ICT Capital-Skill Complementarity and Wage Inequality: Evidence from OECD Countries*

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Abstract

Although it is well known that wage inequality has evolved over recent decades, it is not known the extent to which the evolution of wage inequality is attributed to observed factors such as capital and labor quantities or unobserved factors such as labor-augmenting technology in many countries. To examine this issue, we use cross-country panel data from 14 OECD countries for the years 1970 to 2005 and estimate the aggregate production function extended to allow for capital-skill complementarity and skill-biased technological change. Our results point to a strong influence of the observed expansion of ICT capital equipment relative to high-skilled labor around the world.

KEYWORDS: Skill premium; capital-skill complementarity; technological change; information and communication technology; production function.

JEL CLASSIFICATION: C33, E22, E23, J24, J31, O50.

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1 Introduction

One of the greatest changes in production activities over recent decades is the use of information and communication technology (ICT), which can result in a change in the type of labor needed for production activities. Following the widely accepted concept of capital-skill complementarity (Griliches, 1969), the demand for skilled labor would increase with a rise in the use of ICT relative to the demand for unskilled labor. In that case, the relative wage of skilled to unskilled labor, which is known as the skill premium, would increase as a consequence of the progress of ICT. Nevertheless, it is not known the extent to which the use of ICT can account for a rise in the skill premium. Furthermore, there has been no consensus in the literature as to the extent to which changes in the skill premium are attributed to observed factors such as capital and labor quantities or to unobserved factors such as labor-augmenting technology. We examine this issue by using cross-country panel data from 14 OECD countries for the years 1970 to 2005 and by estimating the aggregate production function extended to allow for capital-skill complementarity and skill-biased technological change.

To understand the sources and mechanism of changes in the skill premium, we consider two types of aggregate production functions: a four-factor production function developed by Krusell, Ohanian, Rios-Rull, and Violante (2000) and a six-factor production function extended to allow for different degrees of substitution between ICT and non-ICT capital equipment, capital structure, high-, medium-, and low-skilled labor. By means of production functions, we decompose changes in the skill premium into changes due to the effects of the relative labor quantity, capital-skill complementarity, and skill-biased technological change. In doing so, we examine the extent to which changes in the skill premium are attributed to observed factors such as capital and labor quantities and to unobserved factors such as labor-augmenting technology. We demonstrate that a rise in the skill premium can be largely attributed to the observed expansion of ICT capital equipment relative to high-skilled labor around the world. Our results indicate that changes in the skill premium can be mostly attributed to observed factors in some OECD countries, such as the United States and Germany. For those countries, a substantial part of international differences in changes in the skill premium can be explained in terms of capital and labor quantities in the six-factor production function.

1See Acemoglu (2002), Bond and Van Reenen (2007), and Goldin and Katz (2010) for surveys on capital-skill (and technology-skill) complementarity.
The rest of this paper proceeds as follows. The next section reviews the related literature. Section 3 presents the aggregate production functions used to account for changes in the skill premium. Section 4 describes the data used for estimation. Section 5 outlines econometric specifications and techniques. Section 6 discusses estimation results. The final section provides a summary and conclusions.

2 Related Literature

The aggregate production function has been a workhorse for the analysis of wage inequality. Bound and Johnson (1992) and Katz and Murphy (1992) estimate a production function with two types of labor (skilled and unskilled labor) to understand the sources of changes in the skill premium (the relative wage of skilled to unskilled labor) in the United States from the 1960s or 1970s to the 1980s. These studies reveal that changes in the skill premium are partially attributable to the relative quantity of skilled labor but mostly to unobserved factors such as skill-biased technological change. For a given elasticity of substitution between skilled and unskilled labor, Acemoglu (2003) and Caselli and Coleman (2006) measure the relative labor-augmenting technology in many countries using a production function with two types of labor. These studies consider cross-country differences in changes in the skill premium to be a consequence of differences in the direction of technological change.

Krusell et al. (2000) develop and estimate a four-factor production function, in which not only skilled labor is distinguished from unskilled labor, but also capital equipment is distinguished from capital structure. Krusell et al. (2000) demonstrate that capital equipment is complementary to skilled labor relative to unskilled labor, and a rise in the skill premium in the United States since the 1980s is mainly a consequence of a rise in capital equipment. Lindquist (2005) reveals similar findings to Krusell et al. (2000) in Sweden. On the other hand, Caselli and Coleman (2002) measure labor-augmenting technology in the United States from 1963 to 1992 using the same production function as in Krusell et al. (2000) for given elasticities of substitution among capital and labor inputs. Caselli and Coleman (2002) find that technological change was biased towards skilled labor during the period. As far as we are aware, there have been no further studies that demonstrate changes in the skill premium are attributable mainly to observed factors such as capital-skill complementarity.
Acemoglu (2002) notes that skilled-biased technological change is a threat to identification of capital-skill complementarity when using time-series data from a single country. From a microeconomic perspective, Akerman, Gaarder, and Mogstad (2015) estimate the impact of broadband internet on firms’ output and workers’ wages using geographical variation in the availability of broadband internet during the 2000s in Norway, and provide firm- and worker-level evidence on the complementarity between broadband internet and skill. From a macroeconomic perspective, Duffy, Papageoriou, and Perez-Sebastian (2004) estimate a three-factor production function with one type of capital and two types of labor using cross-country panel data from the Penn World Tables 5.6, and partially confirm the capital-skill complementarity hypothesis. However, the data used in the analysis do not contain information on wages. A question remains as to the extent to which changes in the skill premium are attributable to capital-skill complementarity in many countries.

A workhorse for the analysis of the impact of ICT has been factor-share equations derived from the translog cost function. Autor, Katz, and Krueger (1998) reveal that the wage-bill share of skilled labor increased with a rise in the proportion of workers using computers in the United States between the years 1984 and 1993. Using data from 11 OECD countries between the years 1980 and 2004, Michaels, Natraj, and Van Reenen (2014) demonstrate that the wage-bill share of high-skilled labor increased with a rise in ICT capital equipment, while the wage-bill share of medium-skilled labor decreased. Eden and Gaggl (2018) is the only study we are aware of that estimates the aggregate production function in which ICT capital equipment is distinguished from non-ICT capital equipment and capital structure. Eden and Gaggl (2018) demonstrate that about half of the decline in labor income share in the United States since the 1950s is attributable to a rise in the income share of ICT capital equipment. These studies focus on the impact of a rise in ICT capital equipment on labor income shares.

3 The Model

In this section, we present the four- and six-factor production functions. Neither the four- nor six-factor production functions has been estimated using cross-country panel data.
3.1 Four-factor production function

We first describe the four-factor production function developed in Krusell et al. (2000). We assume that the output \( y \) is produced by a constant-return-to-scale technology using capital equipment \( k_e \), capital structure \( k_s \), (high-)skilled labor \( \ell_h \), and unskilled labor \( \ell_u \). The four-factor production function is specified as:

\[
y = A k_s^{\alpha} \left\{ \lambda \left[ \mu k_e^\rho + (1 - \mu) (\zeta_h \ell_h)^\rho \right]^\frac{\sigma}{\rho} + (1 - \lambda) (\zeta_u \ell_u)^\sigma \right\}^{\frac{1-\alpha}{\sigma}}, \tag{1}
\]

where \( A \) is factor-neutral technology, and \( \zeta_h \) and \( \zeta_u \) are the efficiency units of skilled and unskilled labor, respectively. The parameter \( \sigma \) governs the degree of substitution between the \( k_e-\ell_h \) composite and \( \ell_u \), while the parameter \( \rho \) governs the degree of substitution between \( k_e \) and \( \ell_h \). Theory restricts the range of parameters such that \( \sigma < 1 \) and \( \rho < 1 \). As confirmed by Fallon and Layard (1975), Krusell et al. (2000), and Duffy et al. (2004), the specification of the production function (1) is consistent with the data, while the alternative specification, in which \( \ell_h \) and \( \ell_u \) are replaced, is not. The production technology exhibits capital-skill complementarity if capital equipment is less substitutable with (or more complementary to) skilled labor than unskilled labor \( (\sigma > \rho) \).

As in Caselli and Coleman (2002), the four-factor production function can also be represented as:

\[
f(k_e, k_s, \ell_h, \ell_u) = k_s^{\alpha} \left\{ \left[ (A_e k_e)^\rho + (A_h \ell_h)^\rho \right]^\frac{\sigma}{\rho} + (A_u \ell_u)^\sigma \right\}^{\frac{1-\alpha}{\sigma}}, \tag{2}
\]

where factor-augmenting technology is of the form: \( A_e = A^{\frac{1}{\alpha}} \lambda^{\frac{1}{\sigma}} \mu^{\frac{1}{\rho}} \), \( A_h = A^{\frac{1}{\alpha}} \lambda^{\frac{1}{\sigma}} (1 - \mu)^{\frac{1}{\rho}} \zeta_h \), and \( A_u = A^{\frac{1}{\alpha}} (1 - \lambda)^{\frac{1}{\sigma}} \zeta_u \). Let \( w_h \) and \( w_u \) denote the wages of high-skilled labor and unskilled labor, respectively, and \( r_e \) and \( r_s \) denote the rental prices of capital equipment and capital structure, respectively. Profit maximization entails equating the value of marginal product with the marginal cost.

\[
w_h = \omega_h \frac{\partial f}{\partial \ell_h}, \tag{3}
\]

\[
w_u = \omega_u \frac{\partial f}{\partial \ell_u}, \tag{4}
\]

\[
r_e = \omega_e \frac{\partial f}{\partial k_e}, \tag{5}
\]

\[
r_s = \omega_s \frac{\partial f}{\partial k_s}. \tag{6}
\]
where \( \omega \) is the wedge representing the deviation from the profit-maximizing conditions in perfectly competitive markets. We allow the size of the wedge to differ by input market. Appendix A.1 provides a detailed derivation of the first-order conditions.

