Can endogenous technology choices explain wage inequality dynamics? Empirical and Theoretical Evidence

Jan Witajewski-Baltvilks

11 February 2013

Please check for the updates of the paper on my website

Abstract

There is a wide agreement among researchers that increase in wage inequality across the OECD countries was caused by introduction of skill-biased production methods, which generated higher demand for skilled than for unskilled workers. However, does a skill-bias of production method originate from the skill-biased nature of new global technological paradigm (i.e. Information Technology) or from the fact that following the increase in a number of college graduates firms have chosen to exploit the new technological paradigm in a way that favoured skilled workers? To study this question, I first observe that while the source of the latter cause is global, the source of the former rests in labour market at the country-level. Therefore to calibrate the model I isolate global from local sources of college wage premium increase using both cross-section and cross-time dimension of the data. The exercise implies that endogenous technology choice at the local level can explain 30% of the increase of college premium in the OECD countries. In econometric analysis I find that countries which experienced higher growth in a number of college graduates than other countries witnessed also higher growth of college wage premium a decade later. A number of arguments (and a setup of the regression) suggests that endogenous technology choice at country level is the most plausible explanation for this finding. One implication is that any policy that affects supply of skilled workforce will have an impact on skill-bias of equilibrium technology and wage inequality dynamics. At theoretical level, I set a microfoundation for the model by showing how research in the R&D sector might generate a tradeoff between skill- and unskill-biased technologies.

1 Introduction

The second half of the 20th century has brought a notable increase in skill premium - i.e. the relative pay of well educated to low-educated workers - in almost all developed countries. The change has attracted a wide interest among researchers and motivated number of studies that aimed to explore its roots. The explanation that won a growing popularity among researchers was a skill-biased nature of the new Information and Communication Technology[1]. In the argument production methods are to the large extend shaped by the technology platform (I will also call it later in the text a General Purpose Technology, a GPT). Technology platform is a technological paradigm, a basis for further secondary innovations and invention of production methods. The example of the technological platforms that we have witnessed since the outbreak of the industrial revolution are steam engine, electric dynamo and now the new ICT technology. A technological platform is also characterized by its world-wide presence (at least in the developed world). The belief is that the new ICT technology platform is by nature ideally matched with high-skilled workers, thus has dramatically increased their productivity (relative to the low-skilled workers) and hence lead to higher relative wages.

However the global change in the nature of technology platfrom - that is to the large extend unpredictable and uncontrolable factor - might be not the only reason for skill premium increase. The alternative (though potentially complimentary) explanation might be the argument that we can label the *endogenous technology choice hypothesis*. For the sake of argument suppose that the new technology platform is actually skill-neutral, yet in some countries a substan-

[1]The other prominent explanations were the institutional changes (weakening of trade unions - e.g. DiNardo, Fortin and Lemieux (1995)), globalization (shifting of low-skill-intensive production to less developed countries - e.g. Wood (1995) and Leamer (1995)). The first of this explanation is unlikely because skill-premium in US started to increase before deunionization (Acemoglu (2000)), the second explanation, although seems to play important role in the raise (Van Reenen (2011)) it cannot fully explain its pattern (Acemoglu (2000)).

tial increase in number of educated workers has motivated firms to exploit the technology platform in the way that favours better educated employees. In particular if the skill-neutral technology platform offers a variety of possibilities for production process - some production methods that are better suited to skilled workers (thus making unskilled workers relatively unproductive) and other that are better suited to unskilled workers - after rapid increase in skilled labour supply we should see firms starting to choose those methods that favour skilled workers.

To illustrate the difference between technological change and endogenous technology choice we can consider the following example: Suppose that both pre-ICT and ICT technological platforms offer two ways to produce output: one is a production in a fully automatized factory where most of the tasks are performed by skilled labour (e.g. programming robots) while unskilled workers perform less important tasks (such as cleaning, guarding etc.). The other way is the production side on which unskilled workers perform the key production tasks while technology and skilled labour assist them by analyzing mistakes, supervising, organizing logistics and training to ensure high performance of unskilled workers. Comparing to the robotized production method the latter production process generates higher demand for unskilled workers and therefore its adoption leads to lower skill wage premium. Consider also two countries: country A has experienced a rapid increase in the supply of skilled workers, country B has not. At the beginning firms in both countries operated under the *logistics and supervision* production method (noone used robotized production line)

How could we portray global skill-biased technological change in this setup? ICT could have lead to improvement in both, *the robotics* production method and *the logistics and supervision* production method. However if the improvement in the robotics was more substantial firms in both countries are likely to switch to robotized production line and skill premium is likely to increase in both countries. In this sense global technological change will have a global effect.

How can we spot the endogenous technology choices then? Suppose ICT was not skill-biased (it improved *robotics* and *logistics and supervision* equally), thus in either country ICT was not a motivation for firms to choose robots. However in country A the sharp increase in supply of skilled workers lead to drop of wages of skilled workers (relative to unskilled) what incentivized firms in country A to hire higher number of such workers and to switch to the robotized product line which makes much better use of skilled workers. In a few years (after robots are installed) the switch of production methods leads to increase in college wage premium. Since country B did not experience increase in skill labour supply there was no technology switch and no skill premium change there. The endogenous technology choice is therefore driven by local changes and has only local consequences.

What would happen if skilled labour supply increased not only in country A but also in country B? We would expect the technology switch and reported growth in skill premium (after initial fall) in both countries. Now suppose that in addition to increase in supply of skilled labour we know that ICT was in fact skill-biased so it did motivate firms to switch to robots. How can we decompose the two effects? How much of the increase in skill premium was driven by new technology choices at the local level, how much by the global skill-biased technological change? An answer to this question is one of the main purposes of this paper.

This paper has three contributions. First, it presents a dynamic model that captures how endogenous technology choices and global technological change shape wage inequality dynamics. Second, it offers empirical identification strategy to calibrate the theoretical model. The calibration exercise shows that endogenous technology choices can explain 30% of growth in college wage premium across OECD countries between 1980 and 2005. Finally, the paper presents a new piece of evidence on wage inequality dynamics: I find that countries that experienced higher growth in number of college graduates than other countries experienced also higher growth of college wage premium a decade later. A number of arguments (and setup of the regression) suggests that endogenous technology choice at country level is the most plausible explanation for this finding.

