{\alpha_b}\left\{[(A_{et}K_{et})^{\rho_2} + (A_{st}L_{st})^{\rho_2}]^{\frac{\rho_1}{\rho_2}} + (A_{ut}L_{ut})^{\rho_1}\right\}^{\frac{1-\alpha_b}{\rho_1}}, \tag{1}$$

where $\alpha_b \in (0,1)$ represents the share of capital structure in total output, and ρ_1 and ρ_2 are two parameters that drive the elasticity of substitution between skilled labor, equipment, and unskilled labor. The elasticity of substitution between skilled labor (or equipment) and unskilled labor is $\sigma_1 = 1/(1-\rho_1)$, and the elasticity of substitution between equipment and skilled labor is $\sigma_2 = 1/(1-\rho_2)$. In this specification, A_e, A_s, and A_u represent the efficiency of equipment (or equipment augmenting technology), the efficiency of skilled labor (or skilled labor augmenting technology), and the efficiency of unskilled labor (unskilled labor augmenting technology), respectively.[7]

Factor markets are assumed to be competitive so that each factor earns its marginal product. The first order conditions with respect K_e, L_s, and L_u yield (upon rearranging terms)

$$\frac{r_eK_e}{w_sL_s} = \left(\frac{A_eK_e}{A_sL_s}\right)^{\rho_2}, \tag{2}$$

$$\frac{w_sL_s}{w_uL_u} = \left[1 + \left(\frac{A_eK_e}{A_sL_s}\right)^{\rho_2}\right]^{\frac{\rho_1-\rho_2}{\rho_2}}\left(\frac{A_sL_s}{A_uL_u}\right)^{\rho_1}, \tag{3}$$

where r_e represents the return to capital equipment (i.e., real interest rate plus the rate of depreciation); and w_s and w_u are the wage rates of skilled and unskilled labor, respectively.

Given data on output, factor inputs, factor prices, and assuming that parameters α_b, ρ_1, and ρ_2 are known, Eqs. (1)–(3) constitute a system of three equations with three unknowns A_e, A_s, and A_u, which has a closed-form solution:

$$A_e = \left(\frac{Y}{K_e}\right)\left(\frac{Y}{K_b}\right)^{\frac{\alpha_b}{1-\alpha_b}}\left(\frac{\alpha_e}{\alpha_e+\alpha_s}\right)^{\frac{1}{\rho_2}}\left(\frac{\alpha_e+\alpha_s}{1-\alpha_b}\right)^{\frac{1}{\rho_1}}, \tag{4}$$

$$A_s = \left(\frac{Y}{L_s}\right)\left(\frac{Y}{K_b}\right)^{\frac{\alpha_b}{1-\alpha_b}}\left(\frac{\alpha_s}{\alpha_e+\alpha_s}\right)^{\frac{1}{\rho_2}}\left(\frac{\alpha_e+\alpha_s}{1-\alpha_b}\right)^{\frac{1}{\rho_1}}, \tag{5}$$

$$A_u = \left(\frac{Y}{L_u}\right)\left(\frac{Y}{K_b}\right)^{\frac{\alpha_b}{1-\alpha_b}}\left(\frac{\alpha_u}{1-\alpha_b}\right)^{\frac{1}{\rho_1}}, \tag{6}$$

where α_j represents the share of factor j in total output.[8]

Having A_e, A_s, and A_u, one can easily implement a growth accounting exercise to assess their importance to output growth. Taking the logarithm of both sides in Eq. (1) and differentiating with respect to time yields

$$g_Y = \varepsilon_b g_{K_b} + \varepsilon_e g_{K_e} + \varepsilon_s g_{L_s} + \varepsilon_u g_{L_u} + \varepsilon_e g_{A_e} + \varepsilon_s g_{A_s} + \varepsilon_u g_{A_u},$$

where g_x represents the growth rate of variable x and $\varepsilon_x = (\partial Y/\partial x)(x/Y)$ is the elasticity of x with respect to output Y. It follows that $\varepsilon_j = \alpha_j$, with $j = b, e, s,$ and u.[9] Furthermore, as will be discussed in the next section, the labor input is

[7] Although the production function in (1) is similar to that in Krusell et al. (2000), there is an important distinction between the two functions. The efficiency of capital equipment is constant in Krusell et al., while it changes over time in my specification.

[8] Using (2) in (1) yields an equation with two unknowns A_s and A_u. Using (2) in (3) yields another equation for A_s and A_u. Solving these two equations for A_s and noticing that $r_eK_e + w_sL_s + w_uL_u = (1-\alpha_b)Y$ yields (5).

[9] Since markets are competitive, $\partial Y/\partial K_e = r_e$, and hence, $\varepsilon_e = (\partial Y/\partial K_e)(K_e/Y) = r_eK_e/Y = \alpha_e$. Using the same steps, it easily follows that $\varepsilon_j = \alpha_j$, for $j = b, s,$ and u.

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quality-adjusted: $L_{jt} = q_{jt}N_{jt}$, where q_{jt} represents the quality index of j-type labor, and N_{jt} is the total hours worked by the corresponding individuals. Let N_t denote the total labor hours worked (i.e., $N_t = N_{st} + N_{ut}$), then the above equation yields

$$g_y = \beta_b g_{k_b} + \beta_e g_{k_e} + \beta_s g_{q_s} + \beta_s g_{n_s} + \beta_u g_{q_u} + \beta_u g_{n_u} + \beta_e g_{A_e} + \beta_s g_{A_s} + \beta_u g_{A_u}, \quad (7)$$

where $\beta_j = \alpha_j/(\alpha_s + \alpha_u)$ and $y \equiv Y/N$, $k_b = K_b/Y$, $k_e = K_e/Y$, and $n_j = N_j/N$. The quality index q_j can be interpreted as human capital accumulated through schooling, job-training, and work experience; whereas A_j can be thought of as an index for technology, institutional quality, effectiveness of the organizational structure, etc., that augments the efficiency of j-type labor.