The first-order conditions (3) and (4) imply that the relative wage of skilled to unskilled labor is proportional to the marginal rate of technical substitution of unskilled for skilled labor. After simple algebra, the relative wage of skilled to unskilled labor is given by

\[
\ln\left(\frac{w_h}{w_u}\right) = \sigma \ln\left(\frac{A_h}{A_u}\right) - (1 - \sigma) \ln\left(\frac{\ell_h}{\ell_u}\right) + \frac{\sigma - \rho}{\rho} \ln\left[\left(\frac{A_e k_e}{A_h \ell_h}\right)^{\rho} + 1\right] + \ln\left(\frac{\omega_h}{\omega_u}\right) .
\] (7)

The coefficient of the first term is positive if \( \sigma > 0 \) (or \( 1/(1 - \sigma) > 1 \)). The coefficient of the second term is negative because \( \sigma < 1 \). The coefficient of the third term is positive if there is capital-skill complementarity (\( \sigma > \rho \)). Within the range of parameter values (\( 0 < \sigma < 1 \) and \( \sigma > \rho \)), the skill premium \( (w_h/w_u) \) decreases with the relative quantity of skilled to unskilled labor \( (\ell_h/\ell_u) \) but increases with the relative quantity of capital equipment to skilled labor \( (k_e/\ell_h) \) and the ratio of skilled to unskilled labor-augmenting technology \( (A_h/A_u) \), holding the relative wedge \( (\omega_h/\omega_u) \) constant. Following equation (7), changes in the skill premium can be decomposed into changes due to the effects of the relative labor quantity, capital-skill complementarity, and the relative labor-augmenting technology (i.e., skill-biased technological change). If there is no capital-skill complementarity (\( \sigma = \rho \)), changes in the skill premium are attributable to either the relative labor quantity effect or the relative labor-augmenting technology effect. The magnitude of skill-biased technological change can be overestimated if capital-skill complementarity is not taken into account.

The first-order conditions (3) and (5) imply that the ratio of the wage of high-skilled labor to the rental price of capital equipment is given by

\[
\ln\left(\frac{w_h}{r_e}\right) = \rho \ln\left(\frac{A_h}{A_e}\right) - (1 - \rho) \ln\left(\frac{\ell_h}{k_e}\right) + \ln\left(\frac{\omega_h}{\omega_e}\right) .
\] (8)
3.2 Six-factor production function

We develop the six-factor production function. We assume that the output \( y \) is produced by a constant-return-to-scale technology using ICT capital equipment \( (k_i) \), non-ICT capital equipment \( (k_n) \), capital structure \( (k_s) \), high-skilled labor \( (\ell_h) \), medium-skilled labor \( (\ell_m) \), and low-skilled labor \( (\ell_\ell) \). The six-factor production function is specified as:

\[
y = A k_s^\alpha \left\{ \lambda \left[ \mu k_i^\rho + (1 - \mu) \left( \zeta_h \ell_h \right)^\rho \right]^{\frac{\sigma}{\rho}} + (1 - \lambda) \left[ \psi \left[ \gamma k_n^\eta + (1 - \gamma) \left( \zeta_\ell \ell_\ell \right)^\eta \right]^{\frac{\zeta}{\eta}} + (1 - \psi) \left( \zeta_m \ell_m \right)^\eta \right]^{\frac{\xi}{\eta}} \right\}^{\frac{1 - \alpha}{\sigma}},
\]

where \( A \) is factor-neutral technology, and \( \zeta_h, \zeta_m, \) and \( \zeta_\ell \) are the efficiency units of high-, medium-, and low-skilled labor, respectively. The six-factor production function involves four substitution parameters. The parameter \( \sigma \) governs the degree of substitution between the \( k_i - \ell_h \) composite and the \( k_n - \ell_m - \ell_\ell \) composite, while the parameter \( \rho \) governs the degree of substitution between \( k_i \) and \( \ell_h \). The parameter \( \xi \) governs the degree of substitution between the \( k_n - \ell_\ell \) composite and \( \ell_m \), while the parameter \( \eta \) governs the degree of substitution between \( k_n \) and \( \ell_\ell \). The production technology exhibits ICT capital-skill complementarity if \( \sigma > \rho \) and non-ICT capital-skill complementarity if \( \eta > \xi \).

When specifying the production function, we bundle capital and labor inputs together in the final nest so that the production technology can exhibit capital-skill complementarity. We choose to pair ICT capital equipment with high-skilled labor, and non-ICT capital equipment with low-skilled labor. ICT capital equipment and high-skilled labor are the least substitutable combination of capital and labor inputs, while non-ICT capital equipment and low-skilled labor are one of the most substitutable combinations. Theory restricts the range of parameters such that \( \sigma < 1, \rho < 1, \xi < 1, \) and \( \eta < 1 \). We confirm that the specification of the production function (9) is consistent with the data. We discuss the further details of the specification in Appendix A.2.

The six-factor production function can also be represented as:

\[
f(k_i, k_n, k_s, \ell_h, \ell_m, \ell_\ell) = k_s^\alpha \left\{ \left[ (A_i k_i)^\rho + (A_h \ell_h)^\rho \right]^{\frac{\sigma}{\rho}} + \left[ (A_n k_n)^\eta + (A_\ell \ell_\ell)^\eta \right]^{\frac{\xi}{\eta}} + (1 - \psi) \left( \zeta_m \ell_m \right)^\eta \right\}^{\frac{1 - \alpha}{\sigma}}, \quad (10)
\]

where factor-augmenting technology is of the form: \( A_i = A_i^{1 - \lambda} \lambda \frac{1}{\beta} \mu \frac{1}{\beta}, A_h = A_h^{1 - \lambda} \lambda \frac{1}{\beta} \eta (1 - \mu) \frac{1}{\beta} \zeta_h, A_n =
\(A_{1-\alpha} (1-\lambda)^{\frac{1}{\sigma}} \psi^{\frac{1}{\eta}} \gamma^{\frac{1}{\xi}}, A_{\ell} = A_{1-\alpha} (1-\lambda)^{\frac{1}{\sigma}} \psi^{\frac{1}{\eta}} (1-\gamma)^{\frac{1}{\eta}} \zeta_{\ell}, \text{ and } A_{m} = A_{1-\alpha} (1-\lambda)^{\frac{1}{\sigma}} (1-\psi)^{\frac{1}{\eta}} \zeta_{m}. \)

Let \(w_{h}, \ w_{m}, \) and \(w_{\ell}\) denote the wages of high-skilled labor, medium-skilled labor, and low-skilled labor, respectively, and \(r_{i}, \ r_{n}, \) and \(r_{s}\) denote the rental prices of ICT capital equipment, non-ICT capital equipment, and capital structure, respectively. Profit maximization entails equating the value of marginal product with the marginal cost.

\[
\begin{align*}
    w_{h} &= \omega_{h} \frac{\partial f}{\partial \ell_{h}}, \quad (11) \\
    w_{m} &= \omega_{m} \frac{\partial f}{\partial \ell_{m}}, \quad (12) \\
    w_{\ell} &= \omega_{\ell} \frac{\partial f}{\partial \ell_{\ell}}, \\
    r_{i} &= \omega_{i} \frac{\partial f}{\partial k_{i}}, \quad (14) \\
    r_{n} &= \omega_{n} \frac{\partial f}{\partial k_{n}}, \quad (15) \\
    r_{s} &= \omega_{s} \frac{\partial f}{\partial k_{s}}, \quad (16)
\end{align*}
\]

where \(\omega\) is the wedge. We allow the size of wedge to differ by input market. Appendix A.1 provides a detailed derivation of the first-order conditions.

The first-order conditions (11) and (12) imply that the relative wage of high- to medium-skilled labor is proportional to the marginal rate of technical substitution of medium- for high-skilled labor. After simple algebra, the relative wage of high- to medium-skilled labor is given by

\[
\ln \left( \frac{w_{h}}{w_{m}} \right) = \sigma \ln \left( \frac{A_{h}}{A_{m}} \right) - (1 - \sigma) \ln \left( \frac{\ell_{h}}{\ell_{m}} \right) \left( \text{technology} \right) - \left( \text{quantity} \right) \\
+ \frac{\sigma - \rho}{\rho} \ln \left[ \left( \frac{A_{i} k_{i}}{A_{h} \ell_{h}} \right)^{\rho} + 1 \right] - \frac{\sigma - \xi}{\xi} \ln \left[ \left( \left( \frac{A_{n} k_{n}}{A_{m} \ell_{m}} \right)^{\eta} + \left( \frac{A_{\ell} \ell_{\ell}}{A_{m} \ell_{m}} \right)^{\eta} \right)^{\frac{\xi}{\eta}} + 1 \right] + \ln \left( \frac{\omega_{h}}{\omega_{m}} \right), \quad (17)
\]

The coefficient of the first term is positive if \(\sigma > 0\). The coefficient of the second term is negative because \(\sigma < 1\). The coefficient of the third term is positive if there is ICT capital-skill complementarity \((\sigma > \rho)\). Within the range of parameter values \((0 < \sigma < 1, \sigma > \rho)\), the relative wage of high- to medium-
skilled labor \((w_h/w_m)\) decreases with the relative quantity of high- to medium-skilled labor \((\ell_h/\ell_m)\) but increases with the relative quantity of ICT capital equipment to high-skilled labor \((k_i/\ell_h)\), and the ratio of high- to medium-skilled labor-augmenting technology \((A_h/A_m)\), holding the relative wedge \((\omega_h/\omega_m)\) constant. The fourth term is negligible if the degree of substitution between the \(k_i-\ell_h\) composite and the \(k_n-\ell_m-\ell_h\) composite does not differ significantly from the degree of substitution between the \(k_n-\ell_h\) composite and \(\ell_m\) \((\sigma \simeq \xi)\). Following equation (17), changes in the relative wage can be decomposed into changes due to the effects of the relative labor quantity, capital-skill complementarity, and the relative labor-augmenting technology.

The first-order conditions (12) and (13) imply that the relative wage of medium- to low-skilled labor is proportional to the marginal rate of technical substitution of low- for medium-skilled labor. After simple algebra, the relative wage of medium- to low-skilled labor is given by

\[
\ln \left( \frac{w_m}{w_\ell} \right) = \xi \ln \left( \frac{A_m}{A_\ell} \right) - (1 - \xi) \ln \left( \frac{\ell_m}{\ell_\ell} \right) + \eta - \xi \eta \ln \left( \frac{A_n k_n}{A_h A_\ell \ell_\ell} \right) + \ln \left( \frac{\omega_m}{\omega_\ell} \right). \tag{18}
\]

The coefficient of the first term is positive if \(\xi > 0\). The coefficient of the second term is negative because \(\xi < 1\). The coefficient of the third term is positive if there is non-ICT capital-skill complementarity \((\eta > \xi)\). Within the range of parameter values \((0 < \xi < 1\) \text{ and } \eta > \xi\), the relative wage of medium- to low-skilled labor \((w_m/w_\ell)\) decreases with the relative quantity of medium- to low-skilled labor \((\ell_m/\ell_\ell)\) but increases with the relative quantity of non-ICT capital equipment to low-skilled labor \((k_n/\ell_\ell)\) and the ratio of medium- to low-skilled labor-augmenting technology \((A_m/A_\ell)\), holding the relative wedge \((\omega_m/\omega_\ell)\) constant. Following equation (18), changes in the relative wage can be decomposed into changes due to the effects of the relative labor quantity, capital-skill complementarity, and the relative labor-augmenting technology.