The hypothesis of endogenous technology choice is not new in the literature. The idea that there might be a tradeoff between developing a technology that is augmenting one factor of production and developing technology that is augmenting other factor dates back to Samuelson (1965). Peri (2009) use the hypothesis to explain why immigration has a negative impact on skill-bias of technology and subsequently very modest effect on low-skilled labour wages in the United States. Caselli and Coleman (2006) who found a positive correlation between level of country GDP and skill bias of technology argue that it can be driven by the fact that less developed countries has a higher share of low-skilled labour and thus firms in these countries choose the unskill-biased technologies (they propose a formal model to describe this argument - the model is used as a basis for the dynamic model presented in section 2). The hypothesis appears also in the theoretical analysis in Acemoglu (2007) which uncovers what are the conditions for inducing a skill-biased technology. However, to the knowledge of the author, no study has used the hypothesis to explain increase in college wage premium across the OECD countries.

It is important to distinguish between endogenous technology choice hypothesis and the hypothesis put forward in Acemoglu (1998, 2000, 2002), often called the directed technology change hypothesis. The latter assumes there is only one global technology (a single production method) which is developed in a profit maximizing, world scale R&D firm and whose skill bias may be influenced by the relative number of skilled and unskilled workers. Instead the former assumes that, if there is a world-scale R&D centre it develops a technology platform that is only a basis for development of a range of production methods - some more, some less skill-biased. Which production methods are chosen depends at the end on individual final-good producers. As a result while directed technological change predicts that supply of skills affects technology at the global level, the endogenous technology choice predicts that skill-bias of the production methods at any country depends on the choices of firms that are influenced by the local (country-level) skills supply.

Is the distinction between changing changing nature of the technology platform and shift of technology choices important? In fact the two concepts are very closely related - both imply the change in the production methods. Yet the differences might turn out to be crucial. Firstly, the shift in technology choices does not have to happen during a major technological change. Thus in future we might observe rapidly changing skill-premium structure even if we will not observe any change in General Purpose Technology. Secondly, and probably more importantly the technology choices of firms appear to be much more predictable and influenced by the policy then the changes in the nature of General Purpose Technology. The direction of GPT is highly random, depending more on the wild nature of discoveries rather than any government policies. In turn, the technology choice hypothesis gives much more room for policy intervention: for instance policy improving early age education or system of subsidies for firms employing unskilled workers might incentivise firms to pay more attention to production methods that favours this kind of workers. Finally, even if we assume that the direction of GPT nature change might be as easily controlled as technology choices, the control of GPT direction would need to involve coordinated world-scale actions. Instead the technology choices of firms depend on the local labour market conditions. This has two implications: the first is that each government might have a tool to govern technology choices and further, wage inequality independently of the other governments. The second implication is that the model that incorporates endogenous technology choice argument might predict a variety of wage inequality dynamics across countries.

Obviously the technology choice hypothesis does not imply that the new ICT technology was skill-neutral - indeed the technology choice and the global technological change hypothesis can be complimentary. In the version of the model that I present in the theoretical part the effects of technological change and the effect of technology choice simply add up together. There is a number of arguments that indeed the nature of ICT is skill-biased (for instance cross-industry studies that shows that industries with greater use of computers has witnessed a larger increase in use of nonproduction workers - e.g. Berman, E., J. Bound and Z. Griliches (1994)). There is little doubt that changing nature of technology platform does influence skill premium - the question is to what extent. And whether part of the skill premium dynamics can be explained with endogenous technology choice.

Until now the key argument in favour of skill-biased technological change effect was the timing: the ICT revolution in US started shortly before the observed increase in skill premium. However around this time we have also witnessed an acceleration in the skilled labour supply. The acceleration might, in line with the technology choice hypothesis, create an incentive for firms to shift towards production methods that favoured skilled workers thus explaining increase in skill premium. In theory this causality might have worked independently of the

ICT revolution. How can we determine whether the increase in skill premium was driven by new technology choices or technological change?

The idea that might help us to separate out the pure effect of technology choice is to use the presumption that the change of nature of technology platform must have a global consequences (at least if we focus on developed countries). In turn the technology choice hypothesis involves changes in skill premium as a response to changes in the conditions of local labour market (i.e. the local relative skilled labour supply). As a result the technology choice hypothesis predicts increase in skill wage premium above the average international increase in countries that have also experienced an increase in skilled labour supply above the average increase. I devise an empirical model that exploits the cross-section and time-series variation in the data to calibrate the model. The results implies that approximately one third of the skill premium increase across OECD countries can be explained with the endogenous technology choice hypothesis while the remaining two thirds - by the skill-biased change in the nature of GPT.

The calibration exercise is a possibility result. In the second part of section 3 I proceede with a more rigorous econometric analysis. The econometric model finds out that countries that did experience higher increase in skilled-labour supply (relative to unskilled labour) have also witnessed larger increase in skill premium. The coefficient is statistically significant and predicts 0.22% increase in skill premium after 1% increase in relative skill supply. In the empirical section I show that the result is not driven by reverse causality, trends in globalization, fall of trade unions or institutional differences between countries. Therefore endogenous technology choice at country level appears to be the most plausible explanation for the results.

There might be other mechanisms that offer similar predictions though. I present and formally describe two of such mechanisms: the spillover effect (higher density of skilled labour helps each skilled worker to utilize the technology and thus increase the productivity) and the incentive for adoption of ICT effect (more skilled workers implies firms has higher incentive to adopt ICT technology, skill biased by nature). I argue that each of this hypothesis is not plausible separately however they might compliment well with the endogenous technology choice effect.

Finally, in the last section I come back to the theoretical foundations of the endogenous technology choice. The heart of the hypothesis is the presence (at any point in time) of a tradeoff: firms might choose between technologies that assign higher productivity to skilled workers and those that assign higher productivity to unskilled workers. The derivation of this tradeoff is therefore vital for entire model. In the last section I demonstrate how the R&D process in which researchers invent a finite number of production processes might generate the trade-off between two types of technologies.