As noted by Hall and Jones (1999), the motivation for considering changes in the capital–output ratio rather than changes in the capital–labor ratio is that in the steady-state the capital–output ratio is constant while the capital–labor ratio continues to grow. Thus, using the capital–labor ratio in the above equation would incorrectly attribute a substantial part of the labor productivity growth to capital deepening.

Eq. (7) decomposes labor productivity (output per hour) into several components that have specific interpretations. The terms $\beta_b g_{k_b}$ and $\beta_e g_{k_e}$ measure the contribution of capital deepening to the labor productivity growth. The terms $\beta_s g_{q_s}$ and $\beta_u g_{q_u}$ represent the contributions of changes in the quality of skilled and unskilled labor, respectively, to the labor productivity growth; while $\beta_s g_{n_s}$ and $\beta_u g_{n_u}$ represent the contribution of changes in labor allocation to the productivity growth. The final terms, $\beta_e g_{A_e}$, $\beta_s g_{A_s}$, and $\beta_u g_{A_u}$, measure the contributions of equipment, skilled, and unskilled augmenting efficiency changes to labor productivity growth, respectively. The discrete time approximation of (7) is given by

$$\hat{y}_t = \bar{\beta}_{bt}\hat{g}_{k_{bt}} + \bar{\beta}_{et}\hat{g}_{k_{et}} + \bar{\beta}_{st}\hat{q}_{st} + \bar{\beta}_{st}\hat{n}_{st} + \bar{\beta}_{ut}\hat{q}_{ut} + \bar{\beta}_{ut}\hat{n}_{ut} + \bar{\beta}_{et}\widehat{A}_{et} + \bar{\beta}_{st}\widehat{A}_{st} + \bar{\beta}_{ut}\widehat{A}_{ut}, \quad (8)$$

where $\hat{x}_t = \ln x_t - \ln x_{t-1}$ represents the growth rate of variable x in year t and $\bar{\beta}_{jt} = 0.5(\beta_{j,t-1} + \beta_{j,t})$.

3. Quantitative analysis

In this section, I will apply the key results presented in the previous section to investigate the effects of capital, skilled, and unskilled labor efficiencies on economic growth and the skill premium since 1950. I start with the construction of key variables used in the model.

3.1. The data

The data on output and capital are obtained from the Bureau of Economic Analysis (BEA), they are in 2000 chain-dollars. Capital structure does not include residential buildings, and capital equipment includes equipment and machinery as well as intangible assets such as software.[10] Since residential buildings are not included in capital structure, residential service is netted out from the gross output.[11]

The key point in this exercise is the construction of the skilled and unskilled labor input and wages. The sources of labor input data are from the Census Surveys 1950 and 1960, and the March Current Population Surveys (CPSs) from 1962 to 2006. Since wages and labor data in the survey refer to one year earlier, the sample spans the period 1949–2005.[12] I consider all employed people between 16 and 70 years old, excluding self-employed workers as in Autor et al. (2008).

Construction of the series for skilled and unskilled labor is accomplished in two steps. First, the data in each year are divided into 72 distinct labor groups (characterized by sex, years of education, and years of experience) and their average labor inputs (measured as total hours) and hourly wages are calculated using census sampling weights.[13] In the second step, I sort these groups into skilled and unskilled labor. Following much of the literature, I assume that everyone who has at least 16 years of schooling is considered as skilled, and those who have fewer years of schooling are classified as unskilled. I will later consider an alternative classification scheme used by Autor et al. (2008) in which the skilled labor class consists of college or college-plus workers and half of the workers with some college; the unskilled labor class consists of high school dropouts, high school graduates, and half of the workers with some college. Qualitative results remain the same.

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10 Krusell et al. (2000) criticize the BEA capital series for not properly taking quality adjustment into account, and they construct an alternative capital equipment series based on the price deflators for investment in equipment and machinery from Gordon (1990). However, the BEA has substantially revised the series by increasingly using the hedonic price techniques for quality adjustment when measuring price changes (Wasshausen and Moulton, 2006). Furthermore, the use of Grodon's series does not come without any concession. First, the series are only available until 1983, which requires imputation of price indexes for the remaining 22 years. Second, Gordon's series declines too rapidly after 1975 suggesting considerable measurement errors (Acemoglu, 2002).

11 This correction also reduces the possible measurement errors stemming from imputation of residential income. However, results are robust even if this correction is not made. Since there is no better alternative to the BEA series, the other measurement errors in output and capital stocks cannot be avoided.

12 Since the Census Surveys are conducted every 10 years, the data between 1950 and 1960 are not available. Also, there is no CPS data before 1962 and the 1963 CPS does not have education data. For intervening years, I impute each *group*'s data by log-linearly interpolating the same group's data in available neighboring surveys. Results qualitatively remain the same, if linear interpolation is used.

13 A complete description of the data sets and construction of aggregate variables are provided in a separate appendix which is available upon request. I also considered an analysis based on weekly wages. However, results based on weekly wages remained mostly the same.