The first-order conditions (11) and (14) imply that the ratio of the wage of high-skilled labor to the rental price of ICT capital equipment is given by

\[
\ln \left( \frac{w_h}{r_i} \right) = \rho \ln \left( \frac{A_h}{A_i} \right) - (1 - \rho) \ln \left( \frac{\ell_h}{k_i} \right) + \ln \left( \frac{\omega_h}{\omega_i} \right). \tag{19}
\]
The first-order conditions (13) and (15) imply that the ratio of the wage of low-skilled labor to the rental price of non-ICT capital equipment is given by

\[
\ln \left( \frac{w_\ell}{r_n} \right) = \eta \ln \left( \frac{A_\ell}{A_n} \right) - (1 - \eta) \ln \left( \frac{\ell_\ell}{k_n} \right) + \ln \left( \frac{\omega_\ell}{\omega_n} \right). \tag{20}
\]

### 3.3 Elasticities

We cannot simply test the four-factor production function against the six-factor production function, because the four-factor production function is not nested by the six-factor production function. We instead test assumptions implicit in the four-factor production function by looking at whether ICT and non-ICT capital equipment are perfect substitutes and whether medium- and low-skilled labor are perfect substitutes. To do so, we calculate Morishima elasticities of substitution among all capital and labor inputs.\(^2\)

The Morishima elasticity of substitution of input \(a\) for input \(b\) is defined as:

\[
\varepsilon_{ab} = -\frac{\partial \ln \left( \frac{x_a(p, y)}{x_b(p, y)} \right)}{\partial \ln \left( \frac{p_a}{p_b} \right)},
\]

where \(x_a\) is the demand for input \(a\) as a function of the vector of input prices \((p)\) and output \((y)\), and \(p_a\) is the price of input \(a\). Appendix A.3 provides the exact expression for the input demand function.

Furthermore, we compare predictions for changes in the skill premium between the four- and six-factor production functions. Because wages are defined as the ratio of total labor compensation to total hours worked, the wage of unskilled labor is calculated as \(w_u = (w_m\ell_m + w_\ell\ell_\ell) / (\ell_m + \ell_\ell)\). The skill premium, \(w_h / w_u\), can be expressed in terms of the relative wages, \(w_h / w_m\) and \(w_m / w_\ell\).

\[
\frac{w_h}{w_u} = \frac{(w_h / w_m) \left( (\ell_m + \ell_\ell) / \ell_m \right)}{1 + (w_\ell / w_m) \left( \ell_\ell / \ell_m \right)}. \tag{22}
\]

When we calculate the impact of capital and labor quantities on the skill premium in the six-factor production function, we focus on the impact through the relative wage, holding \((\ell_m + \ell_\ell) / \ell_m\) and \(\ell_m / \ell_\ell\) constant, so that we can compare two types of production functions.

\(^2\)See Blackorby and Russell (1989) for discussions on the desirable properties of Morishima elasticity relative to other types of elasticities.
4 Data

The data used in the analysis are from the EU KLEMS database, which provides detailed and internationally comparable information on the prices and quantities of capital and labor inputs in many OECD countries. The EU KLEMS database is constructed mainly from data collected by national statistical offices and is grounded in national accounts statistics (O’Mahony and Timmer, 2009). We use the March 2008 version because it contains the longest time series from the years 1970 to 2005. However, there is a difference across countries in the number of years for which data are available. We include as many countries and years as possible in the sample. Our sample comprises 14 OECD countries: Australia, Austria, the Czech Republic, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Portugal, Slovenia, Sweden, the United Kingdom, and the United States. The sample includes 341 country-year observations.

Labor inputs are divided into high-, medium-, and low-skilled labor. High-skilled labor consists of workers who completed college, medium-skilled labor consists of workers who entered college or completed high-school education, and low-skilled labor consists of workers who dropped out of high school or had only compulsory education. Medium- and low-skilled labor constitute unskilled labor. We calculate wages at each skill level by dividing total labor compensation by total hours worked for all workers in all industries. It should be noted that the relative wages reported here need not be the same as those in other studies for several reasons. First, part-time workers are included in the calculation. Second, self-employed workers and family workers are included. Third, all workers are included without age restrictions. Fourth, workers in all industries are included. Finally, compensation and hours for side jobs are included.

Capital inputs are divided into capital equipment such as machines and capital structure such as buildings. Capital equipment is further divided into ICT capital equipment and non-ICT capital equipment. We follow Jorgenson (1963) and O’Mahony and Timmer (2009) in calculating the rental price of capital, also known as the user cost of capital. Appendix A.4 provides a detailed description of the calculation.

All variables measured in monetary values are converted into U.S. dollars using the purchasing power parity index and deflated using the gross value added deflator as described in Timmer, van Moergastel, Stuivenwold, Ypma, O’Mahony, and Kangasniemi (2007). The base year is 1995.

Trends in the skill premium vary across countries. Figure 1 shows the skill premium \( \frac{w_h}{w_u} \) from
the years 1970 to 2005 in 14 OECD countries. For ease of illustration, all countries are classified into three groups. The skill premium exhibits an increasing trend in five countries (Australia, the Czech Republic, Germany, Portugal, and the United States), no clear trend in five countries (Italy, Japan, the Netherlands, Slovenia, and the United Kingdom), and a decreasing trend in four countries (Austria, Denmark, Finland, and Sweden).

Figure 1: Skill premium in OECD countries: \( w_h / w_u \)

(a) Increasing trend

(b) No clear trend

(c) Decreasing trend

Notes: All series are logged and normalized to zero in the initial period. AUS: Australia, AUT: Austria, CZE: the Czech Republic, DEN: Denmark, FIN: Finland, GER: Germany, ITA: Italy, JPN: Japan, NED: the Netherlands, POR: Portugal, SLO: Slovenia, SWE: Sweden, UK: the United Kingdom, and US: the United States.

Figure 2 shows the relative wage of high- to medium-skilled labor \( (w_{h}/w_{m}) \) and the relative wage of high- to low-skilled labor \( (w_{h}/w_{l}) \) in the United States. The two relative wages exhibit the same trends
from the 1970s to the late 1980s, but diverged after the late 1980s. After the late 1980s, the relative wage of high- to low-skilled labor increased more than the relative wage of high- to medium-skilled labor. The same applies to Italy and the United Kingdom. Figure 9 in Appendix A.7 shows the trends for the countries other than the United States. The two relative wages exhibit a similar trend in the majority of countries.

**Figure 2: Relative wages in the United States: \( \frac{w_h}{w_m} \) and \( \frac{w_h}{w_l} \)**

![Relative wages in the United States](image1)

*Notes: All series are logged and normalized to zero in the initial period.*

Trends in the rental price of capital vary across types of capital. Figure 3 shows the rental price of capital in the United States. The rental price of ICT capital equipment fell sharply after the late 1980s, while the rental prices of non-ICT capital equipment and capital structure were unchanged from the 1970s to the 2000s. The rental price of ICT capital equipment fell significantly relative to the rental prices of non-ICT capital equipment and capital structure in all countries (Figure 10 in the appendix).

**Figure 3: Rental prices of capital in the United States: \( r_i \), \( r_n \), and \( r_s \)**

![Rental prices of capital in the United States](image2)

*Notes: All series are logged and normalized to zero in the initial period.*

Trends in the quantities of capital and labor vary across types of capital and labor. Figure 4a shows
the shares of each labor input in the United States. The share of high-skilled labor increased steadily over time, while the share of low-skilled labor decreased. The share of medium-skilled labor was almost unchanged. The same applies to most countries (Figure 11 in the appendix). Figure 4b shows the shares of each capital input in the United States. The share of ICT capital equipment increased significantly in the 1990s and 2000s, while the shares of non-ICT capital equipment and capital structure declined modestly. The same applies to many other countries (Figure 12 in the appendix).

After observing the trends in the prices and quantities of capital and labor inputs, it is worth noting two things. First, the relative quantity of high- to low-skilled labor increased significantly more than the relative quantity of high- to medium-skilled labor in almost all countries, whereas the relative wage of high- to low-skilled labor did not decrease significantly more than the relative wage of high- to medium-skilled labor. This suggests that changes in the relative wages are not likely to be solely attributable to the relative quantity of labor inputs. Second, the rental price of ICT capital equipment fell significantly in most countries, whereas the share of ICT capital equipment increased significantly. The negative co-movement between the price and quantity of capital equipment can be interpreted as evidence of technological change (Greenwood, Hercowitz, and Krusell, 1997). This suggests that technological change is related to ICT capital equipment.
5 Estimation

We first present specifications for labor-augmenting technology and then describe moment conditions for estimating parameters in the four- and six-factor production functions.

5.1 Econometric specifications

We incorporate skill-biased technological change, as well as capital-skill complementarity, in the production functions. As noted by Diamond, McFadden, and Rodriguez (1978), it is not possible to identify the elasticities of substitution without imposing parametric assumptions on skill-biased technological change. Technological change is said to be skill-biased if the relative labor-augmenting technology, $A_h/A_u$, $A_h/A_m$, or $A_m/A_\ell$, increases over time. We allow for skill-biased technological change by specifying the share parameters $\lambda$ and $\psi$ as a function of time. The share parameters $\lambda$ and $\psi$ are specified to lie between zero and one.

$$
\lambda_{ct} = \frac{\exp \left( \sum_{s=1}^{S_c} \lambda_{s,ct} t^s \right)}{1 + \exp \left( \sum_{s=1}^{S_c} \lambda_{s,ct} t^s \right)}, \quad \psi_{ct} = \frac{\exp \left( \sum_{s=1}^{S_c} \psi_{s,ct} t^s \right)}{1 + \exp \left( \sum_{s=1}^{S_c} \psi_{s,ct} t^s \right)}
$$

(23)

where $c$ is an index for countries and $t$ is an index for calendar years. We allow the speed and timing of skill-biased technological change to vary across countries over time by incorporating higher-order trend terms and by varying trend coefficients across countries. We choose the number of higher-order terms to account for trends in the relative wages in each country (see Appendix A.5 for the details). We assume the share parameters $\gamma$ and $\mu$ to be invariant over time to avoid severe multicollinearity. The efficiency unit of labor ($\zeta$) is normalized to one because it is not possible to disentangle the relative efficiency of labor from skill-biased technological change without direct measures of labor quality and technology.