2 Endogenous Technology Choice Model.

To illustrate how labour supply might affect the endogenous technological choice and further, the skill premium and to set the basis for the empirical model in this section I present a simple dynamic model [2]. Consider an economy with one final product. Suppose that a given technology platform offers a menu of production methods for generating this product, each of them utilizing two inputs - skilled and unskilled labour - but each of them characterized by different productivity parameters. In particular suppose that production methods i in the menu offered by the platform is characterized with the following production function:

$$F_i = [(A_{is}L_s)^{\sigma} + (A_{iu}L_u)^{\sigma}]^{\frac{1}{\sigma}} \tag{1}$$

[2] the model is based on the static model by Caselli and Coleman (2006)

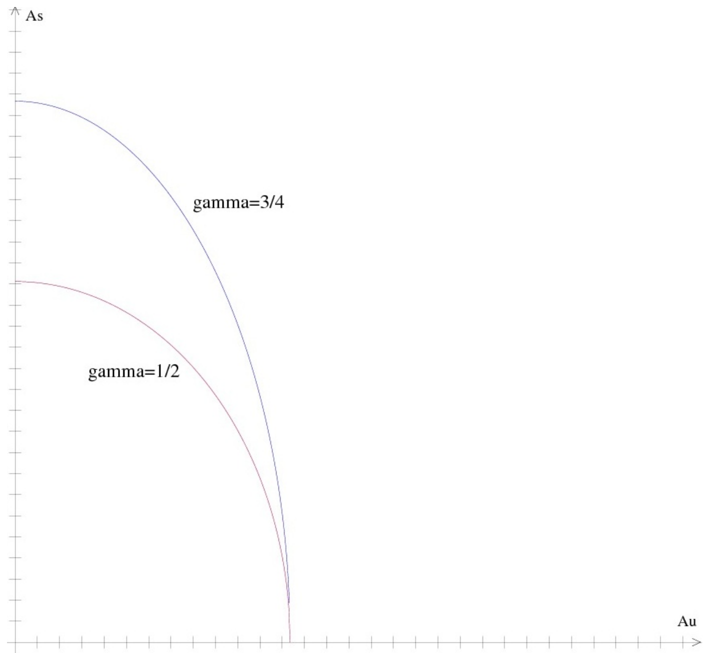

Figure 1: Production methods menu for two different values of gamma.

where L_s and L_u stand for skilled and unskilled labour inputs and $A_{is}$and A_{iu} are the productivity parameters for these two types of labour associated with production method i. The firm apart from choosing the quantities of labour inputs can aslo choose the technology from the menu. The menu of production methods is determined by the current GPT (technology platform) and is described by the set of pairs (A_{is}, A_{iu}) that satisfies

$$\frac{1}{\gamma}A_{is}^{\omega} + A_{iu}^{\omega} \leq B \tag{2}$$

Since every production method is fully characterized by (A_{is}, A_{iu}) pair it can be represented as a point in the A_s, A_u space. Further, the menu of technologies offered by technology platform may be represented by the set of points satisfying (2). Figure 1 gives two examples of such sets differing in the values of γ.

The key point to be noticed in the figure is that - given technology platforms - the firms faces a tradeoff between technologies that gives highly productive role to skilled workers and those that assign a highly productive role to unskilled workers. This is indeed the central assumption of the model and entire technology choice hypothesis. Is it justifieble?

2.1 Potential sources of the trade-off between productivities

For simplicity of the argument in the above model the trade-off between the two productivity parameters at the frontier is explicitly imposed although there are various models in which it will come up in a natural way. One way to generate the trade-off is to introduce in the model the costs of adoption of technologies for firms (in terms of units of their final output). The more advanced the technology it aims to adopt the higher is the cost of adoption. Suppose there are two types of machines, each assisting different type of labour. Adopting advancements in the machines that assist skilled workers and in the machines that assist unskilled workers has different cost: $\frac{c}{\gamma}$ and c respectively. The firm optimization problem can then be stated as:

$$\max_{L_s, L_u, A_s, A_u} \left[(A_s L_s)^\sigma + (A_u L_u)^\sigma\right]^{\frac{1}{\sigma}} - w_s L_s - w_u L_u - \frac{c}{\gamma} A_s^\omega - c A_u^\omega$$

The firm will therefore face the trade-off - it might spend less on the unskilled-dimention of the technology but advance more on the skilled-dimension of the technology or other way around. The trade-off will be rulled by the relative cost of adoption parameter γ. The model in this version is elaborated further in section 5.1

Another model would be one that treats production methods as randomly generated objects. Imagine a Science University that has just devised a new civilizational milestone (such as power of steam, semi-conductors, or radioactive decay). The finding has been passed to the Engineering Institute that will try to work out how to combine the new scientific disovery and two types of labour inputs to generate a final good. In fact they might have various ideas how to do it, each of the idea will involve some degree to which the newly discovered law of nature can compliment the work of skilled and unskilled humans. Thus each idea can be represented with the production function (1) with parameters (A_{is}, A_{iu}).

How the ideas look (what are the pairs (A_{is}, A_{iu}) that engineers could come up with) depends partly on chance, partly on the nature of the scientific discovery made in the Science University. Therefore we might think about each idea, or rather a pair (A_{is}, A_{iu}) that characterize it, as a draw from the bivariate distribution whose parameters depends on the nature of discovery (some discoveries might be skill-biased by nature in the sense that the explored law of nature compliment ideally with the effort of educated workers - then engineers have much higher chances of finding out production methods with very high A_s). Engineers might have n ideas and thus n production methods (with n associated (A_{is}, A_{iu}) pairs) will appear as possibilities to be picked up by firms around the globe.