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Groups within a class are assumed to be perfect substitutes and, following the standard practice in this literature, I use group relative hourly wages as weights for the aggregation of labor inputs into skilled and unskilled classes. The basic idea is based on the assumption that relative wages equal relative qualities of labor.[14] Thus, labor input is quality-adjusted.

The corresponding *quality-adjusted* average wage rate for each class is calculated as $w_{jt} = W_{jt}/L_{jt}$, where W_{jt} is the total compensation paid to the class j workers. The rental price of capital, r_e, is calculated by using the Hall–Jorgenson formula: $r_e = (i - \pi_k^e + \delta)(1 - z\tau)/(1 - \tau)$, where i is the nominal after corporate tax interest rate, π_k^e is the expected rate of inflation in capital equipment price, δ is the rate of economic depreciation, τ is corporate tax rate, and z is the present value of depreciation deduction on a \$1 investment.[15] I set $\delta = 0.125$ as in Greenwood et al. (1997), and following Gale and Orszag (2005), $\tau = 0.35$ (the average statutory tax rate in the US) and $z = 0.83$. The results are robust to alternative depreciation rates (e.g., 10% or 15%). To construct the A_e, A_s, and A_u series, the three parameters must be known—α_b, ρ_1, and ρ_2. The parameter α_b measures the capital structures share and I set it to 0.12 which is consistent with previous estimates (Krusell et al., 2000).

The parameter ρ_1 governs the elasticity of substitution between skilled and unskilled workers (σ_1), and there is now a large labor economics literature focused on estimating its value. The common view is that σ_1 is around 1.5 (Acemoglu, 2002). For example, using the CPSs data over the period 1963–1987 together with a production function with no capital input, Katz and Murphy (1992) find that the elasticity is 1.41; and Autor et al. (2008) extend the period to 2005, and report that it is about 1.6. Krusell et al. (2000), using a production function similar to mine, find that this elasticity is about 1.7. Indeed, based on various econometric estimates, Autor et al. (1998) conclude that this elasticity is very unlikely to be greater than 2. In my main analysis, I will set $\rho_1 = 0.33$ ($\sigma_1 = 1.5$), but I will later present results based on $\rho_1 = 0.5$ ($\sigma_1 = 2$).

The parameter ρ_2 drives the elasticity of substitution between capital equipment and skilled labor. Estimates of the elasticity of substitution between capital (which may contain structures) and skilled labor are usually less than 1.2 (Hamermesh, 1993). Krusell et al. (2000), for example, find that $\rho_2 = -0.495$, implying that the elasticity of substitution between equipment and skilled labor is 0.67. In subsequent analysis, I consider two possibilities: $\rho_2 = -0.5$ ($\sigma_2 = 0.67$) and 0.25 ($\sigma_2 = 1.25$). But $\rho_2 < 0$ is a more plausible choice in the current context, since capital equipment and capital structure enter separately into the production function as in Krusell et al. (2000).

3.2. Main results

Fig. 2a and b plot the corresponding time paths of (log) capital equipment, skilled and unskilled labor efficiencies. There are several interesting aspects to note in these figures, and I start with analyzing the time paths of skilled labor. First, although there is an increase in skill premium since the early 1980s (see Fig. 1), there is *no* acceleration in A_s. Indeed, according to Fig. 2a, the efficiency of skilled labor has grown more slowly since the mid 1980s: the average annual growth rate of A_s between 1950 and 1985 is about 7.8%, while it is 2.5% between 1985 and 2005.[16] These results question the validity of the standard view that the increased wage inequality observed since the early 1980s has resulted from an acceleration in skill-biased technical change. If there had been an acceleration in skill-biased technical change, why is there no signature of it as could be demonstrated by a substantial increase in the growth rate of A_s in both figures?

Second, A_u has declined since around 1970. The average annual growth rate of A_u between 1950 and 1970 is 1%, while it is -1.4% since 1970.[17] Had A_u continued to grow at 1.0% annually after 1970, the skill premium would have been about 24% lower than the actual premium in 2005. The output would have been about 47% higher than the actual output in 2005.

Finally, although A_e has a strong upward trend with an average annual growth rate of 6.8% in Fig. 2a, its trend become less clear when capital is an imperfect substitute with skilled labor (see Fig. 2b). Since the early 1980s, there is no clear trend in A_e. The average annual growth rate of A_e between 1950 and 1980 is about 6.2%, while it is about 0.2% over the period 1983–2005. Interestingly, had A_e continued to grow at 6.2% annually after 1980, the skill premium and output (and hence, per capita income) would have been about 3% and 17%, respectively, higher than the corresponding actual values in 2005.

Table 1 reports the growth accounting exercises based on Eq. (8) with $\rho_1 = 0.33$ and $\rho_2 = -0.5$. The contribution of capital and labor inputs to labor productivity growth over 1950–2005 is 17%. The remaining 83% of growth is attributed to changes in efficiencies. This effect itself is the sum of three components. First, growth in the efficiency of capital equipment accounts for 29% of output growth. Second, growth in the efficiency of skilled labor is the largest contributor to productivity growth in this decomposition, accounting for 68% of output growth. Finally, changes in the efficiency of unskilled labor accounts for -14% of growth. Table 1 also reports the accounting exercises for different time periods.

There are several interesting points in this table that deserve further attention. First, the contribution of capital deepening to labor productivity growth is small. Indeed, a comparison of the two sub-periods reveals that capital deepening cannot be responsible for the observed productivity slowdown during the second period. Second, the contribution of the changes in the

[14] Labor input is usually called *efficiency-adjusted* labor (e.g. Katz and Murphy, 1992). However, in this paper *efficiency* refers to the measured values of A_e, A_s, and A_u.