We allow the degree of competitiveness to vary across countries. Cross-country differences in non-competitive and institutional factors are considered to be substantial relative to their changes over time. Thus, we treat the wedge ($\omega$) as time-invariant country-specific effects. The wedge can then be eliminated by differencing over time.
Four-factor production function  For the four-factor production function, we can obtain the following estimating equations by first-differencing equations (7) and (8).

\[
\Delta \ln \left( \frac{w_{h,ct}}{w_{u,ct}} \right) = \sum_{s=1}^{S} \lambda_{s,c} \Delta r^s - (1 - \sigma) \Delta \ln \left( \frac{\ell_{h,ct}}{\ell_{u,ct}} \right) + \frac{\sigma - \rho}{\rho} \Delta \ln \left[ \frac{A_{e,ct} k_{e,ct}}{A_{h,ct} k_{h,ct}} \right] + 1 + u_{1,ct},
\]

(24)

\[
\Delta \ln \left( \frac{w_{h,ct}}{r_{e,ct}} \right) = -(1 - \rho) \Delta \ln \left( \frac{\ell_{h,ct}}{k_{e,ct}} \right) + u_{2,ct},
\]

(25)

where \( u_{1,ct} \) and \( u_{2,ct} \) are idiosyncratic errors. The errors are allowed to be correlated across equations. The elasticity of substitution between high- and unskilled labor, \( 1 / (1 - \sigma) \), is identified from equation (24), while the elasticity of substitution between capital equipment and high-skilled labor, \( 1 / (1 - \rho) \), is identified from equation (25). These estimating equations are less nonlinear in parameters than those in Krusell et al. (2000).\(^3\)

Six-factor production function  For the six-factor production function, we can obtain the following estimating equations by first-differencing equations (17), (18), (19), and (20).

\[
\Delta \ln \left( \frac{w_{h,ct}}{w_{m,ct}} \right) = \sum_{s=1}^{S} \lambda_{s,c} \Delta r^s + \frac{\sigma}{\xi} \Delta \ln \left( 1 + \exp \left( \sum_{s=1}^{S} \psi_{s,c} r^s \right) \right) - (1 - \sigma) \Delta \ln \left( \frac{\ell_{h,ct}}{\ell_{m,ct}} \right)
\]

\[
+ \frac{\sigma - \xi}{\rho} \Delta \ln \left[ \frac{A_{i,ct} k_{i,ct}}{A_{h,ct} k_{h,ct}} \right] + 1 - \frac{\sigma - \xi}{\xi} \Delta \ln \left[ \frac{A_{n,ct} k_{n,ct}}{A_{m,ct} \ell_{m,ct}} \right] + \left( \frac{A_{n,ct} k_{n,ct}}{A_{m,ct} \ell_{m,ct}} \right)^{\eta} + 1 + v_{1,ct},
\]

(26)

\[
\Delta \ln \left( \frac{w_{m,ct}}{w_{\ell,ct}} \right) = -\sum_{s=1}^{S} \psi_{s,c} \Delta r^s - (1 - \xi) \Delta \ln \left( \frac{\ell_{m,ct}}{\ell_{\ell,ct}} \right) + \frac{\eta - \xi}{\eta} \Delta \ln \left[ \frac{A_{n,ct} k_{n,ct}}{A_{\ell,ct} \ell_{\ell,ct}} \right] + 1 + v_{2,ct},
\]

(27)

\[
\Delta \ln \left( \frac{w_{h,ct}}{r_{i,ct}} \right) = -(1 - \rho) \Delta \ln \left( \frac{\ell_{h,ct}}{k_{i,ct}} \right) + v_{3,ct},
\]

(28)

\(^3\)Krusell et al. (2000) estimate equations for the labor share of income, the wage-bill ratio, and the no-arbitrage condition for capital equipment and structure. In their study, skilled and unskilled labor are treated as endogenous variables, while capital equipment and structure are treated as exogenous variables.
\[
\Delta \ln \left( \frac{w_{\ell,ct}}{r_{n,ct}} \right) = - (1 - \eta) \Delta \ln \left( \frac{\ell_{,ct}}{k_{n,ct}} \right) + v_{4,ct},
\]

where \( v_{1,ct}, v_{2,ct}, v_{3,ct}, \) and \( v_{4,ct} \) are idiosyncratic errors. The errors are allowed to be correlated across equations. The elasticity of substitution between high- and medium-skilled labor, \( 1 / (1 - \sigma) \), is identified from equation (26), while the elasticity of substitution between ICT capital equipment and high-skilled labor, \( 1 / (1 - \rho) \), is identified from equation (28). The elasticity of substitution between medium- and low-skilled labor, \( 1 / (1 - \xi) \), is identified from equation (27), while the elasticity of substitution between non-ICT capital equipment and low-skilled labor, \( 1 / (1 - \eta) \), is identified from equation (29).

### 5.2 Generalized method of moments

We jointly estimate the system of equations (24) and (25) for the four-factor production function and the system of equations (26)–(29) for the six-factor production function using the generalized method of moments (GMM). This approach is semi-parametric because it does not impose a distributional assumption on the errors. It achieves the identification of parameters in a transparent manner, as seen above. We treat all capital and labor inputs as endogenous variables, and use their two-, three-, and four-year lagged values as instrumental variables.

Let \( \theta \) denote a set of parameters to be estimated. The vector of parameters is \( \theta = (\sigma, \rho, \mu, \lambda_{1,c}, \ldots, \lambda_{S,c}) \) for the four-factor production function, and \( \theta = (\sigma, \rho, \xi, \eta, \mu, \gamma, \lambda_{1,c}, \ldots, \lambda_{S,c}, \psi_{1,c}, \ldots, \psi_{S,c}) \) for the six-factor production function. The GMM estimator \( \hat{\theta} \) is chosen to minimize the quadratic form.

\[
\hat{\theta} = \arg \min_{\theta} \ g_{N}(\theta)' W_{N} g_{N}(\theta),
\]

where \( g_{N}(\theta) \) is a vector of moment conditions, and \( W_{N} \) is a weighting matrix. Let \( z \) denote a vector of instrumental variables. The elements of \( g_{N}(\theta) \) are \( N^{-1} \sum_{c=1}^{C} \sum_{t=1}^{T_{c}} z_{jct} u_{jct} \) for \( j = 1, 2 \) in the four-factor production function, and \( N^{-1} \sum_{c=1}^{C} \sum_{t=1}^{T_{c}} z_{jct} v_{jct} \) for \( j = 1, 2, 3, 4 \) in the six-factor production function, where \( C \) is the number of countries, \( T_{c} \) is the number of years used for estimation in country \( c \), and \( N \) is the sum of \( T_{c} \) across countries.
5.3 Decomposition

After estimating production function parameters, we decompose changes in the skill premium into the capital-skill complementarity effect, the relative labor quantity effect, and the relative labor-augmenting technology effect. We then further decompose the above three effects into the effects due to each capital and labor input. As seen in equation (24), the change in the log of the skill premium is additively linear in the capital-skill complementarity effect, the relative labor quantity effect, and the relative labor-augmenting technology effect in the four-factor production function. The results of this decomposition do not depend on the order of decomposition. However, the capital-skill complementarity effect is not additively linear in capital equipment or high-skilled labor. The results of such decomposition are path dependent. Furthermore, as seen in equations (22), (26), and (27), the change in the log of the skill premium is not additively linear in the capital-skill complementarity effect, the relative labor quantity effect, or the relative labor-augmenting technology effect in the six-factor production function. The results of this decomposition are also path dependent. We implement the Shapley decomposition to address the issue of path dependence (Shorrocks, 2013). Appendix A.6 provides a detailed description of the decomposition.

6 Results

We first present the estimates for the elasticities of substitution among capital and labor inputs, and then discuss the sources and mechanism of changes in the skill premium.

6.1 Elasticities of substitution

Four-factor production function Table 1 presents the estimates for the elasticities of substitution in the four- and six-factor production functions. The four-factor production function involves two substitution parameters. The estimated elasticity of substitution is much smaller between capital equipment ($k_e$) and high-skilled labor ($\ell_h$) than between the $k_e-\ell_h$ composite and unskilled labor ($\ell_u$). The results confirm the capital-skill complementarity hypothesis ($\sigma > \rho$). The estimated elasticity of substitution between $k_e$ and $\ell_h$ is similar to that in Krusell et al. (2000), but the estimated elasticity of substitution between the $k_e-\ell_h$...
composite and $\ell_u$ is greater than that in Krusell et al. (2000). Consequently, the difference between the two substitution parameters, $\sigma - \rho$, to which the capital-skill complementarity effect is proportional, is greater here (1.423 vs. 0.896). Our results are consistent with those in Polgreen and Silos (2008), who re-estimate the four-factor production function using alternative U.S. data sets and estimation techniques. Polgreen and Silos (2008) demonstrate that the estimate of $1/(1 - \sigma)$ is greater when they use the data from the National Income and Product Account (NIPA) than when they use the data in Krusell et al. (2000). Our estimates of $1/(1 - \sigma)$ and $1/(1 - \rho)$ are both similar to those obtained from the NIPA data in Polgreen and Silos (2008). Recently, Eden and Gaggl (2018) also obtain close estimates of $1/(1 - \sigma)$ in the United States. The estimated elasticities of substitution are almost unchanged regardless of including and excluding time trends.

