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Egalitarian and elitist education systems as the basis for international differences in wage inequality

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Abstract

This paper investigates one reason why some countries have experienced a strong increase in wage inequality over the last decades while others have not. The explanation is based on the link between the quality of education and induced technological change. A country with qualitatively better-educated skilled workers, relative to unskilled workers, has a higher ratio of human capital to labour than a country where the quality of education is more equal across education levels. These differences lead to different paths of induced technological change across countries, which in turn imply different histories of the distribution of labour income. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

A comparison between the evolution of wages in the US and European countries, for example, Germany, makes one think that differences in education systems might be one of the fundamental reason why the US has experienced a

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considerable increase in wage inequality during the 1980s while Germany has not. One of the advantages that is often claimed for the German education system is the homogeneity in the quality of education across education levels. Leaving school after 9 years and successfully finishing vocational training leads to accumulation of a marketable stock of human capital that is a little smaller than human capital of someone with a university degree.

While it is difficult to define and measure the quality of education, one reason for relative quality differences across education levels might lie in the allocation of educational resources (as teachers and equipment). Some figures from OECD (1993, p. 92) are suggestive of significant cross-country differences: comparing total (public and private) expenditure for education per education level between the US and Germany (converted by using PPPs) shows that in 1991 expenditure per student for primary and secondary education was about the same in the US and Germany (US$5555 for the US and US$5432 for Germany). Expenditure per student in tertiary education, however, was more than twice as much in the US than in Germany (US$13639 for the US and US$6322 for Germany). If expenditure were corrected for GDP per capita, Germany would have an even higher expenditure ratio for primary and secondary education than the US and a still smaller ratio for tertiary education than the US. These differences in the relative allocation of resources might be one of the reasons for differences in relative abilities of graduates.[2]

Direct evidence that differences in abilities between graduates from tertiary education and graduates from primary and secondary education are larger in the US than elsewhere comes from analyses of the OECD (1995) ‘‘International Adult Literacy Survey’’ by Nickell and Bell (1996). Indirect (residual) evidence is provided by Blau and Kahn (1997). Both Blau and Kahn and Nickell and Bell note that, roughly, German unskilled earn more than American unskilled workers but do not have a higher probability of becoming unemployed. As Nickell and Bell (1996, p. 306, their emphasis) put it, ‘‘German men in the bottom wage decile earn more than *twice as much* as American men in a similar position. And yet, they are hardly more likely to be unemployed.’’ Blau and Kahn argue that this finding can be explained to some extent by a larger public sector in Germany that acts as an ‘‘employer of last resort’’. At the same time, however, they stress that differences in the size of the public sector are not enough to account for all of the differences. They therefore conjecture that productivity of unskilled workers in Germany exceeds productivity of unskilled workers in the US. Nickell and Bell give support for their view that ‘‘the German education system produces a much

[2] There is remarkable disagreement in the literature on the question to which extent more resources increase future labour market success of pupils. Card and Krueger (1992, 1996) hold a positive view while Betts (1996) is more sceptical. A broader overview of the literature can be found in Burtless (1996).

more compressed distribution of human capital than the systems in Britain or the United States'' (p. 306) by citing the OECD (1995) study, which found that the variation in literacy levels is much larger in the US than in Germany.

In the model set out in this paper, education systems are classified as egalitarian or elitist. 'Elitist education system' could be understood as a system where differences in the quality of education are large within one level of education. This idea would characterize an education system where the quality of, for example, universities differs greatly. Few universities bring together the best teachers and the best equipment to educate the best students. The term 'elitist education system' is used here in another sense: an education system is more elitist than another education system, if — generally speaking — the quality of education in tertiary education is considered to be more important than the quality of education on the primary and secondary level. Following the formal definition that follows below, an education system is more elitist, if the skill ratio of graduates from tertiary to graduates from primary and secondary education is higher than in another education system.

With the above evidence as background, this paper starts from the hypothesis that the US is a country with a more elitist education system than Germany. Given well-known differences in the evolution of relative labour earnings between these two countries (Abraham and Houseman, 1995; Steiner and Wagner, 1998), one is inclined to ask: what is the impact of the relative quality of education systems on absolute and relative wages of different education groups?

The main findings of the subsequent analysis are the following: differences in education systems, per se, do not have a direct impact on the skill premium. An elitist education system does not lead to higher wage inequality than an egalitarian system, provided that individuals have unconstrained access to education levels. Differences in education systems, however, do have efficiency effects. When an education system is inefficient, incentives to develop new technologies arise that tend to reduce these inefficiencies. Once these technologies are available, this inefficiency is reduced but at the same time the wage structure changes. While the introduction of new technologies in an economy with an elitist education system leads to an increase of wage inequality, new technologies in an economy with an egalitarian education system lead to a decrease of wage inequality.

Two aspects of new technologies are stressed in this paper. First, modern technologies allow skilled workers to do the jobs formerly performed by unskilled and; second, skilled workers perform these 'unskilled jobs' with the same productivity with which they perform 'skilled jobs'. Abilities acquired during education that were traditionally useful only for performing skilled jobs are now of use also when performing unskilled jobs. When modern technologies are available, firms have to decide by which technology to produce. This is equivalent to asking, ''Who should perform unskilled jobs?'' When a firm opts for modern technology, unskilled jobs are performed by skilled workers. When it stays with traditional technology, unskilled jobs continue to be performed by unskilled workers. Since modern technologies allow skilled workers to preserve their productivity lead (skilled perform unskilled jobs with technologies that differ from technologies used by unskilled), firms not only compare relative wages, but also relative productivity. The direction of technological change is therefore determined by relative wages per efficiency unit. Since efficiency units depend on the education system, the education system plays a crucial role in determining the direction of technological change.

It is then immediately clear that technological change is endogenous and that, just as unskilled workers can be replaced by skilled workers, the effect can be the other way round. Technological change can either increase demand for unskilled or for skilled workers, depending on relative productivities. Relative wage income is fixed by free access to all education levels. An elitist education system that leads to a high ratio of abilities of skilled as compared to unskilled workers thereby implies low relative wages per efficiency unit of skilled workers. This creates incentives to develop technologies that allow the replacement of unskilled by skilled workers. The opposite holds true for an economy with an egalitarian education system. In between lies an education system where no incentives exist to create new technologies.[3] As will turn out below, this is the efficient, i.e., output maximizing education system.