[15] Some researchers (e.g., Caselli and Coleman, 2002) use the Treasury-bills (T-bills) nominal interest rate as a proxy for i. However, the T-bills rates do not cover risk-premium; hence, I use corporate bond rates as a measure of the nominal interest rate. In particular, I use Moody's AAA corporate bond rates (http://www.federalreserve.gov/releases/h15/data.htm). I use a simple moving average of the last 2 years inflation as a proxy for expected inflation.

[16] For example, had A_s continued to grow at 7.8% annually after 1985, the skill premium and output would have been about 14% and 45%, respectively, higher than the corresponding actual values in 2005.

[17] According to Eq. (6), A_u does not depend on the parameter ρ_2. Thus, the time plots of A_u in both figures are identical.

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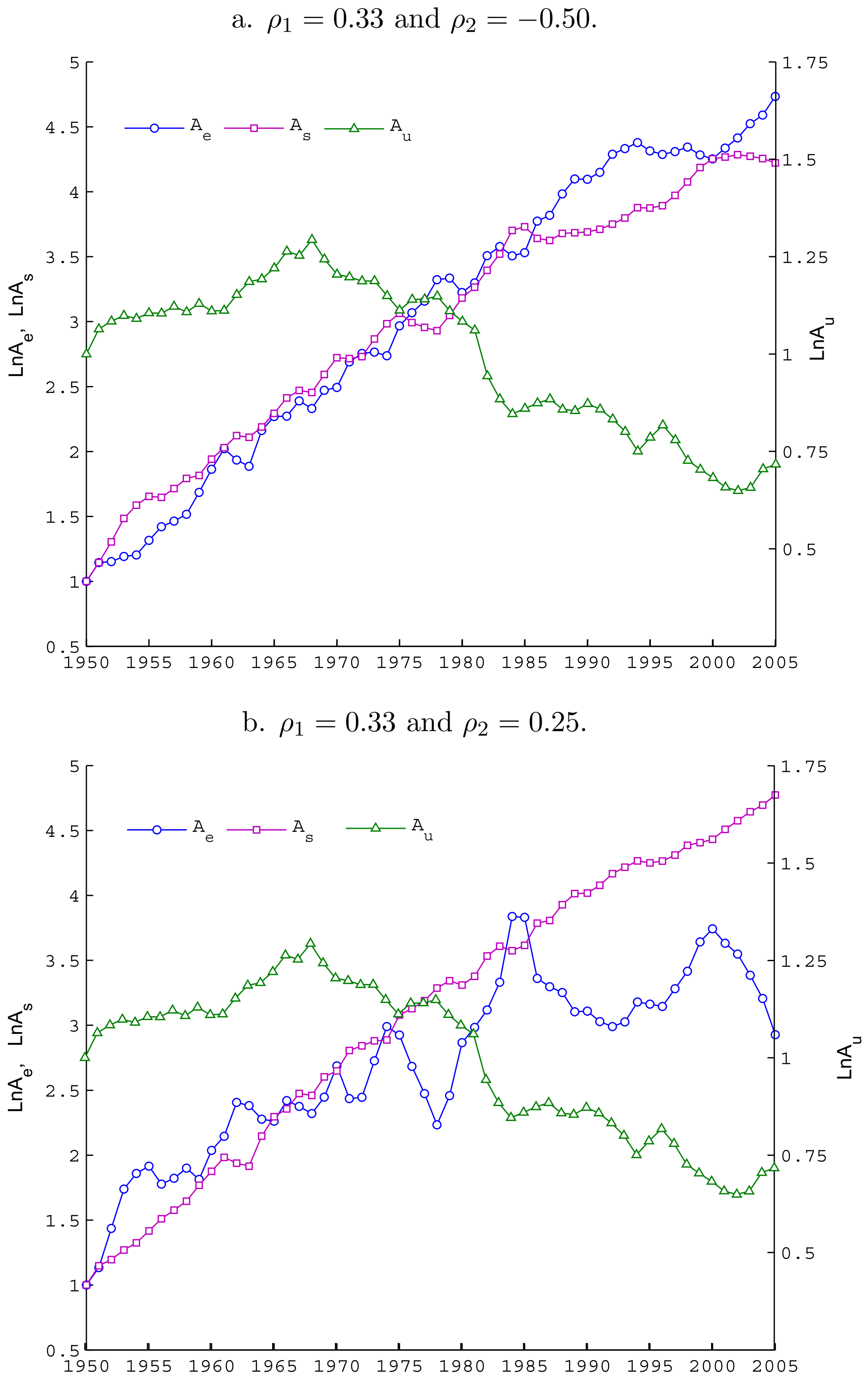

Fig. 2. Time series graphs of $\ln A_e$, $\ln A_s$, and $\ln A_u$ (1950 = 1).

quality of skilled and unskilled labor to productivity growth is also small, suggesting that there has been little variation *within* each class's composition. However, changes in the allocations of labor inputs have substantial opposite effects on labor productivity growth. The results in columns 6 and 8 indicate that most of the new entrants in the labor force have been college graduates. Finally, and more importantly, an inspection of the last three columns reveals that the decline in the efficiency of unskilled labor has been the *main* reason for the productivity slowdown during the second period.

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Table 1
Accounting for US growth (%) with $\rho_1 = 0.33$ and $\rho_2 = -0.5$.