Now consider figure 2 (either right or left panel) that illustrates n random draws from the bivariate distribution. For a moment lets focus on the draw that assigns the highest value to A_s - i.e. skilled workers productivity parameter. We would expect that the probability that this draw happens also to assign highest value of A_u, the productivity parameter of unskilled workers among all the n draws (i.e. that the quarter east-south to that point is empty) is rather low. The existance of the other point that would assign a higher value of A_u

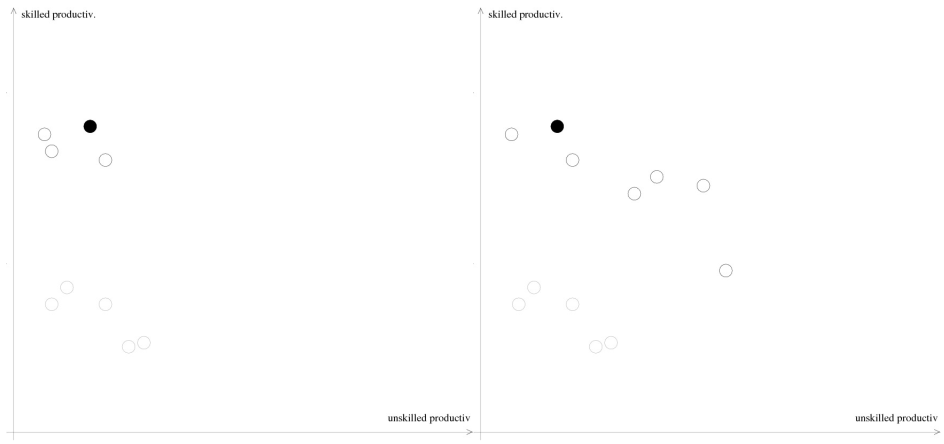

Figure 2: Production methods possibilities in the productivity of unskilled - productivity of skilled space. The panel on the left shows the case of the skill-biased technological platform. The panel on the right presents the case of the skill-neutral technological platform.

and lower value of A_s then implies a trade-off between the two. Intuitively, although researchers at the Engineering Institute working on utilization of ICT technology have high chances of designing a production method in which the skilled workers play the key role and unskilled workers play very modest role, it is likely that they came up with a different production method in which the role of unskilled workers is more significant (and perhaps the role of skilled workers is less significant).

To illustrate this idea with the example, suppose there are two ways of producing output: one is a fully automatized factory where most of the task are performed by skilled labour (e.g. programming robots) while unskilled workers perform less important tasks (such as cleaning, guarding etc.). The other way is the production side on which unskilled workers perform the key production tasks while technology and skilled labour assist them by analyzing mistakes, supervising, organizing logistics and training to maximize unskilled workers performance. Comparing to the former production method the latter production process generates higher demand for unskilled workers.

More generally the model captures the idea that, no matter what is the nature of the current state of science, what were the milestone discoveries, if engineers are able to devise a production method in which the role of unskilled workers and technology is only to assist skilled workers it is very unlikely that they cannot come up with the idea to utilize the milestone discovery in the production method in which the role of skilled workers and technology is limited only to assisting unskilled. The availability of such two production methods implies then a trade-off between productivity of skilled and unskilled workers. Section 5.2 discusses this idea in more detail and illustrates it with a formal model.

2.2 Characterization of the equilibrium

The introduction of new GPT (or technology platform) will involve the change in γ and B parameters and thus the change of menu of available production methods. If the technology platform becomes more skill-biased it will offer opportunities of production methods that make very good use of skilled worker. In the framework presented above this will involve appearance of possibilities to choose production functions with very high productivity parameter for high-skilled workers. We can capture it in the model as increase in γ parameter. Figure 2 pictures how the menu of available (A_{is}, A_{iu}) pairs changes when the platform becomes more skill biased (i.e. γ rises).

Since dynamics plays important role in the empirical analysis we shall incorporate them in the theoretical model. I assume that firms cannot immediately switch technology in response to changes in labour market conditions. This reflects the fact that firms first have to spot the change in the labour market, next they have to develop a new strategy, replace the technology (perhaps by replacing capital goods) and train workers until the new production method operates at its full potential. Therefore I assume that firms can choose technology only for the next period - current technology of the firm was determined one period before.

The firm's value function is then:

$$V\left(A_s, A_u, L_s, L_u\right) =$$

$$\max_{A'_s, A'_u, L_s, L_u} \left\{ \left[\left(A_s L_s\right)^{\sigma} + \left(A_u L_u\right)^{\sigma} \right]^{\frac{1}{\sigma}} - w_u L_u - w_s L_s + \beta E\left[V\left(A'_s, A'_u, L'_s, L'_u\right)\right] \right\}$$

subject to $\frac{1}{\gamma} A'^{\omega}_{is} + A'^{\omega}_{u} \leq B$. x' denotes the value of variable x next period. The First Order Conditions for technology choices are

$$\frac{dE\left[V\left(A'_s, A'_u, L'_s, L'_u\right)\right]}{dA'_s} = \lambda \frac{1}{\gamma} \omega A'^{\omega-1}_{s}$$

$$\frac{dE\left[V\left(A'_s, A'_u, L'_s, L'_u\right)\right]}{dA'_u} = \lambda \omega A'^{\omega-1}_{u}$$

and the envelope conditions are

$$\frac{dV\left(A_s, A_u, L_s, L_u\right)}{dA'_s} = \beta \left[\left(A_s L_s\right)^{\sigma} + \left(A_u L_u\right)^{\sigma} \right]^{\frac{1}{\sigma}-1} \left(A_s L_s\right)^{\sigma-1} L_s$$

$$\frac{dV\left(A_s, A_u, L_s, L_u\right)}{dA'_s} = \beta \left[\left(A_s L_s\right)^{\sigma} + \left(A_u L_u\right)^{\sigma} \right]^{\frac{1}{\sigma}-1} \left(A_u L_u\right)^{\sigma-1} L_u$$

Combining all the above conditions:

$$\frac{E\left[\left[\left(A'_s L'_s\right)^{\sigma} + \left(A'_u L'_u\right)^{\sigma} \right]^{\frac{1}{\sigma}-1} \left(A'_s L'_s\right)^{\sigma-1} L'_s \right]}{E\left[\left[\left(A'_s L'_s\right)^{\sigma} + \left(A'_u L'_u\right)^{\sigma} \right]^{\frac{1}{\sigma}-1} \left(A'_u L'_u\right)^{\sigma-1} L'_u \right]} = \frac{A'^{\omega-1}_{s}}{\gamma A'^{\omega-1}_{u}}$$

Log-linearizing and applying the approximation[3] $\log(E[x]) = E[\log(x)]$:

$$\log\left(\frac{A'_s}{A'_u}\right) = \frac{1}{\omega-\sigma}\log(\gamma) + \frac{\sigma}{\omega-\sigma}E\left[\log\left(\frac{L'_s}{L'_u}\right)\right]$$

This condition already reflects the fact that the higher is the (expected) number of skilled workers in the economy (relative to number of unskilled) the more skilled-biased technology will be chosen by the firm.