Now, assume a new technology has been developed and firms start replacing unskilled workers by skilled workers. This leads to an increase in efficiency, an increase in wages of skilled workers and a decrease in wages of unskilled workers, measured in terms of the consumption good. Technological change, as understood here, produces winners and losers. While demand for certain abilities increase, and these abilities become more valuable, other abilities lose value.[4]

The entire argument hinges on the assumption that modern high-skill technology allows skilled workers to keep their productivity lead relative to unskilled workers when performing unskilled jobs. If workers were equally productive, modern high-skill technologies would never be adopted and wage inequality would not rise. However, this assumption is plausible. If technologies allow skilled workers to keep their productivity lead, these technologies will be adopted by firms. Hence, there are incentives to develop these technologies, and one should expect that they are indeed developed.

[3] This paper focuses on the distributional aspect of technological change. Incentives to develop new technologies that raise productivity of all factors of production can be expected to be always present.

[4] The Hicks–Kennedy–Von Weizsäcker approach to distributional aspects of technological change does not allow to understand both replacement and loss in value. The main references are Kennedy (1964), Samuelson (1965), Drandakis and Phelps (1966) and von Weizsäcker (1966). The lacking microfoundation has been criticized by Nordhaus (1973). An improvement is provided by Binswanger (1974) and an overview is in Binswanger and Ruttan (1978). See Wälde (1997) for a more detailed critique of this literature.

These findings allow to understand several aspects of the literature. The evolution of wages in the US over the 1980s (e.g., Bound and Johnson, 1992; Katz and Murphy, 1992; Juhn et al., 1993) can be understood as an endogenous outcome of technology choice induced by the relative quality of education. These authors argue that technological change must have been one of the reasons why wage inequality increased. This conclusion can, however, be disputed. There are theoretical arguments that suggest that technological change should reduce wage inequality. The present model presents a way to reconcile these opposing views. The paper also provides an answer to the question why wage inequality did not increase in other countries, as shown, for example, for Germany by Abraham and Houseman (1995) and Steiner and Wagner (1998). Finally, the paper provides an interpretation of relative unemployment experience in US and Germany. These aspects are taken up in Section 5 below.

In previous literature, Zeira (1998) has analysed the effects of technology adoption on the growth rate of a country. He shows that a small difference in the productivity parameter of a country's technology (such as land abundance and quality, natural resources or climate) can lead to high differences in GDP per capita. Below a certain threshold level, a country will not adopt new technologies and will therefore not grow, whereas countries above this level do grow. As here, technology adoption in his framework depends on relative prices. However, he does not focus on replacing labour groups by each other, and, therefore, does not draw a link to the education system. Neither does he explicitly (despite a short section on income distribution) study the effect of new technologies on relative wages or differences between the US and Germany.

Lindbeck and Snower (1996) present a model where the allocation of workers to jobs can change. They assume a production function that allows firms to organize production processes such that workers perform one specific task (Tayloristic organization) or perform several tasks (holistic organization). Within this framework, an interpretation of labour-market inequality is given as a shift from Tayloristic to holistic organization of firms. This shift is caused by, among other factors, increasing complementarities between jobs and improvements in human capital that make workers more mobile between different jobs. These changes are viewed as exogenous.

Acemoglu (1998) shows that a high proportion of skilled workers encourages high-skill biased technological change. An increase in the number of skilled workers can therefore lead to an increase of the skill-premium. This can potentially explain the increase in wage inequality in the US. An alternative mechanism based on the composition of jobs is developed by Acemoglu (1996). He shows that changes in the composition of the labour force or a change in relative productivity (biased technological change) can move an economy from one type of equilibrium behaviour of firms to another. This means that, for example, a rise in the number of skilled workers can change the composition of jobs from all jobs, being identical, to some high-capital and some low-capital jobs. This leads to an increase of wages of skilled and a decrease of wages of unskilled workers despite the increase of the share of skilled workers.

This paper extends this literature. The model presented here links the effects of technological change on wages to the schooling system. It explicitly studies the incentives to develop technologies that increase demand for unskilled or skilled workers. The consequence is a precise hypothesis that allows a comparison between labour market performance of different countries: the design of an education system leads to country-specific paths of technology development and adoption, which implies country-specific labour market outcomes.[5]

2. Modelling technological change and the relative quality of education

Consider an economy with three factors of production, skilled and unskilled workers, and physical capital. Skilled workers supply human capital and earn high (per-period) labour income, unskilled workers supply labour and earn low (per-period) labour income. Technological change is modelled by considering the effects of the introduction of a modern technology in an economy where one traditional technology is under use.

The relative quality of education is captured by a skill ratio β, which represents the number of efficiency units supplied by an unskilled worker relative to the number of efficiency units of a skilled worker when both are working with the traditional technology. The skill ratio β between unskilled and skilled workers is (to a large extent) determined by the education system. One can expect that this ratio is lower, the less a country values education of those who work as unskilled workers relative to education of those that work as skilled workers. The ratio β can therefore be used to characterize cross-country differences in educational policy. We will talk about an egalitarian education system when β is higher than some threshold level τ and about an elitist education system when $\beta < \tau$. This threshold level will be defined and determined as the efficient skill ratio between skilled and unskilled workers. As observed in the introduction, the skill ratio β of unskilled (graduates from primary and secondary education) to skilled (graduates from tertiary education) is higher in Germany than in the US.

The traditional technology is given by a simple version of a CES production function, where all distribution parameters have been set to $1/3$ and the productivity parameter has been normalized to unity. The allocation of capital to the

[5] An interesting cross-country perspective is taken by Acemoglu and Pischke (1999), they view differences in changes in wage inequality as partly caused by differences in on-the-job training received by different skill groups.

traditional technology is given by K^{tr}, the number of skilled is denoted by N_H^{tr}, the number of unskilled using this technology is N_L^{tr}. The technology is

$$Y^{\mathrm{tr}} = \left(\left(K^{\mathrm{tr}} \right)^{\theta} + \left(N_H^{\mathrm{tr}} \right)^{\theta} + \left(\beta N_L^{\mathrm{tr}} \right)^{\theta} \right)^{1/\theta}, \qquad \theta < 1. \tag{1}$$

The elasticity of substitution is given by $\varepsilon = (1-\theta)^{-1}$ and the embodied abilities of unskilled β convert the number of unskilled into efficiency units of labour. Abilities of skilled workers have been normalized to unity, since focusing on relative skill differences is sufficient to capture the central aspects of embodied skills acquired during education and induced technological change.