Period	Output per hour $\hat{y}$	Contribution from								
		Capital		Labor				Efficiency		
		$\bar{\beta}_b\hat{k}_b$	$\bar{\beta}_e\hat{k}_e$	$\bar{\beta}_s\hat{q}_s$	$\bar{\beta}_s\hat{n}_s$	$\bar{\beta}_u\hat{q}_u$	$\bar{\beta}_u\hat{n}_u$	$\bar{\beta}_e\widehat{A}_e$	$\bar{\beta}_s\widehat{A}_s$	$\bar{\beta}_u\widehat{A}_u$
1950–2005	2.1 (100)	−0.1 (−6)	0.1 (4)	0.0 (0)	0.6 (30)	0.1 (7)	−0.4 (−18)	0.6 (29)	1.4 (68)	−0.3 (−14)
1950–1970	2.9 (100)	−0.1 (−4)	0.0 (2)	0.0 (−1)	0.5 (16)	0.1 (4)	−0.3 (−10)	0.5 (16)	1.4 (47)	0.9 (30)
1970–2005	1.6 (100)	0.1 (7)	0.1 (7)	0.0 (0)	0.7 (45)	0.1 (10)	−0.3 (−28)	0.7 (43)	1.5 (94)	−1.0 (−65)

Notes: This table reports the growth accounting decomposition based on Eq. (8), in which $\hat{x}$ represents the average annual growth rat of a variable x. Numbers in parentheses represent relative contributions in percentage.

How much will the above accounting results change if $\rho_2 = 0.25$? Eqs. (4)–(6) imply that ρ_2 only affects A_e and A_s. Thus, contributions of factor inputs and A_u to output growth would be identical with those reported in Table 1. Only contributions from A_e and A_s will be different. In this case, growth in the efficiency of capital equipment accounts for about 11% of the average annual output per hour growth between 1950 and 2005, while changes in the efficiency of skilled labor accounts for about 86% of growth.[18]

3.3. Discussion

The analysis in the previous section delivers two important results. First, although the efficiency of skilled labor has a strong upward trend, it has grown more slowly since the mid 1980s. Second, and more interestingly, beginning around 1970, there has been a decline in the absolute level of the efficiency of unskilled labor. Thus, these dramatic changes in skilled and unskilled labor efficiencies are responsible for the substantial widening in the US wage structure.[19] Furthermore, the decline in the absolute level of the efficiency of unskilled labor is the main reason for the overall productivity slowdown since the 1970s.

What caused the efficiency performance of skilled and unskilled labor to change after the early/mid 1970s? Here I suggest two possible explanations for the observed performance of A_s and A_u, but a more detailed analysis of this question is left for the future research. First, Greenwood and Yorukoglu (1997) argue that the slowdown in productivity after 1974 may have resulted from the information technology (IT) revolution. In particular, they argue that new ITs required a substantial period of learning by workers who would work with the technology: during this learning process, productivity was depressed as labor adapted to more powerful new technologies. Given that unskilled labor is not equipped with necessary training to use the new technologies, their productivity might even decline upon implementing them.

Second, there may be a decline in the average ability level of workers in both sectors. This can happen, for example, when able people who would otherwise work in less skill-intensive jobs get more education in response to increases in the college premium, and then subsequently work in skill-intensive jobs. As a result, over time the less skill-intensive sector will be populated with less able workers. At the same time, the average ability of workers in skill-intensive jobs may also decline, if the new entrants have lower ability than the average ability of workers in skill-intensive jobs.

4. Robustness and comparison to previous works

4.1. Alternative classification of labor

The analysis presented in the previous section is based on a classification in which the skilled labor class consists of college or college-plus workers. In this section, I consider an alternative classification used by Autor et al. (2008) in which the skilled labor class consists of college or college-plus workers and half of the workers with some college; and the unskilled labor class consists of high school dropouts, high school graduates, and half of the workers with some college. For the sake of brevity, I only present results based on $\rho_1 = 0.33$ and $\rho_2 = -0.5$. Qualitative implications based on $\rho_1 = 0.33$ and $\rho_2 = 0.25$ are similar to those presented in this section (and available upon request).

Fig. 3 plots the time paths of efficiency indexes. These plots are similar to those in Fig. 2a, except that the decline in A_u is more substantial than that in Fig. 2a. Moreover, compared to the time path of A_u in Fig. 2a, A_u grew more slowly between

[18] Growth in the efficiency of capital equipment accounts for about 18 (7)% of the average annual output per hour growth over 1950–1970 (1970–2005), while changes in the efficiency of skilled labor accounts for about 46 (130)% of growth over the corresponding period.

[19] Some economists argue that the skill premium has increased because trade with less developed countries (LDCs) raised the demand for skilled labor in developed countries (e.g., Wood, 1994). However, this is not a convincing explanation on two grounds. First, as Krugman (1995) argues, volumes of trade with LDCs are still too small to explain the substantial increases in the skill premium. Second, if the conventional trade story is correct, then the skill premium should have declined in LDCs. However, several empirical studies find that the skill premium in many LDCs has also risen (e.g., Behrman et al., 2000). Some recent studies have proposed new models in which trade between symmetric countries (i.e., the north–north trade) can increase the demand for skilled labor, which in turn raises the skill premium (see, e.g., Epifani and Gancia, 2008; Unel, 2010). Although exposure to trade induces a skilled-biased technical change in these models, it cannot generate a decline in the efficiency of unskilled labor.