If we combine this result with the first order conditions for labour choices we find that

$$\log\left(\frac{w_s}{w_u}\right)\bigg|_t = -(1-\sigma)\log\left(\frac{L_s}{L_u}\right)\bigg|_t + \sigma\log\left(\frac{A_s}{A_u}\right)\bigg|_t =$$

$$-(1-\sigma)\log\left(\frac{L_s}{L_u}\right)\bigg|_t + \frac{\sigma}{\omega-\sigma}\log(\gamma)\bigg|_{t-1} + \frac{\sigma^2}{\omega-\sigma}E_{t-1}\left[\log\left(\frac{L_s}{L_u}\right)\bigg|_t\right]$$

The first term is the standard effect associated with diminishing returns to each type of labour: if we increase number of skilled workers (relative to unskilled) they will become (relatively) less productive and earn smaller skill premium.

The second effect is associated with exogenous change in the nature of technology platform: If the technology platform becomes more skill-biased (γ goes up) the menu of available production methods will now include numerous production processes that involves high productivity of skilled workers. The firms will respond to this change in opportunities with a shift of opimal production

[3]This approximation is correct if the variance of relative supply of skilled labour, $\log\left(\frac{L_s}{L_u}\right)$ is small, firms before time t do not expect any rapid changes in relative skilled labour supply. If we focus of optimization problem of firms in early 70s this is exactly what would be expected: until then the number of skilled workers grew steadily in constant trend and the deviations from this trend was marginal. At the beginning of 70s firms could have believed the variance of relative skilled labour is very low. Later it turned out that they were wrong since the growth of supply jumped up.

method choice towards the ones that favour skilled workers. This will in turn increase their relative productivity and skill premium.

Finally, the third term captures the key mechanism of endogenous technology choice hypothesis: higher (expected) number of skilled workers gives an incentive for firms to pick up the production method that fits them better. As a result their relative productivity increases and so does the skill premium.

To close the model we should model the supply side of the labour market. For simplicity of the analysis I assume the supply of skilled and unskilled workers is vertical, thus in equailibrium $L_s = \overline{L_s}$, $L_u = \overline{L_u}$ where $\overline{L_u}$ and $\overline{L_s}$ are determined exogenously.

We could also model firms' expectation about next period relative supply of skilled labour. Firms will build it based on current relative supply of skills and some other observables, captured in the vector X_t:

$$E_{t-1}\left[\log\left(\frac{L_s}{L_u}\right)\bigg|_t\right] = \log\left(\frac{L_s}{L_u}\right)\bigg|_{t-1} + X_{t-1}$$

Collecting all these conditions we find that the equilibrium skill wage premium is determined as:

$$\log\left(\frac{w_s}{w_u}\right)\bigg|_t = -\left(1-\sigma\right)\log\left(\frac{L_s}{L_u}\right)\bigg|_t + \frac{\sigma}{\omega-\sigma}\log\left(\gamma\right)\bigg|_{t-1} + \\ + \frac{\sigma^2}{\omega-\sigma}\left(\log\left(\frac{L_s}{L_u}\right)\bigg|_{t-1} + X_{t-1}\right) \quad (3)$$

The skill wage premium depends therefore on the exogenous changes in current relative skilled labour supply, the skill-bias of the global technological platform and last period relative supply of skills as long as the latter was used by firms last period to form predictions about current relative supply of skills. The relative supply of skills at time t, $\log\left(\frac{L_s}{L_u}\right)\big|_t$ is going to be correlated with firms' prediction, $\left[g \log \left(\frac{L_s}{L_u} \right) \Big|_{t-1} + X_{t-1} \right]$. How high is the correlation depends how well firm could forecast the changes.

3 Empirical Model and Regression Results.

In this chapter I design and estimate the empirical model that aims at finding out to what extent new technology choices (motivated by skilled labour supply increase) could have contributed to overall increase in skill premium. The strategy is first to derive a possibility result of how much of the increase in skill premium (among OECD countries) can be explained with the rising number of skilled workers in these countries. The second step is then investigate wheather there is an evidence for the causal impact of relative skill supply on country-level technology choices and thus on skill premium. Obviously the key challenge at that stage is to minimize the potential impact of reverse causality and omitted variables (and trends).

The empirical model can be directly derived from equation (3). The equation is restated below:

$$\log \left(\frac{w_s}{w_u} \right) \Big|_t = -(1-\sigma) \log \left(\frac{L_s}{L_u} \right) \Big|_t + \frac{\sigma}{\omega - \sigma} \log(\gamma) \Big|_{t-1} + \\ + \frac{\sigma^2}{\omega - \sigma} \left(\log \left(\frac{L_s}{L_u} \right) \Big|_{t-1} + X_{t-1} \right) \tag{4}$$

The callibration of this model involves two identification problems: first, we have to isolate the effect of actual increase in relative skills supply (the first term in the equation above, it will decrease skill premium due to diminishing returns to skilled labour) and the effect of expected increase in relative skills supply (the last term in the equation above, it will increase college wage premium as firms wish to adjust their technology choices to higher number of skilled workers). If expectation is exactly the same as actual change the identification would not be possible. The firms however cannot perfectly forecast and we can exploit this fact for the identification.

The second identification problem is to isolate out changes in global technological platform from new choices of technologies driven by increasing number of skilled workers. For this purpose we are going to use the fact that growth in number of skilled workers varied across countries. Thus we can use a cross-section of the data to isolate the role of technology choices from the role of global technological change. The assumption that is required for identification is that, within OECD, all countries face the same technology platform – i.e. the access to all available production methods is free among all developed countries. Therefore the parameter γ will be considered as global and will be indexed by the time but not by the country index. [4]

The model should take into account that some countries might have traditionally different productivities of skilled and unskilled labour not related to the type of technology used (perhaps due to difference in educational system the skilled workers productivity relative to unskilled workers productivity in some countries is lower than in others). To account for this fact I include country fixed effects in the empirical model.