Modern technologies can be either high-skill or low-skill. Consider first the introduction of modern high-skill technology, the type of technological change that will turn out to be more relevant from an empirical point of view. The introduction of such a technology leads to a replacement of unskilled workers in the production process by skilled workers. Before introducing high-skill technologies formally, let us consider an example of what high-skill technologies might be. Imagine a production line in the automobile industry and let it be schematically represented as in Fig. 1. The upper half (1a and 1b) shows production processes before and the lower half (2a and 2b) after high-skill-biased technological change. Assume the production of a vehicle involves, among other things, assembling the car body with the chassis. When only the traditional technology is available, this task is performed by, say, four unskilled who use a certain amount of tools or machines. Every unskilled worker does one out of these four tasks. This is process (1a). The task of skilled consists in coordinating the four tasks involved in the assembling process itself and in coordinating the assembling process with other processes (1b) as, for example, enamelling. Technological change then means that the car body is no longer put on the chassis manually piece by piece, but with the help of industry robots. Instead of four unskilled workers doing mainly manual work, one skilled worker is left, who operates the new production unit. This modern technology is represented by (2a). The technology for enamelling remains unchanged (2b).

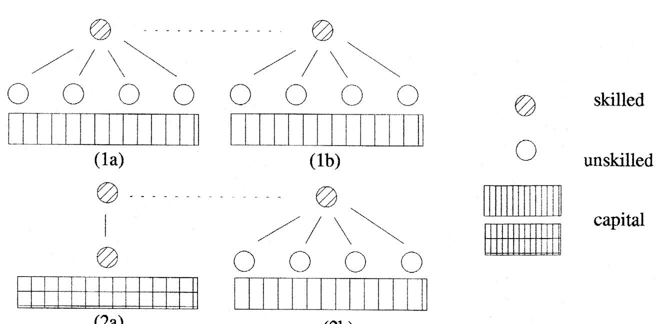

Fig. 1. Introducing high-skill technologies.

Formally, such a (modern) technology can differ from the traditional technology (1) in many respects, such as distribution parameters, the elasticity of substitution or the overall productivity level. In the present example, only differences in factor input and embodied productivity differentials of different factors of production will be considered. The high-skill technology is

$$Y^{\mathrm{m}} = \left((K^{\mathrm{m}})^{\theta} + \left(N_{H_0}^{\mathrm{m}}\right)^{\theta} + \left(N_{H_1}^{\mathrm{m}}\right)^{\theta} \right)^{1/\theta}. \tag{2}$$

Two aspects make technology (2) a different technology from technology (1). First, unskilled workers are replaced in the production process by skilled workers. Second, skilled workers keep their embodied productivity lead when performing traditionally unskilled jobs.

When modern technology is available, firms can produce a good with two technologies. When they use the traditional technology (1), unskilled jobs are performed by unskilled workers. When they use modern technology (2), unskilled jobs are performed by skilled workers. Hence, one efficiency unit supplied by skilled workers is a perfect substitute for one efficiency unit supplied by unskilled workers. On the second point, modern technology allows to make productive use of abilities of skilled workers also for performing traditionally unskilled jobs. These abilities were traditionally useful only for performing skilled jobs. If a skilled worker replaces an unskilled worker, when only the traditional technology is available, it would not be clear if the productivity of a skilled worker would be much higher than the productivity of an unskilled worker. Returning to the example above, a skilled worker is trained for coordination activities, and not for manual work in assembling pieces of a car body. Hence, his or her productivity would be more or less the same, if not less, than that of an unskilled worker. The reason for supposing that these abilities are now also useful for performing unskilled jobs stems from the underlying idea of R&D. When firms think about developing new technologies, they take the ability distribution (represented by β) in the workforce as given. There are gains to be had from a new technology, if this technology allows for profitable use of these abilities when also performing unskilled tasks. Firms will therefore tend to develop technologies that permit an expansion of the range of applicability of these abilities.

New technologies do not necessarily replace unskilled workers by skilled workers. The direction that technological change takes is endogenously determined through economic incentives. In principle, relative demand for skilled workers can rise or fall. The alternative to the modern *high*-skill technology (2) is a modern *low*-skill technology that allows replacement of skilled workers by unskilled workers. This takes the form

$$Y^{\underline{\mathrm{m}}} = \left((K^{\underline{\mathrm{m}}})^{\theta} + \left(\beta N_{L_0}{}^{\underline{\mathrm{m}}}\right)^{\theta} + \left(\beta N_{L_1}{}^{\underline{\mathrm{m}}}\right)^{\theta} \right)^{1/\theta}. \tag{3}$$

Here, as well, workers keep their productivity when moving between jobs. An unskilled worker who now performs traditionally skilled jobs keeps productivity

β. Which of these two technologies (technologies (2) or (3)) will be adopted is an endogenous decision and will be studied below.

Introducing high-skill technologies has different implications for the capital intensity per job than introducing low-skill technologies. Let 'automation' denote a process where new technologies permit production of the same amount of output with fewer workers, but with higher capital intensity. This term can then be used as a short form for 'introducing the modern high-skill technology' since, as will be seen in Section 4, the introduction of low-skill technologies does not imply that new technologies are characterized by a higher capital intensity than old technologies.

3. The framework of analysis

The effects of automation are analysed in an overlapping generations framework. Individuals live for two periods and decide the occupation they want to work in at the beginning of the first period. They can either start working immediately or obtain education for one period and then work in the second period only. Those who start working immediately are the unskilled, the others are the skilled workers. We only study two periods in this paper. The present section looks at a steady state of an economy that uses the traditional technology (1) only. This will be called the original equilibrium and will be assumed to prevail in t. Section 4 looks at period $t+1$, where the modern technology (2) is introduced. The effects of new technologies will be derived by comparing these two points in time.

3.1. The original equilibrium and school quality

The criterion for choosing between working or studying is expected lifetime income. As long as lifetime income of a skilled worker is higher than lifetime income of an unskilled worker, individuals will opt for education and become skilled. In equilibrium, lifetime income of both groups is identical and in a steady state,

$$w_L + (1+r)^{-1} w_L = (1+r)^{-1} w_H . \tag{4}$$

The sum of discounted labour earnings w_L of an unskilled equals the present value of lifetime income of a skilled worker. The latter has labour earnings w_H in the second period, with the first period spent studying. Under free mobility of capital, the interest rate r is determined in international capital markets. For simplicity, suppose education has no other than opportunity costs. Relative wage earnings are then given by

$$\frac{w_H}{w_L} = 2 + r . \tag{5}$$

Taking the production side into consideration allows us to determine the relative supply of skilled and unskilled workers. It is useful to determine relative supply of human capital and labour rather than relative supply of skilled and unskilled workers. Human capital is supplied by skilled workers and is given by

$$H = N_H . \tag{6a}$$

Labour is supplied by unskilled workers and equals the product of the number of unskilled and productivity of this group β,

$$L = \beta N_L . \tag{6b}$$

Marginal productivities of human capital and labour are given by $Y_H = (Y^{\mathrm{tr}}/H)^{1/\varepsilon}$ and $Y_L = (Y^{\mathrm{tr}}/L)^{1/\varepsilon}$. The inverse relative labour demand curve is then

$$\frac{Y_H}{Y_L} = \left(\frac{L}{H}\right)^{1/\varepsilon} \Leftrightarrow \frac{w_H}{w_L} = \beta^{-1}\left(\frac{L}{H}\right)^{1/\varepsilon},$$

where the equality of wages and value marginal products, $w_H = Y_H$ and $w_L = \beta Y_L$, is used.