Table 1: Production function estimates

| Production functions | 1/(1 - $\rho$) | 1/(1 - $\sigma$) | 1/(1 - $\xi$) | 1/(1 - $\eta$) |
|---------------------|----------------|----------------|--------------|--------------|
| Four factors        | $k_e$ & $\ell_h$ | $k_e$ & $\ell_h$ & $\ell_u$ | 0.667 | 11.861 |
| Without trends      | (0.326) | (4.885) | [0.310] | [5.338] |
| With trends         | (0.271) | (5.123) | [0.309] | [6.038] |
| Six factors         | $k_i$ & $\ell_h$ | $k_i$ & $\ell_h$ & $\ell_u$ | $k_n$, $\ell_m$, $\ell_{\ell}$ | 0.894 | 11.237 | 4.680 | 7.527 |
| With trends         | (0.110) | (3.223) | (0.996) | (3.097) | [0.087] | [5.027] | [1.508] | [3.750] |

Notes: Standard errors in parentheses are clustered at the country level, and those in square brackets are Newey-West adjusted with the optimal lag length (Newey and West, 1994).

Six-factor production function The six-factor production function involves four substitution parameters. The estimated elasticity of substitution is much smaller between ICT capital equipment ($k_i$) and high-skilled labor ($\ell_h$) than between the $k_i$-$\ell_h$ composite and $k_n$-$\ell_m$-$\ell_{\ell}$ composite. The estimated elasticity of substitution is smaller between the $k_n$-$\ell_{\ell}$ composite and medium-skilled labor ($\ell_m$) than between non-ICT capital equipment ($k_n$) and low-skilled labor ($\ell_{\ell}$). These results confirm the capital-skill complementarity hypothesis. The estimates of three substitution parameters $\sigma$, $\xi$, and $\eta$ are not very different at 0.911, 0.786, and 0.867, respectively, while the estimate of the substitution parameter $\rho$ is different from
the other three substitution parameters at \(-0.119\). The results imply that the capital-skill complementarity effect is mostly attributable to the term including ICT capital equipment.

**Morishima elasticities**  We examine Morishima elasticities of substitution among all capital and labor inputs. Tables 2a presents the estimates of Morishima elasticities in the four-factor production function. Morishima elasticities are asymmetric, but we can observe some regularity. Capital equipment is much more substitutable with unskilled labor than high-skilled labor, while unskilled labor is more substitutable with high-skilled labor than capital equipment. The former result is consistent with capital-skill complementarity. The latter result indicates that the elasticity of substitution is greater between labor inputs than between capital and labor inputs.

**Table 2: Morishima elasticities of substitution**

(a) Four-factor production function

|        | \(k_e\) | \(\ell_h\) | \(\ell_u\) |
|--------|---------|------------|------------|
| \(k_e\) | 0.664   | 11.948     |            |
|        | (0.271) | (5.123)    |            |
| \(\ell_h\) | 0.664   | 11.948     |            |
|        | (0.271) | (5.123)    |            |
| \(\ell_u\) | 1.542   | 11.069     |            |
|        | (0.943) | (4.434)    |            |

(b) Six-factor production function

|        | \(k_i\) | \(k_n\) | \(\ell_h\) | \(\ell_m\) | \(\ell_\ell\) |
|--------|---------|---------|------------|------------|--------------|
| \(k_i\) | 7.616   | 0.894   | 8.245      | 7.585      |              |
|        | (3.264) | (0.110) | (6.253)    | (1.501)    |              |
| \(k_n\) | 1.997   | 10.134  | 4.680      | 7.527      |              |
|        | (0.299) | (2.966) | (0.996)    | (3.097)    |              |
| \(\ell_h\) | 0.894   | 7.616   | 8.245      | 7.585      |              |
|        | (0.110) | (3.264) | (6.253)    | (1.501)    |              |
| \(\ell_m\) | 1.997   | 5.797   | 10.134     | 6.411      |              |
|        | (0.299) | (8.746) | (2.966)    | (5.777)    |              |
| \(\ell_\ell\) | 1.997   | 7.527   | 10.134     | 4.680      |              |
|        | (0.299) | (3.097) | (2.966)    | (0.996)    |              |

Notes: Elasticities are evaluated at the sample means for all countries and all years. Standard errors in parentheses are clustered at the country level.

Table 2b presents the estimates of Morishima elasticities in the six-factor production function. ICT capital equipment is much more substitutable with non-ICT capital equipment, medium-skilled labor, and
low-skilled labor than high-skilled labor, while non-ICT capital equipment is more substitutable with low-skilled labor than medium-skilled labor. These results are consistent with capital-skill complementarity. ICT and non-ICT capital equipment are substitutes at an elasticity of eight, and medium- and low-skilled labor are substitutes at an elasticity of six. Neither ICT and non-ICT capital equipment nor medium- and low-skilled are perfect substitutes. These results are inconsistent with assumptions in the four-factor production function.

### 6.2 Skill premium

#### 6.2.1 Accounting for changes in the skill premium

The skill premium is predicted very well by both the four- and six-factor production functions. The actual values of the skill premium almost overlap the predicted values from the four-factor production function in all countries (see Figure 13 in the appendix). Furthermore, the actual values of the relative wage of high- to medium-skilled labor and of medium- to low-skilled labor almost overlap the predicted values from the six-factor production function in all countries (see Figures 14 and 15 in the appendix). Given that the skill premium can be expressed in terms of the relative wages of high- to medium-skilled labor and of medium- to low-skilled labor, the actual values of the skill premium also match the predicted values from the six-factor production function.

#### 6.2.2 Impact of capital and labor quantities

We examine the impact of capital and labor quantities on the skill premium. Table 3a presents the estimated elasticities of the skill premium with respect to capital equipment, high-skilled labor, and unskilled labor in the four-factor production function. The elasticities of the skill premium are calculated by differentiating equation (7) with respect to capital and labor quantities and evaluated at the sample mean for all countries and all years. The results indicate that the skill premium increases with a rise in capital equipment and unskilled labor, but decreases with a rise in skilled labor. The impact of skilled labor is expected to be greater in absolute value than that of unskilled labor, because a rise in skilled labor results in a decline in the skill premium not only through the relative quantity effect but also through the capital-skill complementarity effect. In fact, the impact of skilled labor is 2.6 greater in absolute value than that
of unskilled labor. The impact of capital equipment is 1.6 greater in absolute value than that of unskilled labor.

Table 3: Elasticities of the skill premium with respect to capital and labor quantities

(a) Four-factor production function

|  |  |  |  |
|---|---|---|---|
| $k_e$ | $\ell_h$ | $\ell_u$ |
| 0.135 | -0.219 | 0.084 |
| (0.068) | (0.075) | (0.036) |

(b) Six-factor production function

|  | $k_i$ | $k_n$ | $\ell_h$ | $\ell_m$ | $\ell_l$ |
|---|---|---|---|---|---|
|  | 0.107 | -0.021 | -0.196 | 0.099 | 0.011 |
|  | (0.027) | (0.034) | (0.038) | (0.034) | (0.008) |

Notes: Elasticities are evaluated at the sample means for all countries and all years. Standard errors in parentheses are clustered at the country level.

Table 3b presents the estimated elasticities of the skill premium with respect to ICT and non-ICT capital equipment and high-, medium-, and low-skilled labor in the six-factor production function. The elasticities of the skill premium can be calculated by differentiating equation (22) with respect to capital and labor quantities and evaluated at the sample mean for all countries and all years. The results indicate that the skill premium increases with a rise in ICT capital equipment and medium-skilled labor, but decreases with a rise in high-skilled labor. The skill premium does not change significantly with a change in non-ICT capital equipment or low-skilled labor. The impact of high-skilled labor is expected to be greater in absolute value than that of medium-skilled labor, because a rise in high-skilled labor results in a decline the skill premium not only through the relative quantity effect but also through the capital-skill complementarity effect. In fact, the impact of high-skilled labor is almost twice as large in absolute value as that of medium-skilled labor. The impact of ICT capital equipment is similar in absolute value to that of medium-skilled labor.

When comparing elasticity estimates between the four- and six-factor production functions, the effect of ICT capital equipment is similar in magnitude to that of total capital equipment. The effects of high- and medium-skilled labor are similar in magnitude to those of high-skilled and unskilled labor, respectively. Given that ICT capital equipment increased much more rapidly than total capital equipment, and medium-skilled labor did not change significantly in the majority of countries, ICT capital equipment and
high-skilled labor are likely to be key factors in determining changes in the skill premium.

6.2.3 Decomposition of changes in the skill premium

We decompose changes in the skill premium into the capital-skill complementarity effect, the relative quantity effect, and the relative labor-augmenting technology effect. Figure 5 shows the decomposition results in the four-factor production function. The skill premium in the United States fell in the 1970s and rose from the 1980s to the 2000s. The fall in the skill premium in the 1970s is partially attributable to the relative quantity effect, while the rise in the skill premium after the 1970s is almost entirely attributable to the relative labor-augmenting technology effect. In a similar way, the rise in the skill premium in Australia and Germany is almost entirely attributable to the relative labor-augmenting technology effect. In contrast, the increase in the skill premium in the Czech Republic and Portugal is almost entirely attributable to the capital-skill complementarity. However, in most countries, the capital-skill complementarity effect is small relative to the relative labor-augmenting technology effect.

The main reason for this is presumably that an increase in capital equipment is not large enough relative to an increase in high-skilled labor in the data. As mentioned above, the estimated elasticities of substitution imply a greater response of the skill premium to changes in capital equipment than those in Krusell et al. (2000). The real value of capital equipment could increase more rapidly if changes in the quality of capital equipment are taken into account. Krusell et al. (2000) construct and use the quality-adjusted measure of capital equipment based on the results of Gordon (1990). We consider it to be an important step, but Gordon’s (1990) data are available only between the years 1947 and 1983 in the United States. The adjustment procedure involves extrapolating capital equipment price series after the year 1983. An alternative way to allow for changes in the quality of capital equipment is to distinguish between ICT and non-ICT capital equipment.
Figure 5: Decomposition of changes in the skill premium: four-factor production function

Notes: All series are logged and normalized to zero in the initial period. Complementarity, quantity, and technology indicate the capital-skill complementarity effect, the relative quantity effect, and the relative labor-augmenting technology effect.
Figure 6: Decomposition of changes in the skill premium: six-factor production function

Notes: All series are logged and normalized to zero in the initial period. Complementarity, quantity, and technology indicate the capital-skill complementarity effect, the relative quantity effect, and the relative labor-augmenting technology effect.
Although changes in the skill premium over recent decades can be accounted for by means of the four- or six-factor production functions, the decomposition results differ greatly between the four- and six-factor production functions. The fraction of the skill premium attributable to observed factors is understated in the four-factor production function relative to the six-factor production function. Figure 6 shows that the capital-skill complementarity effect and the relative quantity effect are greater in magnitude in the six-factor production function than in the four-factor production function. The rise in the skill premium in the United States is attributable almost entirely to the capital-skill complementarity effect and only marginally to the relative labor-augmenting technology effect. The rise in the skill premium in Australia and Germany is entirely attributable to the capital-skill complementarity effect. The capital-skill complementarity effect is large in all countries. The results imply that, if there were no increase in high-skilled labor relative to medium- and low-skilled labor, the skill premium would increase in all countries.