Above observations and assumptions add up to form the following empirical model:

$$w_{it} = \alpha_1 l_{it} + \alpha_2 l_{it-5} + \alpha_3 l_{it-10} + d_t + c_i + \varepsilon_{it}$$

[4] In fact the assumption might be much less restrictive: countries technology platforms might be characterized (see equation (2)) by the different B parameter (thus we allow some countries to have higher overall productivity). Furthermore given that the estimation uses a first difference regression (as described later) at any moment of time the countries might face different γ parameter (that captures the skill-bias of technological platform, the menu of available production methods, see equation (2)). In fact the only restriction needed is that the change of γ parameter should be uncorrelated with the country growth of relative skills supply.

where $w_{it} = \log\left(\frac{w_s}{w_u}\right)$, $l_{it} = \log\left(\frac{L_s}{L_u}\right)$ in country i at time t and d_t and c_i are time and country fixed effects. [5].

Because the country fixed effect might be potentially correlated with skills supply (e.g. more egalitarian education system - that decreases the skill premium - might also discourage higher education, affecting the supply of skills) it might potentially bias the estimates. One way to remove this problem is to look at the above equation in first differences:

$$\triangle w_{it} = \alpha_1 \triangle l_{it} + \alpha_2 \triangle l_{it-10} + \hat{d}_t + \triangle \varepsilon_{it} \tag{5}$$

The regression in (5) is directly derived from the framework in section 2 and as such can be interpreted as estimation of that model. However the interpretation of the results does not have to be limited to that framework only. For better understanding of the results we can restate equation (5) in a more intuitive form. The presence of the time dummies allow us to rearrange the equation in the following way:

$$(\triangle w_{it} - \triangle w_t) = \alpha_1 (\triangle l_{it} - \triangle l_t) + \alpha_2 (\triangle l_{it-10} - \triangle l_{t-10}) + \triangle \epsilon_{it}$$

where b_t is the cross-country average of variable b at time t and $\epsilon_{it} = \varepsilon_{it} - \varepsilon_t$.

Therefore the effect that we actually meassure with the regression is the impact of deviation of skill supply growth from the average international growth on the deviation of the growth in college wage premium from its growth observed globally. Putting it differently, we can examine if countries that experienced higher growth in number of college graduates than other countries experienced also higher growth of college wage premium a decade later. If yes there must be some country-level mechanism that generates this dependance. In addition

[5] I use both, five and ten years lags since it is difficult to assume apriori how long is the adjustment time for technology

to endogenous technology choice there are other potential candidates for such mechanism. I discuss them in detail below and either I argue that they are unlikely to drive the results or I introduce appropriate control to capture their effect. The regression results leads to the conclusion that endogenous technology choice appears to be the most plausible candidate among these mechanisms.

Operating in the context of labour market equilibrium we need to keep in mind that the relative productivity and relatvie wage will impact relative skills supply. Although this should be a serious problem for estimating the causal effect of skills supply on skill premium it should not be a problem for finding out the impact of past relative supply of skills. It is not likely that workers can predict that in a decade growth of college wage premium in their country will be higher than in other countries. Second, even if they could predict this, it is not obvious why the *change* in relative skill supply should depend on growth of college wage premium a decade later: if workers who take decision on education in 1990 predict that in their countries college premium will grow substantially they may be more keen to go into college. However the same is true for workers in 1985 and earlier cohorts.

It is far more likely that if relative skills supply (deviation from international trend) is affected by the deviation of skill-premium from the international trend it depends on its current or past values. Therefore the possibility we should consider is whether the current innovation to skill premium deviation might be correlated with the past skill premium deviation.

Assume that the innovation for the *level* of skill wage premium (in deviation from international level) is the IMA(1,1) process:

$$w_{it} - w_t = X\alpha + \epsilon_{it}$$

where X is the set of controls in the regresssion and

$$\epsilon_{it} = \eta_{it} + \beta\eta_{it-10} + \epsilon_{it-10}$$

It follows that the change in the innovation can be expressed as:

$$\Delta\epsilon_{it} = \eta_{it} + \beta\eta_{it-10} \tag{6}$$

The source of the upward bias of the results might be the MA component in the innovation in skill premium. The MA components are associated with the factors that impact the increase (or decrease) of skill premium (relative to international increase) over the 5 years period (the time period of the observation). This might be a change in the labour or tax policy, change in education system that leave permament stamp on skill premium. Most of these factors are unlikely to lead to further increase in skill premium a decade later (it is difficult to imagine a tax policy reform that would lead to increase of skill premium in 80s and yet to another increase in 90s). The exception might be globalization and falling importance of trade unions (we could imagine the globalization or trade union collapse process to lead to increase in college wage premium over 20-30 years). For this reason I attempt to control for both in the empirical model.

Finally the argument that the results are unlikely to be biased by the autocorrelation of changes in college wage premium comes from the the inspection of the data. In almost all countries the period of raising relative skill supply comes first and only after certain time we can see the beginning of an upward trend in skill premium.

The source of the data is the EU KLEMS dataset, 2008 release covering annual data between 1970 and 2005 for 23 countries (although the panel is not balanced). The data contains information on total hours worked and total compensation for three groups of employees: high-skilled (those with at least tertiary education), medium-skilled (those with secondary education) and low-skilled (those with at most primary education).

To simplify the analysis and keep the clarity of the picture I merge the two groups: low-skilled and medium skilled workers into one group of "unskilled" workers. Because the hours of medium-skilled might be worth more than the hours of low-skilled in computation of unskilled labour supply I use the standard approach to weight the medium-skilled workers hours by their productivity relative to low-skilled workers productivity. Hence unskilled labour supply is computed as $L_u = L_l + (w_m/w_l)L_m$. As a result the labour supply of unskilled is measured in terms of low-skilled hours equivalents.

To avoid potential problems with cyclicality I use only the datapoints in 1970, 1975, 1980, 1985, 1990, 1995 and 2005 and meassure the differences over 5 year periods. Obviously the 5 year difference is effectively an average of the annual differences in a 5 years period.