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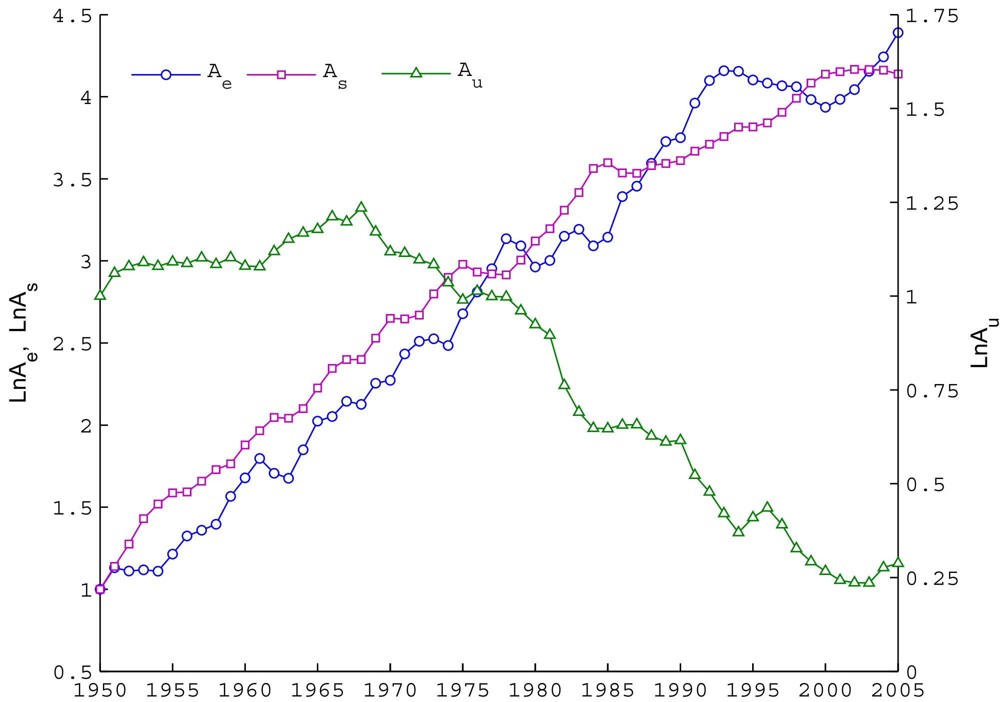

Fig. 3. Plots of $\ln A_e$, $\ln A_s$, and $\ln A_u$ under alternative definition of skill. *Notes:* These figures represent the time paths of the (log) efficiencies of capital equipment, skilled, and unskilled labor with $\rho_1 = 0.33$ and $\rho_2 = -0.5$. The (log) initial values are normalized to 1.

Table 2
Accounting for US growth under alternative definition of skill (%).

Period	Output per hour $\hat{y}$	Contribution from								
		Capital		Labor				Efficiency		
		$\bar{\beta}_b\hat{k}_b$	$\bar{\beta}_e\hat{k}_e$	$\bar{\beta}_s\hat{q}_s$	$\bar{\beta}_s\hat{n}_s$	$\bar{\beta}_u\hat{q}_u$	$\bar{\beta}_u\hat{n}_u$	$\bar{\beta}_e\widehat{A}_e$	$\bar{\beta}_s\widehat{A}_s$	$\bar{\beta}_u\widehat{A}_u$
1950–2005	2.1 (100)	−0.1 (−6)	0.1 (4)	0.0 (0)	0.8 (38)	0.1 (5)	−0.5 (−26)	0.6 (27)	1.8 (90)	−0.7 (−33)
1950–1970	2.9 (100)	−0.1 (−4)	0.0 (2)	0.0 (−1)	0.6 (21)	0.1 (3)	−0.4 (−14)	0.4 (14)	1.8 (63)	0.5 (17)
1970–2005	1.6 (100)	0.1 (7)	0.1 (7)	0.0 (0)	0.7 (45)	0.1 (10)	−0.3 (−28)	0.6 (40)	1.9 (122)	−1.4 (−90)

Notes: This table reports the growth accounting decomposition based on an alternative definition of skill with $\rho_1 = 0.33$ and $\rho_2 = -0.5$. In this table, $\hat{x}$ represents the average annual growth rate of a variable x, and numbers in parentheses represent relative contributions in percentage.

1950 and 1970. The average annual growth rates of A_u over the two periods 1950–1970 and 1970–2005 are 0.6% and −2.4%, respectively; whereas they are 1.0% and −1.4% in Fig. 2a. Table 2 presents accounting results based on Eq. (8). Although the contributions of subcomponents are different, the total contribution of factor inputs, and hence, efficiencies, remains almost the same.

4.2. Higher substitution between skilled and unskilled labor

As discussed in Section 3, the estimate of the elasticity of substitution between skilled and unskilled labor has been between 1 and 2, and the consensus is that it is about 1.5. In this section, I will investigate how much the results change when skilled and unskilled labor become more substitutable with each other. To this end, I now assume that the elasticity of substitution between skilled and unskilled labor is 2 (i.e., $\rho_1 = 0.5$).

Fig. 4 presents the time paths of capital equipment, skilled, and unskilled labor efficiencies under this higher elasticity of substitution.[20] Although these plots are similar to those in Fig. 2a, there are important differences between the two figures. First, the decline in A_u after 1970 is not as substantial as that in Fig. 2a. Moreover, compared to the time path of A_u in Fig. 2a, A_u grew relatively more rapidly until 1970. The average annual growth rates of A_u over the two periods 1950–1970 and 1970–2005 are 1.8% and −0.2%, respectively; whereas they are 1.0% and −1.4% in Fig. 2a. Second, compared to the time paths of A_e and A_s in Fig. 2a, they have grown more slowly. For example, the average annual growth rates of A_e and A_s between 1950

[20] For brevity, I only present results based on $\rho_2 = -0.5$; but the qualitative implications of the analysis based on $\rho_2 = 0.25$ are similar to that presented in this section.