Combining supply and demand gives the equilibrium ratio of labour to human capital as a function of the skill ratio β,

$$\frac{L}{H} = ((2+r)\beta)^{\varepsilon}. \tag{7}$$

Specifying how many individuals are born and die in every period would allow us to determine absolute (and not only relative) quantities. This, however, is of no importance for the results in this paper and is omitted. As can be seen from (7), a country with a more elitist education system (a lower β) has a higher human capital to labour ratio (where these quantities are measured in efficiency units) than a country with a more egalitarian system. In terms of the introductory example, the US is human capital richer than Germany.

3.2. Incentives to develop a modern technology

There are incentives to develop a modern technology, as long as the introduction of a new technology allows production at lower unit costs. The unit cost function of the traditional technology (1) is given by

$$c^{\mathrm{tr}}(r,w_H,w_L) = \left(r^{1-\varepsilon} + (w_H)^{1-\varepsilon} + (\beta^{-1}w_L)^{1-\varepsilon}\right)^{1/(1-\varepsilon)}. \tag{8}$$

For the modern high-skill technology (2), the equivalent function is

$$c^{\mathrm{m}}(r,w_H,w_H) = \left(r^{1-\varepsilon} + (w_H)^{1-\varepsilon} + (w_H)^{1-\varepsilon}\right)^{1/(1-\varepsilon)}. \tag{9}$$

Unit costs of the high-skill technology are therefore lower than unit costs of the traditional technology if

$$c^{\mathrm{m}}(r,w_H,w_H) < c^{\mathrm{tr}}(r,w_H,w_L) \Leftrightarrow w_H < \beta^{-1}w_L \Leftrightarrow (2+r)\beta < 1, \tag{10}$$

where the last step follows from inserting (5). R&D for the modern technology will therefore take place, and it will be adopted as soon as developed, if wages per efficiency unit of skilled workers, w_H, are smaller than wages per efficiency unit of unskilled workers, $\beta^{-1} w_L$. Since relative wage income is fixed by the occupational choice (5), the modern high-skill technology will be developed if the productivity advantage of skilled compared to unskilled workers is high enough, i.e., if β is sufficiently small. In other words, there are incentives to develop modern high-skill technologies only if the quality of primary and secondary education is sufficiently low or the quality of tertiary education is sufficiently high.

If the condition in (10) holds with equality, i.e., if $(2+r)\beta = 1$, there would be no incentives to develop new technologies. If the LHS of (10) is strictly greater than unity, i.e., if $(2+r)\beta > 1$, there are incentives to develop modern low-skill technologies of type (3), which allow replacement of skilled by unskilled workers.[6] Hence, technological change can take two directions: It can be either low-skill labour saving or high-skill labour saving. The direction it takes is determined by relative wages, which in turn depend on differences in embodied skills. The direction of technological change is therefore endogenously determined.

The relative quality of education has this crucial impact on the direction of technological change for two reasons. First, the productivity differential β between unskilled and skilled workers is preserved under modern technologies. Second, technologies permit replacement of factors of production. If modern technologies only allowed replacement, i.e., if productivity differences β were occupation specific and hence disembodied, adopting the modern high-skill technology would never be profitable, and there would only be incentives to develop the modern low-skill technology. When both types of worker have the same productivity β in performing unskilled jobs, a comparison of unit costs as in (10) shows that it is profitable to replace unskilled by skilled workers only if $w_H < w_L$. This never holds in the original equilibrium, given the education decision (5). As stressed above, the assumption that modern high-skill technologies allow skilled workers to preserve their productivity advantage is based on the observation that it is precisely these higher embodied abilities of skilled workers that provide the R&D incentives to develop technologies that allow replacement of unskilled by skilled workers. These abilities are required ''anyway'' for performing the skilled job, they are ''already there'', so there are gains from using these abilities more intensively, i.e., from using them also in other occupations.

If factors of production could not be substituted, introducing a new technology would not imply any change compared to the original equilibrium. There, when only the traditional technology (1) is available, skilled and unskilled workers do

[6] This can be easily seen by performing the same steps as in (10) for the modern low-skill technology.

not directly compete for jobs. Technological constraints prevent unskilled from performing jobs of skilled workers and skilled workers would not want to work as unskilled, due to lower wage income they would earn. Productivity differentials β therefore do not play a direct role. When modern technologies (2) and (3) are available, skilled and unskilled workers can be employed in both skilled and unskilled jobs. They are now perfect substitutes and the productivity differential β has a direct impact on relative demand. When β is high, unskilled workers replace skilled, when it is low, skilled workers replace unskilled.[7]

4. The impact of automation

This section studies the economy when the introduction of the modern high-skill technology comes as a surprise to economic agents, i.e., after education decisions of workers who are young in $t+1$ have been taken, and before new workers enter the labour market. As a consequence, the factor endowment of the economy does not change compared to the original equilibrium. This assumption reflects slower supply reactions than changes in technologies.[8]

4.1. Factor allocation between technologies

We will now assume that inequality (10) holds and that the new technology has been developed. In this case, firms start to replace the traditional technology by the modern one. This process increases demand for skilled workers, which raises their labour earnings. The process comes to a halt when unit costs are the same for both technologies. By (10), wages per efficiency unit are then equalized in the new equilibrium,

$$w_H(t+1) = \beta^{-1} w_L(t+1). \tag{11}$$

The effect of the new technology on relative wages can directly be seen by comparing this latter equation with relative wages in the original equilibrium (5), i.e., before the introduction of the modern technology. Firms using the modern

[7] This result is not driven by an assumption that one factor of production must completely replace another factor of production. If firms could choose the number of workers of each type for the unskilled job, i.e., if the modern high-skill technology (2) was of the form

$$Y^{\mathrm{m}} = \left((K^{\mathrm{m}})^{\theta} + \left(N_{H_0}^{\mathrm{m}}\right)^{\theta} + \left(\beta N_{L_1}^{\mathrm{m}} + N_{H_1}^{\mathrm{m}}\right)^{\theta} \right)^{1/\theta},$$

firms would find it profitable to set $N_{L_1}^{\mathrm{m}}$ to zero. This directly follows from (10).