The results from the random effect regression are presented in table 1. As predicted by the model the coefficient on the current change in skills supply is negative - this reflects the diminishing returns to skilled labour. The effect is substantial (10% increase in relative skill supply is associated with 8% drop in skill premium) though very close to the estimates obtained by Katz and Murphy (1999) in the similar regression of skill premium series on skill supply series using US data. Nevertheless, as mentioned above, this result should not be taken as causal effect due to likely reverse causality.

The results show also a significant positive effect of past increases in relative supply of skilled labour. The effect is also substantial in economic terms: a 10% increase in relative skill supply involves 2.2% increase in skill premium. Inter-

	(1)	(2)	(3)	(4)	(5)	(6)
Dlog(hhs/hus)	-0.804 ***	-0.825 ***	-0.803 ***	-0.822 ***	-0.793 ***	-0.786 ***
	(0.125)	(0.133)	(0.126)	(0.138)	(0.132)	(0.137)
Dlog(hhs/hus)_{t-5}	-0.255 *	-0.224	-0.253 *	-0.222	-0.242	-0.242
	(0.144)	(0.154)	(0.145)	(0.158)	(0.151)	(0.155)
Dlog(hhs/hus)_{t-10}	0.218 **	0.217 **	0.225 **	0.213 **	0.191 **	0.183 *
	(0.09)	(0.097)	(0.092)	(0.101)	(0.096)	(0.1)
d85		-0.006		-0.007	-0.018	-0.021
		(0.05)		(0.052)	(0.05)	(0.051)
d90		-0.03		-0.028	-0.034	-0.031
		(0.048)		(0.052)	(0.048)	(0.051)
d95		0.013		0.015	-0.001	0,000
		(0.038)		(0.042)	(0.038)	(0.042)
d00		0.013		0.013	0.006	0.003
		(0.037)		(0.043)	(0.036)	(0.042)
year			0.001			
			(0.002)			
log(hhs)_{t-10}					-0.041 *	-0.042 *
					(0.024)	(0.025)
Dlog(uniondens)				-0.034		-0.053
				(0.145)		(0.142)
Dlog(export/gdp)				-0.006		0.004
				(0.089)		(0.087)
constant	0.167 ***	0.163 ***	-1.466	0.161 ***	0.274 ***	0.272 ***
	(0.026)	(0.033)	(4.181)	(0.036)	(0.072)	(0.075)
Rsquare	0.5803	0.5887	0.5816	0.5894	0.6143	0.6156

Table 1. The dependent variable is five years change of college wage premium (in logs). The independent variables are the 5 year change in the ratio of college graduates to remaining part of labour force (in logs), its 5 and 10 years lags, dummy variables for each year (or linear trend), the proportion of skilled labour in total labour (lagged 10 years), 5 years change in ratio of export to GDP (in logs), and 5 years change in trade union density (in logs). All estimations comes from Random Effect regressions.

estingly the time needed for the change in relative labour supply to be reflected in the change in skill premium is rather long: the coefficient is positive and significant only for the relative skill supply lagged by 10 years - the coefficient on five years lag is not significantly different from zero and in fact negative.

Can the result be driven by difference potency to adopt ICT across countries? It could be that countries which experienced high growth of skilled labour a decade earlier are able to adopt faster new technologies that just happened to be skill biased. Large change in skill supply results in a higher stock of skilled labour, including engineers and scientist. This might translate into higher capacity for adopting technologies that had just developed - like ICT in 80s. If the new technologies are (by nature) skill-biased we will see higher increase in skill premium in these countries.

To check for this possibility we can include in the regression a control for the stock of high-skilled labour (total hours worked) 10 years ago [6]. The column (4) in table 1 shows that inclusion of this control does not change the results significantly - the effect of a change in skill supply on change in skill premium is still siginificant at 5% confidence level and the coefficient has dropped marginally to 0.21. The regression shows also that the stock of skilled labour does not matter for skill premium increase. The coefficient is not significant and if anything it is negative. Almost exactly the same results are obtained if instead of controlling for stock of skilled labour lagged 10 years we control for stock lagged 5 years and 15 years.

The results might be also driven by different exposure to globalization: countries that becomes quickly exposed to globalization might experience quicker growth of demand for educated worker. This will encourage more workers to become skilled. If in a next decade the same country continue to become more

[6] the lag seems to be necessary since we need to allow a time before the decision to adopt a new technology and a point at which the effect of adoption will be reflected in wage data

exposed to globalization than other countries the demand for educated workers might shift further increasing the skill premium. This would generate a spurious correlation between college premium increase today and college workforce growth ten years ago. To control for change in exposure to globalization I inlcude in the regression the change of the ratio of export to GDP. The results stay robust to this inclusion. Although not reported in the table I have included also the level (rather than growth) of ratio of export to GDP. Again this does not affect the results.

Another possibility is that results are driven by the collapse of trade-unions: if number of unskilled workers drops significantly this might undermine the bargaining power of the trade-unions and lead to increase in wage inequality. Moreover this effect is likely to be delayed. Nevertheless inclusion of the change in trade union density does not change the results. Furthermore it seems that trade unions does not have significant impact on college wage premium in OECD countries.

A final remark on the result is a warning that the positive coefficient on lagged skill supply *does not* imply that increased supply of skills brings in long run the increase in skill premium. If we take the Katz and Murphy estimates of the slope of demand (reconfirmed later by the more careful instrumental variable estimates in Ciccone and Peri and by results of regression in Table 1), an increase in relative skill supply leads first to approximately 7% drop in skill premium. If we use estimates from the regression results we will expect the skill premium to rebound in a decade and increase by approximately 2%. This means that the initial level of skill premium will not be restored and the long run effect of skill supply on skill premium will be a 5% drop.

At this stage we can return to the calibration of the model from section 2 and calculate what is the contribution of endogenous technology choice in the total increase in skill premium. Since a number of countries do not have observation before 1980, I will consider the period 1990-2005. Over these 15 years the relative skill supply in 12 OECD countries (that have data for entire period) has increased by 32% that, using Katz and Murphy estimates of demand curve, should translate into 18% drop in skill premium. Instead the skill premium in this period has raised by 28%. This leaves 56% of unexplained wage increase (0.193 log points). In period 1980-1995 the relative skills supply has increase by 90%. This according to the model and the estimates above should lead to 15% (0.062 log points) increase in skill premium due to endogenous technology choice between 1990 and 2005. The residual increase left is then 35% (0.131 log points) that can be probably attributed to skill-biased technology change. This leads to the conclusion that endogenous technology choice can explain 32% (0.062 out of 0.193 log points) of the increase in skill premium that could not be explained in the standard demand-supply (Katz and Murphy model) framework.