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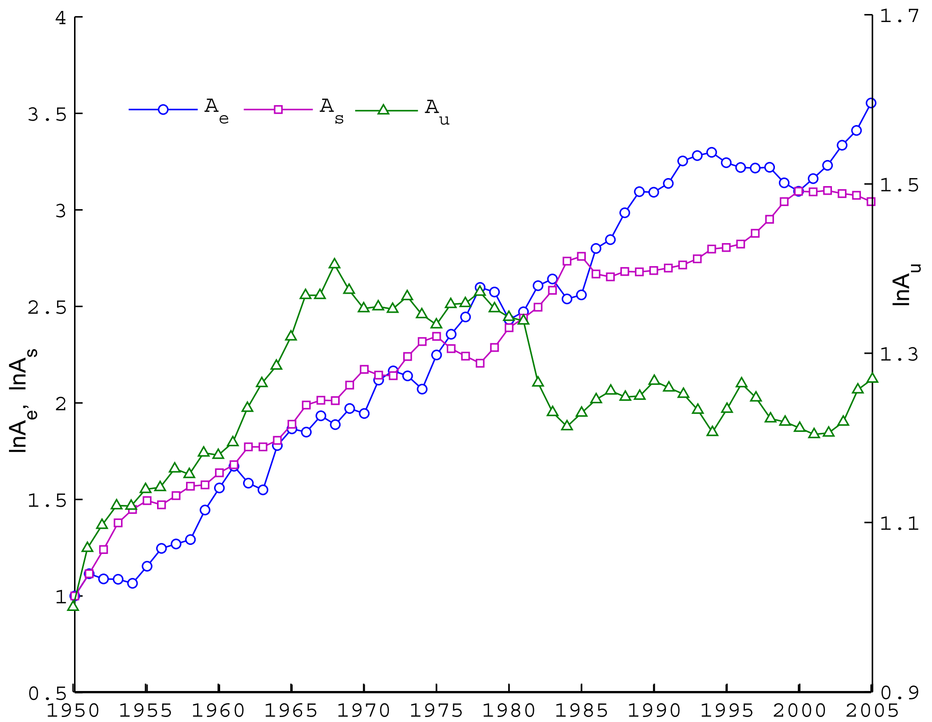

Fig. 4. Efficiency indexes under $\rho_1 = 0.5$ and $\rho_2 = -0.5$ (1950 = 1).

Table 3
Accounting for US growth with $\rho_1 = 0.5$ and $\rho_2 = -0.5$ (%).

Period	Output per hour $\hat{y}$	Contribution from								
		Capital		Labor				Efficiency		
		$\bar{\beta}_b \hat{k}_b$	$\bar{\beta}_e \hat{k}_e$	$\bar{\beta}_s \hat{q}_s$	$\bar{\beta}_s \hat{n}_s$	$\bar{\beta}_u \hat{q}_u$	$\bar{\beta}_u \hat{n}_u$	$\bar{\beta}_e \widehat{A}_e$	$\bar{\beta}_s \widehat{A}_s$	$\bar{\beta}_u \widehat{A}_u$
1950–2005	2.1 (100)	−0.1 (−6)	0.1 (4)	0.0 (0)	0.6 (30)	0.1 (7)	−0.4 (−18)	0.4 (21)	0.9 (42)	0.4 (21)
1950–1970	2.9 (100)	−0.1 (−4)	0.0 (2)	0.0 (−1)	0.5 (16)	0.1 (4)	−0.3 (−10)	0.3 (10)	0.9 (32)	1.5 (52)
1970–2005	1.6 (100)	0.1 (7)	0.1 (7)	0.0 (0)	0.7 (45)	0.1 (10)	−0.3 (−28)	0.5 (31)	0.9 (56)	−0.2 (−14)

Notes: This table reports the growth accounting decomposition based on a higher elasticity of substitution between skilled and unskilled labor. In this table, $\hat{x}$ represents the average annual growth rate of a variable x, and numbers in parentheses represent relative contributions in percentage.

and 2005 are 3.7% and 4.6%, respectively; while they are 6.8% and 5.9% in Fig. 2a. These results are not surprising given that in the current set-up skilled and unskilled labor are more substitutable with each other.[21] Consistent with these observations, the accounting results reported in Table 3 represent a more positive contribution from A_u to the labor productivity growth until 1970, and a less negative contribution during the post 1970 period.

4.3. Alternative production specifications

Setting $\alpha_b = 0$ and replacing K_e with $K = K_b + K_e$ in Eq. (1) yields the production function used by Caselli and Coleman (2002). To make the comparison with Caselli and Coleman (2002) more precise, I only present the results based on $\rho_1 = 0.33$ and $\rho_2 = 0.25$ (i.e., capital and skilled labor are gross substitutes).[22] Furthermore, for the sake of brevity, I do not report the accounting results based on this production function (and they are available upon request).

Fig. 5 plots the time paths of capital, skilled and unskilled labor efficiencies. A_s and A_u are somewhat similar to those in Figs. 2b, although A_s has grown relatively faster in Fig. 5: the average annual growth rate of A_s between 1950 and 2005 is

[21] For example, in the extreme case where skilled and unskilled labor are perfect substitutes, the differences between skilled and unskilled labor efficiency will disappear (assuming that labor is perfectly mobile).