[8] We therefore do not study a long-run steady state, but the effects of the introduction of a new technology in an economy that was in a steady state (the original equilibrium of Section 3). In a longer perspective, where the steady state with the new technology would be studied, the ratio of the number of skilled to unskilled changes after the introduction of a new technology. When the modern high-skill technology is introduced, this ratio rises (Wälde, 1997).

technology (2) will be called modern firms. Some firms will continue to produce with the traditional technology (1), as labour can work in traditional firms only and full employment prevails given wage flexibility.

To simplify notation, factor inputs will be measured in efficiency units, following (6a) and (6b). Production functions are then

$$Y^{\mathrm{tr}} = \left((K^{\mathrm{tr}})^{\theta} + (H^{\mathrm{tr}})^{\theta} + (L^{\mathrm{tr}})^{\theta} \right)^{1/\theta}, \tag{12}$$

$$Y^{\mathrm{m}} = \left((K^{\mathrm{m}})^{\theta} + (H_0^{\mathrm{m}})^{\theta} + (H_1^{\mathrm{m}})^{\theta} \right)^{1/\theta}. \tag{13}$$

Computing the allocation of human capital between firms gives (cf. Appendix)

$$H^{\mathrm{tr}} = L, \tag{14a}$$

$$H_0^{\mathrm{m}} = H_1^{\mathrm{m}} = \frac{1}{2}(H - L). \tag{14b}$$

This shows that the amount of human capital allocated to modern firms is independent of the stock of capital in the economy as a whole. It does, however, depend on the type of capital, since only the modern technology allows replacement of unskilled by skilled workers. The allocation of physical capital to modern and traditional firms directly follows from the allocation of human capital and labour. We have

$$K^{\mathrm{tr}} = 2L\frac{K}{H+L}, \tag{15a}$$

$$K^{\mathrm{m}} = (H - L)\frac{K}{H+L}. \tag{15b}$$

The expression $K/(H+L)$ is the ratio of the economy's capital stock to the sum of the economy's endowment with human capital and labour. Call this expression the capital richness of the economy. This expression is multiplied by the allocation of labour and human capital to both technologies. The allocation of human capital and labour to the traditional technology is, by (14a), $H^{\mathrm{tr}} + L = 2L$. The allocation of human capital to the modern technology is $H_1^{\mathrm{m}} + H_2^{\mathrm{m}} = H - L$. The capital stock per technology is therefore proportional to the sum of the allocation of human capital and labour to this technology. In other words: the capital richness per technology is identical to the capital richness of the economy.

The new aggregate technology is simply $Y^{\mathrm{agg}} = Y^{\mathrm{tr}} + Y^{\mathrm{m}}$. Inserting equilibrium factor allocations into (12) and (13) gives (cf. Appendix)

$$Y^{\mathrm{agg}} = \left(K^{\theta} + 2^{1-\theta}(H + L)^{\theta} \right)^{1/\theta}. \tag{16}$$

The major change in the aggregate technology from the original equilibrium, where only the traditional technology (1) was available, is that human capital and labour are now perfect substitutes. This, of course, is the consequence of the technology used by modern firms, where human capital can perform the same tasks as labour does in traditional firms. The immediate consequence is clear: Wages of unskilled workers were an increasing function of productivity of their skilled colleagues in the original equilibrium. Wages of unskilled fall in the new equilibrium, the higher the stock of human capital, i.e., the more skilled individuals there are or the higher their productivity.

4.2. Efficiency, capital intensity and wages

Technological change increases efficiency. Both the introduction of the modern high-skill and the introduction of the modern low-skill technology, whichever is profitable, lead to an increase in output per capita. This finding is proven for automation.

Proposition 1. (*Automation and efficiency*) *Automation increases output per capita,* $Y^{agg}/(N_H + N_L) > Y^{tr}/(N_H + N_L)$.

Proof. In order to show that automation incre ases output per capita, it is sufficient to show that automation increases output since the population size is constant. Given technologies of the type $Y = (K^\theta + H^\theta + L^\theta)^{1/\theta}$ as used here, output is maximized, holding capital K constant, when the stock of human capital equals the stock of labour, $H = L$. This equality, however, does not generally hold, as the equilibrium ratio of labour to human capital (7) shows. The modern high-skill technology ''removes the border between jobs'' and allows human capital to flow into unskilled jobs. This leads to an equalization of the amounts of factors of production in efficiency units in both occupations, and in both technologies as shown by (14a)with (14b). Since this is the output maximizing factor allocation, automation results in increases in output if, under the traditional technology, the stock of human capital is higher than the stock of labour. □

Corollary. (*Efficiency in education and new technologies*) *Efficient education systems provide zero incentives to substitute between factors of production.*

Proof. An education system is defined to be efficient when the skill ratio of graduates β is such that output per capita is maximized. Output per capita in the original equilibrium (i.e., where only the traditional technology (1) is available) is maximized when $H = L$. By the equilibrium ratio of labour to human capital (7), the efficient skill ratio τ is then given by $(2 + r)\tau = 1$. When the skill ratio is efficient, $\beta = \tau$, no incentives exist to develop new technologies, since unit cost of modern and traditional technologies are the same, as can be seen from (10). □

The equality determining the efficient skill ratio τ, $(2 + r)\tau = 1$, can be understood when comparing private incentives to study with social gains. An individual will study as long as $w_H > (2+r)w_L$, which follows from (4). Society wants an individual to study as long as (under the traditional technology) the marginal productivity of a skilled worker exceeds the marginal productivity of an unskilled worker, $Y_H > Y_L$. When value marginal products equal wages, this latter inequality is equivalent to $w_H > \beta^{-1} w_L$. Comparing private incentives with social optimality, the efficient number of skilled will result if $2 + r = \beta^{-1}$, which is the equation defining the efficient skill ratio τ.

When β differs from τ, private incentives to study remain unchanged but social gains from an additional unit of human capital change. Marginal productivities of human capital and labour will therefore differ in equilibrium and an incentive to replace factors of production exists. In an elitist education system where $\beta < \tau$, abilities of skilled workers are too high relative to abilities of unskilled workers (or, equivalently, education of unskilled workers is of relatively too bad quality), there is too much human capital in the economy, human capital is therefore cheap and will be used to replace labour. Similarly, when the education system is egalitarian, $\beta > \tau$, there is too much labour and human capital tends to be replaced by labour. Since under an efficient education system value marginal products are the same for human capital and labour, no incentives to substitute between factors of production exist.

Proposition 2. (*Introducing the modern high-skill technology and capital intensity per job*) *The capital intensity in modern firms is higher than the capital intensity in traditional firms, that is*

$$K^{\mathrm{m}} / \left(N_{H_0}^{\mathrm{m}} + N_{H_1}^{\mathrm{m}} \right) > K^{\mathrm{tr}} / \left(N_H^{\mathrm{tr}} + N_L^{\mathrm{tr}} \right).$$

Capital intensity is measured by the ratio of capital to number of workers (which is the easier to observe ratio compared to the capital to human capital ratio).