Trends in the skill premium can be attributed to observed factors in the six-factor production function for some, though not all, countries. Trends in the skill premium attributable to observed factors can be calculated as the sum of the capital-skill complementarity effect and the relative quantity effect, while the trends in the skill premium attributable to unobserved factors can be calculated as the relative labor-augmenting technology effect. Figure 7 shows that trends in the skill premium attributable to observed factors line up very well with the data in the United States, Australia, Germany, Slovenia, and Sweden. This result supports the view that changes in the skill premium are mainly a consequence of changes in capital and labor quantities (Krusell et al., 2000). Trends in the skill premium attributable to observed factors also line up partially with the data in Italy during the 1980s and 1990s, the Netherlands after the late 1980s and the United Kingdom before the 2000s. For the rest of the countries, however, the skill premium did not increase as much as predicted by observed factors in the six-factor production function. This result can be interpreted as evidence supporting the view that there are cross-country differences in the direction of technological change (Acemoglu, 2003; Caselli and Coleman, 2006).
Figure 7: Trends in the skill premium attributable to observed factors: six-factor production function

Notes: All series are logged and normalized to zero in the year 1995. Complementarity and quantity indicate the capital-skill complementarity effect and the relative quantity effect.
6.2.4 International differences in changes in the skill premium

We examine the extent to which international differences in changes in the skill premium are attributed to observed factors. Table 4 presents the decomposition of differences in changes in the skill premium compared with the United States based on the six-factor production function. The first two columns report the actual and predicted differences in changes in the skill premium compared with the United States, respectively. All values in the first column are positive, meaning that the skill premium increased most in the United States among 14 OECD countries. The next seven columns report the portions attributable to observed factors, such as ICT and non-ICT capital equipment, high-, medium-, and low-skilled labor, and unobserved factors, such as the ratio of high- to medium-skilled labor-augmenting technology, and the ratio of medium- to low-skilled labor-augmenting technology. The last two columns report the percentages of the portions attributable to observed factors, including ICT and non-ICT capital equipment and high-, medium-, and low-skilled labor, in the actual and predicted differences in changes in the skill premium, respectively. The results indicate that, in Australia, Germany, Italy, Slovenia, Sweden, and the United Kingdom, a substantial part of the differences are attributable to differences in changes in capital and labor quantities. The main factors in accounting for such differences are high-skilled labor in Australia, Germany, Sweden, and the United Kingdom, and ICT capital equipment in Germany, Italy, Slovenia, and Sweden.

However, a significant fraction of cross-country differences remains unexplained in terms of observed factors in the six-factor production function. In Austria, Denmark, Finland, Japan, the Netherlands, differences in changes in the skill premium compared with the United States are attributed to unobserved factors such as high-skilled labor-augmenting technology.

6.2.5 Wage-bill shares

We have so far discussed the sources and mechanism of changes in the skill premium based on the production function. This approach naturally requires parametric assumptions on the production function. With the objective of understanding the impact of ICT capital equipment on the demand for skilled labor, one can do so by estimating the factor-share equations derived from the translog cost function. However, it is not possible to predict the impact of ICT capital equipment on the relative wages from the estimated
Table 4: Decomposition of differences in changes in the skill premium from the United States: six-factor production function

| Countries | \( \ln \left( \frac{w_h}{w_u} \right) \) | Data | Model | \( k_i \) | \( k_n \) | \( \ell_h \) | \( \ell_m \) | \( \ell_L \) | \( A_h/A_m \) | \( A_m/A_L \) | Error | \( k_i, k_n, \ell_h, \ell_m, \ell_L \) |
|-----------|---------------------------------|------|-------|---------|---------|---------|---------|---------|---------|---------|--------|-----------------|
| AUS       | 0.223                           | 0.158|       | -0.025  | -0.001  | 0.170   | 0.002   | -0.007  | -0.049  | 0.072   | -0.004 | 62.2%           |
| AUT       | 0.446                           | 0.411|       | 0.049   | -0.005  | 0.031   | -0.002  | 0.008   | 0.215   | 0.048   | 0.065  | 18.3%           |
| CZE       | 0.057                           | 0.015|       | 0.006   | 0.015   | -0.011  | 0.010   | -0.000  | -0.038  | 0.025   | 0.009  | 33.2%           |
| DEN       | 0.482                           | 0.390|       | -0.116  | -0.003  | 0.052   | -0.004  | 0.012   | 0.389   | -0.004  | 0.064  | 0.0%            |
| FIN       | 0.592                           | 0.397|       | -0.260  | -0.010  | -0.051  | 0.008   | 0.053   | 0.686   | -0.040  | 0.111  | 0.0%            |
| GER       | 0.039                           | 0.054|       | 0.075   | -0.006  | -0.041  | 0.019   | 0.001   | -0.017  | 0.036   | -0.013 | 122.1%          |
| ITA       | 0.156                           | 0.196|       | 0.105   | 0.012   | 0.013   | 0.031   | -0.014  | -0.033  | 0.080   | 0.002  | 94.6%           |
| JPN       | 0.350                           | 0.336|       | 0.029   | -0.003  | -0.033  | 0.022   | 0.036   | 0.253   | 0.037   | -0.005 | 14.7%           |
| NED       | 0.511                           | 0.490|       | 0.064   | 0.000   | 0.099   | -0.006  | 0.001   | 0.281   | 0.044   | 0.006  | 31.1%           |
| POR       | 0.035                           | -0.101|      | -0.076  | -0.004  | 0.008   | -0.003  | 0.000   | 0.002   | -0.047  | 0.018  | 0.0%            |
| SLO       | 0.150                           | 0.147|       | 0.088   | 0.012   | 0.030   | 0.003   | 0.004   | -0.038  | 0.025   | 0.022  | 92.3%           |
| SWE       | 0.169                           | 0.155|       | 0.056   | 0.012   | 0.060   | -0.002  | 0.007   | 0.004   | 0.006   | 0.011  | 79.1%           |
| UK        | 0.458                           | 0.488|       | -0.007  | -0.011  | 0.290   | 0.012   | 0.029   | 0.220   | -0.090  | 0.045  | 68.4%           |

Notes: The error is a consequence of transformation from \( w_h/w_m \) and \( w_m/w_L \) to \( w_h/w_u \).
factor-share equations, while it is possible to predict the impact of ICT capital equipment on the wage-bill share of skilled labor, as well as the demand for skilled labor, from the estimated production function. We end this section by examining the implications of production function estimates for the impact of ICT capital equipment on the wage-bill shares of high-, medium-, and low-skilled labor. The analysis here provides additional support to our estimates if reaching the same results as Michaels et al. (2014), who examine the impact of ICT capital equipment on the wage-bill shares of high-, medium-, and low-skilled labor by estimating factor-share equations.

The wage-bill share of high-skilled labor can be expressed in terms of the relative wages \( \frac{w_h}{w_m} \) and \( \frac{w_m}{w_\ell} \).

\[
\frac{w_h \ell_h}{w_h \ell_h + w_m \ell_m + w_\ell \ell_\ell} = \left( \frac{w_h}{w_m} \right) \ell_h + \left( \frac{w_\ell}{w_m} \right) \ell_\ell \tag{30}
\]

This means that, if the predicted values of the relative wages fit well with the actual values, the predicted values of wage-bill shares automatically fit well with the actual values. The same applies to the wage-bill shares of medium- and low-skilled labor. We measure the impact of ICT capital equipment on the wage-bill shares of high-, medium-, and low-skilled labor by comparing the actual wage-bill shares with the counterfactual wage-bill shares if there were no change in ICT capital equipment after the initial period of observation. Figure 8 shows that the wage-bill share of high-skilled labor increased with a rise in ICT capital equipment, while the wage-bill share of medium-skilled labor decreased. The wage-bill share of low-skilled labor did not change with a rise in ICT capital equipment. The polarization of wage-bill shares is observed in almost all countries. The results are consistent with those of Michaels et al. (2014).
Figure 8: Impact of ICT capital equipment on wage-bill shares: \( \frac{w_h \ell_h}{(w_h \ell_h + w_m \ell_m + w_l \ell_l)}, \frac{w_m \ell_m}{(w_h \ell_h + w_m \ell_m + w_l \ell_l)}, \) and \( \frac{w_l \ell_l}{(w_h \ell_h + w_m \ell_m + w_l \ell_l)} \)

(a) United States  
(b) Australia  
(c) Austria  
(d) Czech Republic  
(e) Denmark  
(f) Finland  
(g) Germany  
(h) Italy  
(i) Japan  
(j) Netherlands  
(k) Portugal  
(l) Slovenia  
(m) Sweden  
(n) United Kingdom

Notes: All series are normalized to zero in the initial period.
7 Conclusion

This paper has examined the sources and mechanism of changes in the skill premium using cross-country panel data from 14 OECD countries for the years 1970 to 2005. We have estimated the aggregate production function extended to allow for capital-skill complementarity and skill-biased technological change to understand the extent to which changes in the skill premium are attributed to changes due to the effects of the relative labor quantity, capital-skill complementarity, and skill-biased technological change. We have shown that a rise in the skill premium can be largely attributed to the observed expansion of ICT capital equipment relative to high-skilled labor around the world. A substantial part of international differences in changes in the skill premium can be attributed to observed factors for some countries.