[22] Under the capital skill complementary case (i.e., $\rho_2 = -0.5$), I find that the efficiency of skilled labor has grown much slower than that presented in Fig. 2a. The average annual growth rate of A_s between 1950 and 2005 is about 1.2%, and A_s has been mostly unchanged since the late 1970s. A lack of change in the efficiency of skilled labor in the last three decades does not seem plausible given that the demand for skilled labor has increased substantially over the same period. This suggests that aggregate capital may not be complementary to skilled labor, and perhaps this is why Caselli and Coleman only present the results based on $\rho_2 = 0.25$.

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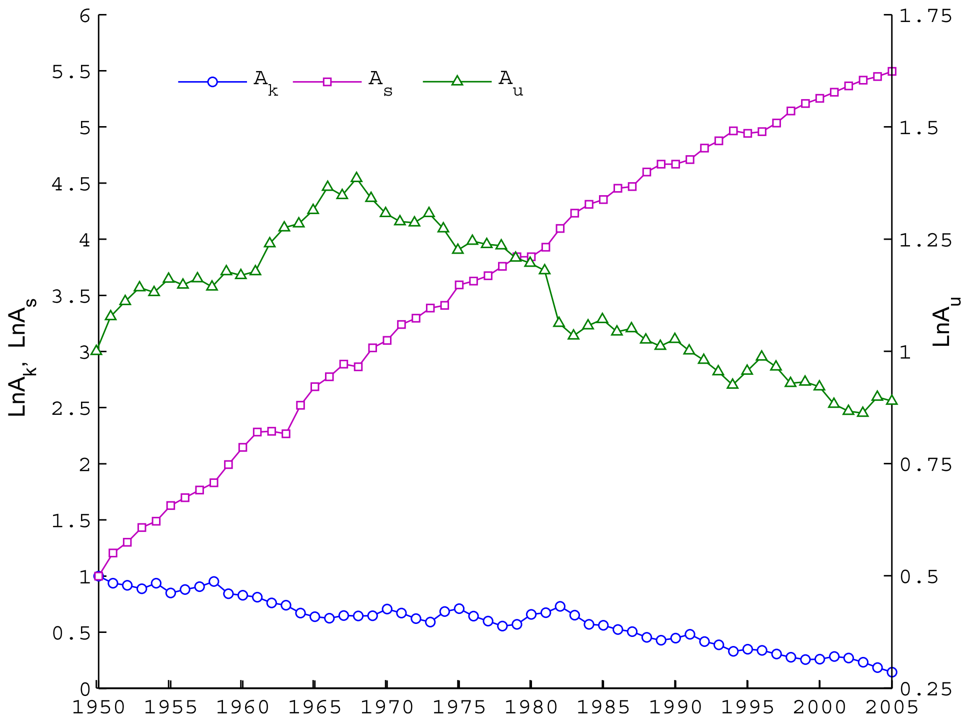

Fig. 5. Efficiency indexes under $\rho_1 = 0.33$ and $\rho_2 = 0.25$ (1950 = 1).

8.2%, whereas it is 6.9% in Fig. 2b. The evolution of A_k in Fig. 5 is considerably different from A_e in Fig. 2b: it has decreased at an average annual rate of 1.6%.

The time paths of A_s and A_u presented in Fig. 5 are similar to Caselli and Coleman's. The time path of A_k is different than that of Caselli and Coleman (2002) who find that A_k rises from the mid 1960s to the mid 1980s. However, the differences between the two plots stem from differences in parameter ρ_1 and the time periods considered in two papers. For example, if I set $\rho_1 = 0.25$, I find that the efficiency of capital (slightly) rises from the mid 1960s to the late 1980s, as in Caselli and Coleman (2002).[23] But such a trend again disappears when the whole time period (1950–2005) is considered.

The analysis based on the capital skill complementarity model with two capital inputs is preferable to that in Caselli and Coleman (2002) on two grounds. First, as I discussed in Section 1, their specification assumes that capital structure and capital equipment are perfect substitutes, which does not seem plausible on a priori grounds. Moreover, several other studies have found that a production function with two different capital inputs is more consistent with the data (e.g., Greenwood et al., 1997; Krusell et al., 2000). Second, their presentation delivers that the efficiency of capital has decreased at an annual rate of 1.6%, which cannot explain dramatic increases in the investment in capital equipment.

5. Conclusion

The relative supply of skilled labor has increased rapidly since the late 1960s, and the skill premium has increased sharply since 1980. It has been argued that this pattern is a result of the acceleration of skill-biased technical change. In this paper, using a production framework in which skilled and unskilled labor are imperfect substitutes, I analyze the time paths of skilled and unskilled labor efficiencies and investigate their implications for the economic growth and wage inequality in the US over the last half-century.

I find no evidence of an acceleration in the growth rate of skilled labor efficiency since the late 1970s to support the common view that there has been an acceleration in the new skilled-biased technologies. I also find a decline in the absolute level of the efficiency of unskilled labor since sometime around 1970, although the magnitude of the decline decreases as the elasticity of substitution between skilled and unskilled labor increases. Finally, I document that the evolution of the efficiency associated with capital equipment depends on the elasticity of substitution between capital equipment and skilled labor. These patterns imply that (i) the decline in unskilled labor efficiency also has an adverse effect on labor productivity growth; (ii) the dramatic rise in the US skill premium over the last two decades has not only been driven by increases in skilled labor efficiency, but also by declines in unskilled labor efficiency.

[23] The time path of A_k is not shown, but it is available upon request. The seemingly strong upward trend in A_k over the period 1965–1985 in Caselli and Coleman (2002) stems from their zooming of the vertical axis.

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