Proof. By (15a) with (15b), the capital stock per efficiency unit of human capital and labour are equalized across technologies, $K^{\mathrm{m}}/(H_0^{\mathrm{m}} + H_1^{\mathrm{m}}) = K^{\mathrm{tr}}/(H^{\mathrm{tr}} + L^{\mathrm{tr}})$. By (6b), this is equivalent to $K^{\mathrm{m}}/(N_{H0}^{\mathrm{m}} + N_{H1}^{\mathrm{m}}) = K^{\mathrm{tr}}/(N_H^{\mathrm{tr}} + \beta N_L^{\mathrm{tr}})$. Since $\beta < 1$ (otherwise, (10) would not hold and automation would not take place), the RHS of this equality exceeds $K^{\mathrm{tr}}/(N_H^{\mathrm{tr}} + N_L^{\mathrm{tr}})$. □

Proposition 3. (*Increasing capital intensity*) *The introduction of the modern high-skill technology increases the capital intensity in traditional firms.*

Proof. From the first order condition for capital input in traditional firms $Y_{K^{\mathrm{tr}}}^{\mathrm{tr}} = r$, the equilibrium capital stock in traditional firms is given by $K^{\theta} = \rho(H^{\theta} + L^{\theta})$, where ρ is a constant depending on the interest rate r. Changes in the capital intensity between period t and period $t+1$ in a traditional firm are then given by $\frac{\mathrm{d}}{\mathrm{d}\,N_H} K/N_H^{\mathrm{tr}} + N_L$, where $K^{\theta} = \rho({N_H^{\mathrm{tr}}}^{\theta} + N_L^{\theta})$ solved for K has to be inserted. This derivative is positive, as long as $L/H > \beta^{1/(1-\theta)}$. By the equilibrium condition (7), this is always the case. □

The effects of modern high-skill technologies on capital intensity can be understood as follows. Since the capital endowment per job is higher in modern firms than in traditional firms and the capital intensity in traditional firms rises, the capital intensity after automation is higher in both types of firms than before automation. The important aspect of this finding is the difference from increasing capital intensity due to capital accumulation. In standard growth models, technological change allows for capital deepening that takes place uniformly across all firms or workers. Here, technological change leads to a division of firms into capital-rich firms and capital-poor firms.

When comparing output between a modern and a traditional firm, a given level of output can be produced with fewer workers when the modern technology is used, simply because the average worker in a modern firm is more productive than the average worker in a traditional firm. This captures the idea that ‘‘a task that required many unskilled some years ago can now be done by one skilled as long as he or she has the right equipment’’, i.e., the modern high-skill technology.[9]

Introducing the modern high-skill technology has been called automation, which distinguishes this form of technological change from the introduction of low-skill technologies. The motivation for this name results from

Proposition 4. (*Introducing the modern low-skill technology and capital intensity per job*) *When the modern low-skill technology is introduced, the capital intensity of modern firms is lower than the capital intensity of traditional firms,* $K^{\mathrm{m}}/(N_{L0}^{\mathrm{m}} + N_{L1}^{\mathrm{m}}) < K^{\mathrm{tr}}/(N_H^{\mathrm{tr}} + N_L^{\mathrm{tr}})$.

Proof. An introduction of the modern low-skill technology leads to equalization of the capital stock per efficiency unit of human capital and labour as was the case when automation takes place (cf. Proposition 2). This expression now reads $K^{\mathrm{m}}/(L_0^{\mathrm{m}} + L_1^{\mathrm{m}}) = K^{\mathrm{tr}}/(H^{\mathrm{tr}} + L^{\mathrm{tr}})$, where the labour stock in modern firms has replaced the human capital stock in the denominator of the expression of Proposition 2. By (6b), this is equivalent to

$$K^{\mathrm{m}}/\left(\beta N_{L_0}^{\mathrm{m}} + \beta N_{L_1}^{\mathrm{m}}\right) = K^{\mathrm{tr}}/\left(N_H^{\mathrm{tr}} + \beta N_L^{\mathrm{tr}}\right) \Leftrightarrow K^{\mathrm{m}}/\left(N_{L_0}^{\mathrm{m}} + N_{L_1}^{\mathrm{m}}\right) = K^{\mathrm{tr}}/\left(\beta^{-1} N_H^{\mathrm{tr}} + N_L^{\mathrm{tr}}\right).$$

Since $\beta < 1$, the RHS of this equality is smaller than $K^{\mathrm{tr}}/(N_H^{\mathrm{tr}} + N_L^{\mathrm{tr}})$. □

[9] Note that differences in capital endowment per job and output per worker are not causal to rising wage differentials, but result from embodied productivity differentials between these groups and the availability of the modern technology.

The expression automation is often associated with a process where a new generation of firms is more capital intensive and has higher output per worker than traditional firms, which are partly replaced. Proposition 2 has shown that introducing modern high-skill technologies leads to a division of firms into more and less capital intensive firms and implies that the capital intensity of modern firms is higher than capital intensity of traditional firms. This proposition shows that the introduction of the modern low-skill technology would not imply that modern firms are more capital intensive than traditional firms. Hence, the term automation is appropriate for the process where modern high-skill technologies become available. The fact that only automation leads to modern firms that are more capital intensive than traditional firms can be regarded as further support for the view that automation, in addition to the fact that it predicts observed changes in relative wages, is empirically more relevant than introduction of modern low-skill technologies.

Proposition 5. (*Winners from automation*) *The labour group operating the new production units (skilled workers in this example) gain from automation,* $w_H(t+1) > w_H(t)$.

Proposition 6. (*Losers from automation*) *Factors of production that are replaced by the modern technology lose through automation,* $w_L(t+1) < w_L(t)$.

Proof. When an economy is human capital rich, i.e., when (10) holds, firms will employ human capital for unskilled jobs as soon as the modern high-skill technology is available. The stock of human capital working in traditional firms therefore shrinks. This reduces productivity of labour and physical capital. As a consequence, physical capital leaves traditional firms as well. This again reduces productivity of labour. Since labour cannot move to other firms, labour rewards fall.
Automation takes place when there is too much human capital, i.e., when wages per efficiency unit of skilled workers are lower than wages per efficiency unit of unskilled workers as in (10). The process of factor flows to modern firms comes to an end, when wages per efficiency units are equalized as in (11). This equalization implies an increase in wages per efficiency unit of skilled workers. Since wage income of a skilled worker is proportional to the wage per efficiency unit of a skilled worker, wage income of skilled workers rises. □

Summarizing, the effect of the relative quality of schooling on induced technological change and wages is as follows. The relative quality of schooling is given by β. Assume it lies below the efficient level, i.e., $\beta < \tau$. Individuals base their education decision on private incentives, which differ from social returns as long as β differs from τ. When β is too low, i.e., when the productivity of graduates from primary and secondary education is low relative to productivity of graduates from tertiary education, too many individuals decide to work as skilled and the stock of human capital is socially too large. The marginal product of human capital is therefore lower than the marginal product of labour and there are social gains from using human capital in jobs usually performed by labour. Some firms will perceive these potential gains, will undertake R&D and develop technologies that allow the replacement of labour by human capital.