We have demonstrated that the skill premium can change significantly in response to changes in capital and labor quantities in the six-factor production function, in which ICT capital equipment is distinguished from non-ICT capital equipment, and medium-skilled labor is distinguished from low-skilled labor. If the evolution of wage inequality is attributed to such unobserved factors as skill-biased technological change, policies that induce skill-biased technological change would have a direct impact on the level of wage inequality. On the other hand, if the evolution of wage inequality is attributed to such observed factors as ICT capital equipment and high-skilled labor, policies that induce compositional changes in capital and labor inputs would affect the level of wage inequality regardless of whether skill-biased technological change is induced. Our results support the latter view, while partially confirming the former view.
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A Appendix

A.1 Derivation of the first-order conditions

We consider a profit maximization problem of a representative firm in competitive markets. The production technology is given by

\[ y_t = f(k_t, \ell_t; A_t), \]  

(31)

where \( k_t \) and \( \ell_t \) are the vectors of capital and labor inputs in period \( t \), i.e., \( k_t = (k_{1t}, \ldots, k_{jt}, \ldots, k_{Jt}) \) and \( \ell_t = (\ell_{1t}, \ldots, \ell_{jt}, \ldots, \ell_{Jt}) \).

Let \( \chi_t \) denote investment and \( q \) the price of investment. The Bellman equation of the problem can be written as:

\[ V(k_t) = \max_{k_{j,t+1}, \ell_{j,t}, \chi_{j,t}} \left\{ y_t - \sum_{j=1}^{J_t} q_{jt} \chi_{jt} - \sum_{j=1}^{J_t} w_{jt} \ell_{jt} + \beta_{t+1} \mathbb{E}_t [V(k_{t+1})] \right\} \]

(32)

subject to the law of motion of capital:

\[ k_{j,t+1} = (1 - \delta_j) k_{jt} + \chi_{jt}. \]

(33)

The discount factor is given by \( \beta_t = 1/(1 + i_t) \), where \( i \) is an interest rate.

The first-order condition with respect to \( k_{j,t+1} \) is

\[ q_{jt} = \beta_{t+1} \mathbb{E}_t \left[ \frac{\partial V_{t+1}}{\partial k_{j,t+1}} \right]. \]

(34)

By the envelope theorem,

\[ \frac{\partial V_t}{\partial k_{jt}} = \frac{\partial f_t}{\partial k_{jt}} + q_{jt} (1 - \delta_j). \]

(35)

Assume the firm make the investment decisions with the knowledge of \( A_{t+1} \) and \( q_{j,t+1} \). The first-order condition can be rewritten as:

\[ \frac{\partial f_{t+1}}{\partial k_{j,t+1}} = \delta_j q_{j,t+1} + i_{t+1} q_{jt} - (q_{j,t+1} - q_{jt}) \equiv r_{j,t+1}, \]

(36)

where \( r_{jt} \) is referred to as the rental price of capital or the user cost of capital. The first-order condition
with respect to $\ell_{jt}$ is simply

$$\frac{\partial f_t}{\partial \ell_{jt}} = w_{jt}.$$  

(37)

Equations for the no-arbitrage condition for capital equipment and structure and for the wage-bill ratio in Krusell et al. (2000) can be obtained from equations (36) and (37), respectively. In the main text, we allow for the deviation from the profit-maximizing conditions in perfectly competitive markets.

### A.2 Specification of the six-factor production function

We specify the six-factor production function in a way that resembles previous studies and satisfies theoretical restrictions on the substitution parameters. Raveh and Reshef (2016) and Eden and Gaggl (2018) distinguish ICT capital equipment from non-ICT capital equipment and capital structure in the production function à la Krusell et al. (2000). With our notation, the production functions in Raveh and Reshef (2016) and Eden and Gaggl (2018) can be, respectively, written as:

\[
y = A \left\{ \lambda k^\mu_i (\zeta_h \ell_h)^{1-\mu} + (1 - \lambda) k^\gamma_n (\zeta_m \ell_m + \zeta_{\ell_{\ell}})^{1-\gamma} \right\}^{\frac{1}{\sigma}}.
\]

(38)

and

\[
y = A (k_n + k_s)^\alpha \left\{ \lambda \mu k^\rho_i + (1 - \mu) (\zeta_h \ell_h)^{\rho} + (1 - \lambda) (\zeta_m \ell_m + \zeta_{\ell_{\ell}}) \right\}^{\frac{1-\mu}{\sigma}}.
\]

(39)

In both cases, ICT capital equipment is paired with high-skilled labor in the final nest. Because these studies are most concerned with the complementarity between ICT capital equipment and high-skilled labor, it is natural to consider the combination of these two. Non-ICT capital equipment is included in the CES (constant elasticity of substitution) aggregate for the production function (38) but not for the production function (39). When comparing the production functions (38) and (39), the former is more flexible in the degree of substitution between non-ICT capital equipment and other inputs, while the latter is more flexible in the degree of substitution between ICT capital equipment and high-skilled labor. The six-factor production function (9) is similar to the production functions (38) and (39) in that ICT capital equipment is paired with high-skilled labor in the final nest, while it is more flexible in that it allows for not only ICT capital-skill complementarity but also non-ICT capital skill complementarity. In addition, the six-factor production function (9) distinguishes between medium- and low-skilled labor, as well as
between non-ICT capital equipment and capital structure. A minor remaining question is whether non-ICT capital equipment is paired with medium- or low-skilled labor. We choose to pair non-ICT capital equipment with low-skilled labor, because we cannot reject the null hypothesis of $\eta \geq 1$ if non-ICT capital equipment is paired with medium-skilled labor.

### A.3 Demand for inputs

The input demand functions can be derived from the marginal-rate-of-technical-substitution conditions and the production function. In the four-factor production function, the input demand functions are

$$
\ell_h = \frac{y}{A} \left[ \frac{r_s (1 - \alpha)}{\omega_s \alpha} \right]^{\alpha} \left[ \frac{\omega_h (1 - \mu)}{w_h} \right]^{\frac{1}{1-\sigma}} \lambda^{\frac{1}{1-\sigma}} B^{\frac{1}{(1-\rho)(1-\sigma)}} C^{\frac{1}{1-\sigma} - \frac{\sigma - \rho}{\sigma}} \tag{40}
$$

$$
\ell_u = \frac{y}{A} \left[ \frac{r_s (1 - \alpha)}{\omega_s \alpha} \right]^{\alpha} \left[ \frac{\omega_u (1 - \lambda)}{w_u} \right]^{\frac{1}{1-\sigma}} C^{\frac{1}{1-\sigma} - \frac{\sigma - \rho}{\sigma}} \tag{41}
$$

$$
k_e = \frac{y}{A} \left[ \frac{r_s (1 - \alpha)}{\omega_s \alpha} \right]^{\alpha} \left( \frac{\omega_e \mu}{r_e} \right)^{\frac{1}{1-\sigma}} \lambda B^{\frac{1}{(1-\rho)(1-\sigma)}} C^{\frac{1}{1-\sigma} - \frac{\sigma - \rho}{\sigma}} \tag{42}
$$

$$
k_s = \frac{y}{A} \left[ \frac{r_s (1 - \alpha)}{\omega_s \alpha} \right]^{\alpha-1} C^{1-\alpha} \tag{43}
$$

where

$$
B = \left[ \omega_e^{\frac{\rho}{1-\sigma}} \mu^{\frac{1}{1-\rho}} r_e^{-\frac{\rho}{1-\sigma}} + \omega_h^{\frac{\rho}{1-\sigma}} (1 - \mu)^{\frac{1}{1-\sigma}} w_h^{-\frac{\rho}{1-\sigma}} \right]^{-\frac{1}{1-\rho}} \tag{44}
$$

$$
C = \left[ \lambda^{\frac{1}{1-\rho}} B^{\frac{1}{1-\sigma}} + \omega_u^{\frac{\sigma}{1-\sigma}} (1 - \lambda)^{\frac{1}{1-\sigma}} w_u^{-\frac{\sigma}{1-\sigma}} \right]^{-\frac{1}{1-\sigma}} \tag{45}
$$
In the six-factor production function, the input demand functions are

\[
\ell_h = \frac{y}{A} \left[ \frac{(1 - \alpha) r_s}{\alpha \omega_s} \right]^{\alpha} \left[ \frac{w_h}{\omega_h (1 - \mu)} \right]^{\frac{1}{\sigma}} \lambda^{\frac{1}{1 - \sigma}} D^{-\frac{\alpha - \rho}{(1 - \rho)(1 - \sigma)}} G^{\frac{1 - \alpha + \sigma \alpha}{1 - \sigma}},
\]

(46)

\[
\ell_m = \frac{y}{A} \left[ \frac{(1 - \alpha) r_s}{\alpha \omega_s} \right]^{\alpha} \left[ \frac{w_m}{\omega_m (1 - \psi)} \right]^{\frac{1}{\sigma}} (1 - \lambda)^{\frac{1}{1 - \sigma}} F^{-\frac{\alpha - \xi}{(1 - \xi)(1 - \sigma)}} G^{\frac{1 - \alpha + \sigma \alpha}{1 - \sigma}},
\]

(47)

\[
\ell_k = \frac{y}{A} \left[ \frac{(1 - \alpha) r_s}{\alpha \omega_s} \right]^{\alpha} \left[ \frac{w_k}{\omega_k (1 - \gamma)} \right]^{\frac{1}{\sigma}} (1 - \lambda)^{\frac{1}{1 - \sigma}} \psi^{\frac{1}{1 - \xi}} E^{-\frac{\xi - \eta}{(1 - \eta)(1 - \xi)}} F^{-\frac{\alpha - \xi}{(1 - \xi)(1 - \sigma)}} G^{\frac{1 - \alpha + \sigma \alpha}{1 - \sigma}},
\]

(48)

\[
k_i = \frac{y}{A} \left[ \frac{(1 - \alpha) r_s}{\alpha \omega_s} \right]^{\alpha} \left[ \frac{w_i}{\omega_i} \mu \right]^{\frac{1}{\sigma}} \lambda^{\frac{1}{1 - \sigma}} D^{-\frac{\alpha - \rho}{(1 - \rho)(1 - \sigma)}} G^{\frac{1 - \alpha + \sigma \alpha}{1 - \sigma}},
\]

(49)

\[
k_n = \frac{y}{A} \left[ \frac{(1 - \alpha) r_s}{\alpha \omega_s} \right]^{\alpha} \left[ \frac{w_n}{\omega_n} \gamma \right]^{\frac{1}{\sigma}} (1 - \lambda)^{\frac{1}{1 - \sigma}} \psi^{\frac{1}{1 - \xi}} E^{-\frac{\xi - \eta}{(1 - \eta)(1 - \xi)}} F^{-\frac{\alpha - \xi}{(1 - \xi)(1 - \sigma)}} G^{\frac{1 - \alpha + \sigma \alpha}{1 - \sigma}},
\]