Once these modern high-skill technologies are available, producers, when considering employment for unskilled jobs, compare factor rewards per efficiency unit to be paid to a skilled worker under the modern technology with factor rewards per efficiency unit to be paid to an unskilled under the traditional technology. Since modern technologies allow skilled workers to preserve their productivity lead, factor rewards per efficiency unit of skilled worker under the modern technology equal the marginal productivity of human capital. Wages per efficiency unit of unskilled workers equal the marginal productivity of labour. Since marginal productivity of human capital is lower than marginal productivity of labour, firms will adopt the modern technology and replace unskilled workers by skilled workers. In order to attract skilled workers, modern firms have to offer wages that lie above wages paid in traditional firms. This raises wages of skilled workers. Unskilled workers in traditional firms end up working with fewer skilled workers, which reduces their productivity and their wages. New technologies therefore lead to changes in the values of skills.

5. Induced technological change and cross-country results

5.1. Induced technological change and rising wage inequality

Studies of the evolution of the wage distribution in the US (e.g., Bound and Johnson, 1992; Katz and Murphy, 1992; Juhn et al., 1993) generally[10] conclude that technological change during the 1980s has reduced demand for unskilled workers and thereby real labour income of these groups, which has led to an increase of wage inequality. This conclusion is not easily reconciled with views of the direction of technological change. Technological change is generally considered, at least since Hicks (1932), as an endogenously determined, ''induced'' process. Inventions have a tendency to replace a relatively expensive factor of production by a less expensive one, which could suggest that technological change

[10] Leamer (1994) finds that technological change favours production workers (as opposed to non-production workers). But he himself is sceptical about linking this finding to changes in income inequality, since there is only a weak link from skilled vs. unskilled to non-production vs. production workers.

could not be a reason of wage inequality at all. Since induced technological change leads to an increase of demand for relatively cheap factors of production, the introduction of new technologies should tend to reduce wage inequality. Labour groups with low earnings, which are relatively cheap compared to other labour groups, should gain from technological change.

The above analysis has shown that the relevant measure for scarcity of a factor is the wage rate per efficiency unit and not observed labour earnings. If efficiency differences between labour groups are high enough, low labour earnings of a certain group of labour do not imply incentives to increase demand for this group through new technologies. On the contrary, technological change would reduce demand for their services and increase wage inequality. A distinction therefore has to be drawn between cheap in terms of wage levels per efficiency unit, which determine the direction of technological change, and cheap in terms of observed wage earnings.

5.2. Cross-country differences in wage inequality

The main difference in the labour market history of the 1970s and 1980s between the US and Germany is the fairly stable wage structure in Germany and the rising wage inequality in the US in conjunction with the rising unemployment rate in Germany and the roughly trendless unemployment rate in the US.

The differences in changing wage structures can now be given the following interpretation. The schooling system in the US is more elitist than the education system in Germany. These differences translate into differences in factor endowment of the economies (7) and differences in incentives to develop new technologies. Observing only relative wages as given by (5), the US and Germany cannot be distinguished in the original equilibrium. The US skill differentials, however, induced the development of a technology of production that permitted replacement of unskilled workers, who were relatively more expensive in efficiency units, by skilled workers. This led to the increase in wage inequality in the US, to (11). The less elitist education system in Germany led to a factor endowment that did not necessitate the development of technologies that replace unskilled by skilled workers. Relative wages in Germany therefore remained unchanged at (5). Technological change was skill-biased in the US but not skill-biased in Germany.

Given this interpretation, some qualifications are required with respect to the development of new technologies. A literal interpretation of the above model would mean that new technologies were adopted only in the US but not in Germany. This is certainly not true, neither would one expect this. Incentives to develop new technologies do not only result from gains from replacing factors of production, but also from increasing total factor productivity as stressed in recent models of growth (Romer, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1992; cf. also Wälde, 1999). It is well known that labour productivity in the US is higher than in other G7 countries but that labour productivity of these countries converges. One should therefore expect that new technologies are introduced in the US earlier than elsewhere but that, basically, technologies are the same. That is, computers are used in Germany as well. This is what was found by DiNardo and Pischke (1997, Table I). The percentage of workers using a computer was 37.4 in the US in 1989 and 35.3 in Germany in 1991–1992. Comparing France (a country with an equally stable wage distribution as Germany and with an education system that is closer to the German system than to the US system) and the US, Card et al. (1996, Table 1) also find close similarities in overall usage rates (34.0% for France in 1991). The main difference in induced technology change between the US and Germany does therefore not lie in the use of new technologies but in how these technologies are used. Proposition 2 provides a precise prediction how this difference can be detected. In the US, one should find a segregation of the economy into unskilled firms with a low capital per worker ratio and skilled firms with a high capital per worker ratio (''McDonald's vs. Microsoft'') whereas in Germany, this distinction should be less pronounced.

Some first evidence that supports this view also comes from DiNardo and Pischke (1997, Table 1) and Card et al. (1996, Table 1): computers per unskilled worker (the percentage of unskilled workers that use a computer) relative to computers per skilled workers is higher in Germany and in France than in the US. The computer usage ratio of high school to college graduates was 0.48 in the US in 1989 (computed from DiNardo and Pischke, 1997, Table 1), 0.53 in Germany[11] (in 1991–1992) and 0.73 in France.[12]

6. Conclusion

This paper has shown that countries that differ in their education systems differ in the direction of technological change. In a country where the skill ratio of graduates from tertiary education to graduates from secondary education is large, there are incentives to develop and adopt technologies that allow replacement of unskilled (graduates from secondary education) by skilled workers (graduates from tertiary education). These incentives do not exist in countries with a more equal

[11] This ratio would even be higher for Germany relative to the US if workers with an education level 'less than high school' and 'some college' were added to the group of high school graduates. A note of care is in order, however, since education levels are not directly comparable across countries. We therefore consider this to be only first supportive evidence and more evidence is needed on this point. I am grateful to Steve Pischke for discussions related to these aspects.

[12] It is sometimes argued that the increase in wage inequality in the US corresponds to the increase in unemployment in Germany. Apart from empirical evidence against this view (Nickell and Bell, 1996; Card et al., 1996), the present paper predicts that even if wages were downward rigid in Germany (assume wL in the model cannot fall) there would not have been an increase in unemployment due to biased technological change as there was no biased technological change in Germany and therefore no downward pressure on wages.

skill ratio between skilled and unskilled workers. The skill bias in technological change is therefore predicted to crucially depend on the education system. In the US, new technologies have led to replacement of unskilled by skilled workers, which caused an increase in wage inequality. In Germany, new technologies were adopted by all skill groups, and therefore did not change the wage structure. The rising unemployment rates in Germany therefore require an explanation other than skill-biased technological change.

From a theoretical point of view, the paper introduces a novel form of technological change. The introduction of a modern high-skill technology is assumed to allow replacement of unskilled workers by skilled workers without a loss in productivity of skilled workers. Skilled workers perform the same tasks as unskilled workers but — due to the new technology — can use their skills acquired during education to perform these tasks more quickly. The analogy is the introduction of a modern low-skill technology that allows replacement of skilled workers by unskilled workers where the productivity differential also prevails. The productivity differential between labour groups is a central determinant of relative wages per efficiency unit. Since wages per efficiency unit are the measure that determines which factor of production will be replaced, the direction of technological change and implied changes in relative wages depend on relative productivities and — since relative productivities are assumed to depend on the education system — on the relative quality of education.

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Appendix

A.1. Deriving equilibrium properties (14a)–(15b)

In equilibrium, capital must pay equal returns in both technologies (which, given arbitrage possibilities, equals an internationally given interest rate r).

Human capital earns same income whether employed for managerial purposes in a traditional or in a modern firm or whether working in the production process,

$$Y_{K^{\mathrm{m}}}^{\mathrm{m}} = Y_{K^{\mathrm{tr}}}^{\mathrm{tr}}, \quad Y_{H_i^{\mathrm{m}}}^{\mathrm{m}} = Y_{H^{\mathrm{tr}}}^{\mathrm{tr}}, \qquad i = 0,1. \tag{17}$$

Factor markets clear so that

$$K^{\mathrm{tr}} + K^{\mathrm{m}} = K, \quad H^{\mathrm{tr}} + H_0^{\mathrm{m}} + H_1^{\mathrm{m}} = H, \tag{18}$$

where K is the capital stock in the economy under free international capital mobility. Conditions (17) can be written as

$$\frac{K^{\mathrm{m}\theta} + H_1^{\mathrm{m}\theta} + H_2^{\mathrm{m}\theta}}{K^{\mathrm{m}\theta}} = \frac{K^{\mathrm{tr}\theta} + H^{\mathrm{tr}\theta} + L^{\theta}}{K^{\mathrm{tr}\theta}}, \tag{19}$$

$$\frac{K^{\mathrm{m}\theta} + H_1^{\mathrm{m}\theta} + H_2^{\mathrm{m}\theta}}{H_1^{\mathrm{m}\theta}} = \frac{K^{\mathrm{tr}\theta} + H^{\mathrm{tr}\theta} + L^{\theta}}{H^{\mathrm{tr}\theta}}, \tag{20}$$

By dividing these equations, it follows immediately

$$\frac{H_1^{\mathrm{m}}}{K^{\mathrm{m}}} = \frac{H^{\mathrm{tr}}}{K^{\mathrm{tr}}}. \tag{21}$$

Substituting into (19) shows

$$\frac{H_2^{\mathrm{m}}}{K^{\mathrm{m}}} = \frac{L}{K^{\mathrm{tr}}}. \tag{22}$$

By deriving an analogous equation to (20) for H_2^{m}, and dividing it by (20) gives

$$H_1^{\mathrm{m}} = H_2^{\mathrm{m}}, \tag{23}$$

which is clear from looking at the symmetry property of the automation technology (5). Dividing (21) by (22) using (23) gives $H^{\mathrm{tr}} = L$. Since the number of skilled workers is the same in both production activities in the modern technology (23) and because of the factor market clearing condition for human capital (18), the number of skilled workers using the modern technology is simply

$$H^{\mathrm{m}} = H - L. \tag{24}$$

We now compute the allocation of capital K. Solving (22) for K^{m}, by employing the capital market clearing condition (18) gives $H_2^{\mathrm{m}}/K^{\mathrm{m}} = L/(K - K^{\mathrm{m}}) \Leftrightarrow H_2^{\mathrm{m}}(K - K^{\mathrm{m}}) = H_2^{\mathrm{m}}K - H_2^{\mathrm{m}}K^{\mathrm{m}} = K^{\mathrm{m}}L \Leftrightarrow H_2^{\mathrm{m}}K = K^{\mathrm{m}}(L + H_2^{\mathrm{m}})$. Since by (23) and (24) $H_2^{\mathrm{m}} = \frac{1}{2}(H - L)$, we find $K^{\mathrm{m}} = \dfrac{\frac{1}{2}(H-L)}{\left(L + \frac{1}{2}(H-L)\right)}K = \dfrac{H-L}{H+L}K$. Consequently, $K^{\mathrm{tr}} = (2L/(H+L))K$.

A.2. Deriving the aggregate technology (16)

$$Y^{\mathrm{tr}}\left(\left(\frac{2L}{H+L}K\right)^{\theta}+L^{\theta}+L^{\theta}\right)^{1/\theta}=\left(\left(\frac{2K}{H+L}\right)^{\theta}+2\right)^{1/\theta}L,$$

$$Y^{\mathrm{m}}=\left(\left(\frac{K}{H+L}\right)^{\theta}+2^{1-\theta}\right)^{1/\theta}(H-L)$$

$$=\left(\left(\frac{1}{2}\right)^{\theta}\left(\frac{2K}{H+L}\right)^{\theta}+2^{1-\theta}\right)^{1/\theta}(H-L)$$

$$=\left(2^{\theta}\left(\frac{1}{2}\right)^{\theta}\left(\frac{2K}{H+L}\right)^{\theta}+2^{\theta}\cdot 2^{1-\theta}\right)^{1/\theta}\left(\frac{1}{2^{\theta}}\right)^{1/\theta}(H-L)$$

$$=\left(\left(\frac{2K}{H+L}\right)^{\theta}+2\right)^{1/\theta}\frac{H-L}{2}.$$

Therefore,

$$Y=\left(\left(\frac{2K}{H+L}\right)^{\theta}+2\right)^{1/\theta}\frac{H+L}{2}=\left(K^{\theta}+2^{1-\theta}(H+L)^{\theta}\right)^{1/\theta}.$$

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