(50)

\[
k_s = \frac{y}{A} \left[ \frac{(1 - \alpha) r_s}{\alpha \omega_s} \right]^{\alpha} \left[ \frac{w_s}{\omega_s} \right]^{\frac{1}{\sigma}} G^{1 - \alpha},
\]

(51)

where

\[
D = \left[ \omega_t^{\frac{\rho}{1 - \rho}} \mu^{\frac{1}{1 - \rho}} r_i^{\frac{-\rho}{1 - \rho}} + \omega_h^{\frac{\rho}{1 - \rho}} (1 - \mu)^{\frac{1}{1 - \rho}} w_h^{\frac{-\rho}{1 - \rho}} \right]^{\frac{-1 - \rho}{\rho}},
\]

(52)

\[
E = \left[ \omega_n^{\eta} \gamma^{\frac{1}{1 - \eta}} r_n^{\frac{-\eta}{1 - \eta}} + \omega_k^{\eta} (1 - \gamma)^{\frac{1}{1 - \eta}} w_k^{\frac{-\eta}{1 - \eta}} \right]^{\frac{-1 - \eta}{\eta}},
\]

(53)

\[
F = \left[ \psi^{\frac{1}{1 - \xi}} E^{-\frac{\xi}{1 - \xi}} + \omega_m^{\frac{\xi}{1 - \xi}} (1 - \psi)^{\frac{1}{1 - \xi}} w_m^{\frac{-\xi}{1 - \xi}} \right]^{\frac{-1 - \xi}{\xi}},
\]

(54)

\[
G = \left[ \lambda^{\frac{1}{1 - \sigma}} D^{-\frac{\alpha}{1 - \sigma}} + (1 - \lambda)^{\frac{1}{1 - \sigma}} F^{-\frac{\alpha}{1 - \sigma}} \right]^{\frac{-1}{\sigma}}.
\]

(55)

The Morishima elasticity of substitution (21) can be rewritten as:

\[
\epsilon_{ab} = \frac{\partial \ln x_a(p, y)}{\partial \ln p_b} - \frac{\partial \ln x_b(p, y)}{\partial \ln p_b},
\]

(56)

It is straightforward to calculate the elasticity from the input demand functions (40)–(43) in the four-factor production function and from the input demand functions (46)–(51) in the six-factor production function.
A.4 The rental price of capital

Capital is divided into eight categories: (i) computing equipment, (ii) communications equipment, (iii) software, (iv) transport equipment, (v) other machinery and equipment, (vi) non-residential structures and infrastructures, (vii) residential structures, and (viii) other assets. We classify categories (i), (ii), and (iii) as ICT capital equipment \((k_i)\), (iv) and (v) as non-ICT capital equipment \((k_n)\), and (vi) as capital structure \((k_s)\). ICT and non-ICT capital equipment constitute capital equipment \((k_e)\).

As seen from equation (36), the rental price of capital \((r_{jt})\) is determined by the price of investment \((q_{jt})\), the depreciation rate \((\delta_j)\), and the interest rate \((i_t)\). The price of investment is calculated by dividing the nominal value by the real value of investment for each \(j = \{e,i,n,s\}\). The depreciation rate is calculated from the average of depreciation rates of capital components weighted by the share of capital components. Following O’Mahony and Timmer (2009), the interest rate is calculated as:

\[
    i_t = \frac{r_t k_t - \sum_j \delta_j q_{jt} k_{jt} + \sum_j (q_{jt} - q_{j,t-1}) k_{jt}}{\sum_j q_{j,t-1} k_{jt}},
\]

where \(r_t k_t = \sum_j r_j k_j\) for \(j = \{e,s\}\) in the four-factor production function and for \(j = \{i,n,s\}\) in the six-factor production function.

A.5 Country-specific trends

We choose the order of country-specific trend polynomials to account for trends in the relative wages in each country. In the share parameter \(\lambda\), we include cubic trends for the United States; quadratic trends for Finland, Italy, and Netherlands; linear trends for Australia, Austria, Denmark, Germany, and Japan; and no trend for the Czech Republic, Portugal, Slovenia, Sweden, and the United Kingdom. In the share parameter \(\psi\), we include quadratic trends for Finland, Germany, and Italy; linear trends for Austria, Denmark, Japan, the Netherlands, Portugal, Sweden, the United Kingdom and the United States; and no trend for Australia, the Czech Republic, and Slovenia.
A.6 Shapley decomposition

We consider measuring the contribution of each factor to changes in the skill premium using the Shapley decomposition (Shorrocks, 2013). The determinant factor of the skill premium is denoted by $d_\kappa$ and indexed by $\kappa = \{1, 2, \ldots, \tau\}$. The subscripts $c$ and $t$ suppressed for notational simplicity. Changes in the skill premium can be represented as:

$$\Delta \ln \left( \frac{w_h}{w_u} \right) = f (d_1, d_2, \ldots, d_\tau). \quad (58)$$

Let $\Gamma(\Upsilon)$ denote the amount of changes in the skill premium if the factors, $d_\kappa$ for $\kappa \notin \Upsilon$, are held fixed at the initial value, $o = (o_1, \ldots, o_\tau)$ denote the order in which the factors are held fixed, and $\Upsilon(o_1, o) = \{ o_{t'} | t' > t \}$ denote the set of factors that remain unfixed after the $t$-th factor is held fixed. The marginal contribution of the $\kappa$-th factor can be written as:

$$\Lambda^o_{d_\kappa} = \Gamma(\Upsilon(d_\kappa, o) \cup \{d_\kappa\}) - \Gamma(\Upsilon(d_\kappa, o)). \quad (59)$$

The Shapley decomposition is implemented by averaging the marginal contributions of each component over all possible sequences. Let $\mathcal{O}$ denote the set of sequences. The Shapley decomposition is

$$\Lambda_{d_\kappa} = \frac{1}{\tau!} \sum_{o \in \mathcal{O}} \Lambda^o_{d_\kappa}. \quad (60)$$

Thus, in the four-factor production function, changes in the skill premium can be decomposed as:

$$\Delta \ln \left( \frac{w_h}{w_u} \right) = \Lambda_{k_e} + \Lambda_{\ell_h} + \Lambda_{\ell_u} + \Lambda_{A_{h}}. \quad (61)$$

where the four terms represent the marginal contributions of $k_e$, $\ell_h$, $\ell_u$, and $A_{h}/A_{u}$, respectively. In the six-factor production function, changes in the skill premium can be decomposed as:

$$\Delta \ln \left( \frac{w_h}{w_u} \right) = \Lambda_{k_i} + \Lambda_{k_n} + \Lambda_{\ell_h} + \Lambda_{\ell_m} + \Lambda_{\ell_\ell} + \Lambda_{A_{h}} + \Lambda_{A_{m}} + \Lambda_{A_{\ell}} + \Lambda_{\ell_m} + \Lambda_{\ell_{\ell}}. \quad (62)$$

where the nine terms represent the marginal contributions of $k_i$, $k_n$, $\ell_h$, $\ell_m$, $\ell_\ell$, $A_{h}/A_{m}$, $A_{m}/A_{\ell}$, $\ell_m/\ell_\ell$, $\ell_{\ell}$.
\( \ell_m + \ell_\ell)/\ell_m \), respectively. The last two terms are considered errors because they appear as a consequence of transformation from \( w_h/w_m \) and \( w_m/w_\ell \) to \( w_h/w_u \). Differences in changes in the skill premium from the United States can be decomposed as:

\[
\Delta \ln \left( \frac{w_{h,us,t}}{w_{u,us,t}} \right) - \Delta \ln \left( \frac{w_{h,c,t}}{w_{u,c,t}} \right) = \sum_{d_k} \left( \Lambda_{d_k,us,t} - \Lambda_{d_k,c,t} \right),
\]

(63)

where \( d_k = \{k_e, \ell_h, \ell_u, A_h/A_u\} \) in the four-factor production function and \( d_k = \{k_i, k_n, \ell_h, \ell_m, \ell_\ell, A_h/A_m, A_m/A_\ell, \ell_m/\ell_\ell, (\ell_m + \ell_\ell)/\ell_m\} \) in the six-factor production function.

### A.7 Additional figures

Figures 9, 10, 11, and 12, respectively, show trends in the relative wages, the rental prices of capital, the shares of each labor input and the shares of each capital input in the countries other than the United States. Figure 13 shows the predicted values of the skill premium from the four-factor production function along with the actual values of the skill premium in all countries. Figures 14 and 15 show the predicted values of the relative wage of high- to medium-skilled labor and of medium- to low-skilled labor, respectively, from the six-factor production function along with the actual values in the data in all countries.
Figure 9: Relative wages in OECD countries: \( w_h / w_m \) and \( w_h / w_\ell \)

(a) Australia  (b) Austria

(c) Czech Republic  (d) Denmark  (e) Finland

(f) Germany  (g) Italy  (h) Japan

(i) Netherlands  (j) Portugal  (k) Slovenia

(l) Sweden  (m) United Kingdom

Notes: All series are logged and normalized to zero in the initial period.
Figure 10: Rental prices of capital in OECD countries: $r_t$, $r_n$, and $r_s$

Notes: All series are logged and normalized to zero in the initial period.
Figure 11: Shares of high-, medium-, and low-skilled labor in OECD countries: $\ell_h/ (\ell_h + \ell_m + \ell_l)$, $\ell_m/ (\ell_h + \ell_m + \ell_l)$, and $\ell_l/(\ell_h + \ell_m + \ell_l)$

(a) Australia  
(b) Austria  
(c) Czech Republic  
(d) Denmark  
(e) Finland  
(f) Germany  
(g) Italy  
(h) Japan  
(i) Netherlands  
(j) Portugal  
(k) Slovenia  
(l) Sweden  
(m) United Kingdom
Figure 12: Shares of ICT capital equipment, non-ICT capital equipment, and capital structure in OECD countries: \( k_i / (k_i + k_n + k_s) \), \( k_n / (k_i + k_n + k_s) \), and \( k_s / (k_i + k_n + k_s) \)
Figure 13: Predicted skill premium from the four-factor production function: $w_h/w_u$

Notes: All series are logged.
Figure 14: Predicted relative wage from the six-factor production function: \( \frac{w_h}{w_m} \)

Notes: All series are logged.
Figure 15: Predicted relative wage from the six-factor production function: $w_m / w_\ell$

Notes: All series are logged.