4 Other explanations.

The empirical results presented above points out that skill premium dynamics are not explained solely by global factors (such as nature of General Purpose Technology) but are also shaped by mechanisms operating at local level that respond to the local dynamics of skill supply. One candidate for this mechanism, sketched in section 2, is that changes in the labour market might change the optimal choice of production method from the set of available technologies. In this section I put forward two alternative (but potentially complimentary) explanations: one attributing the changes in productivities to the presence of spillovers in the production, the second: arguing that higher number of skilled labour could simply motivate firms to adopt faster the ICT technology that is itself skill-biased.

4.1 Spillovers effect.

How the presence of spillover might translate higher skill supply into higher skill premium? Suppose that how well a skilled worker use the technology depends on how many other skill workers are around. This might be because operating a technology requires certain degree of experimentation and sharing experience can facilitate the process and improves the outcome. If there is one machine specialist in the city he needs to experiment alone, if there are a few - they might meet over coffee to share what each of them have learnt, if there are hundreds, they might organize a conference and invite speakers from outside.

A nicely illustrative example of such system of information exchange (although in the context of depeloped countries agriculture) is Bandiera and Rasul (2006). She studied the adoption of new crop varieties (a newly introduced technology) among farmers in Northern Mozambique and found that the outcome depends crucially on the interaction with other farmers.

The effect does not have to be immediate - indeed we could expect that it takes time before new workers establish connection with the old ones, before they trust each other, find a common language and learn how to utilize each other experience. Therefore we would predict that increase in skilled workers supply first drives down their productivity due to diminishing returns to skilled workers, but after some time the additional workers might contribute in knowledge sharing and increase the productivity of every skilled workers. Thus the spillover effect can explain the pattern observed in the data.

To illustrate this line of thought we might consider a formal model that includes the spillover effect. The productivity of skilled workers (how well they utilize the technology that is devoted to them) depends positively on the density of skilled workers in the economy [7]. With the ammended prouction function

[7] I do not include a similar effect for unskilled workers since spillover in their case is less likely. Nevertheless inclusion of spillover for unskilled would not change the result

the profit maximization for the firm i in country j is then:

$$\max_{L_{is},L_{iu}} P_i \left[\left(\left(\frac{L_{js}}{L} \right)^{\beta} A_{is} L_{is} \right)^{\sigma} + (A_{iu} L_{iu})^{\sigma} \right]^{\frac{1}{\sigma}} - w_s L_{is} - w_u L_{iu}$$

The combination of the two first order conditions gives then:

$$\left(\frac{L_{is}}{L_{iu}} \right)^{\sigma-1} \left(\frac{L_{js}}{L} \right)^{\sigma\beta} \left(\frac{A_{is}}{A_{iu}} \right)^{\sigma} = \frac{w_s}{w_u}$$

And denoting $l_i = \log\left(\frac{L_{is}}{L_{iu}}\right)$, $l_j = \log\left(\frac{L_{js}}{L}\right)$, $a = \log\left(\frac{A_{is}}{A_{iu}}\right)$ and $w = \log\left(\frac{w_s}{w_u}\right)$:

$$(\sigma - 1)\, l_i + \sigma\beta l_j + \sigma a_i = w$$

Adding time indices (that takes into account that the effect of spillover is not immediate):

$$(\sigma - 1)\, l_{it} + \sigma\beta l_{jt-1} + \sigma a_{it} = w_t \tag{7}$$

If the firm is the representative firm (or if firms are symmetric in the sense that they face the same a and the same p) then we can drop the firm indices:

$$(\sigma - 1)\, l_t + \sigma\beta l_{t-1} + \sigma a_t = w_t$$

The spillover model predicts therefore that following increase in relative skill supply we first observe a drop of skill premium due to diminishing returns to relative skill supply and later its increase due to the spillover effect.

The problem with this hypothesis is that it cannot explain a long time lag (10 years) between changes in skill supply and changes in skill premium. Although, as argued before, establishing connections and learning how to share experience might take some time, it is unplausible that some of this effect would not be reflected in five years. Yet the data show no positive dependence of skill premium on relatvie skills lagged five years.

The spillover effect might however play an important role if it is augmented with the endogenous technology choice effect: suppose that the firm knows about the spillover effects and it knows that higher number of skilled workers implies that new technology directed to skilled workers will be used more efficiently. This creates additional incentive for the firm to shift towards such technology. More formally we can put this logic in the model that follows.

The line of logic is best protrayed in the version of the model in which firm has to pay (in the units of its final output) for adoption of technology. Moreover progressing on the skill-dimension of the technology (i.e. the technology that assist skilled) and the unskilled-dimension of the technology (the one that works with unskilled) has different cost: $\frac{c}{\gamma}$ and c respectively. Then the profit maximization is given by:

$$\max_{L_{is},L_{iu},A_{is},A_{iu}} \left[\left(\left(\frac{L_{js}}{L}\right)^{\beta} A_{is}L_{is}\right)^{\sigma} + \left(A_{iu}L_{iu}\right)^{\sigma}\right]^{\frac{1}{\sigma}} - w_s L_{is} - w_u L_{iu} - \frac{c}{\gamma}A_{is}^{\omega} - cA_{iu}^{\omega}$$

Combining two First Order Conditions we arrive to:

$$\left(\frac{A_{is}}{A_{iu}}\right)^{\sigma-1}\left(\frac{L_{is}}{L_{iu}}\right)^{\sigma}\left(\frac{L_{js}}{L}\right)^{\sigma\beta} = \frac{1}{\gamma}\left(\frac{A_{is}}{A_{iu}}\right)^{\omega-1}$$

Again changing the notation, as above and adding time indices[8]:

$$(\sigma-1)\,a_{it} + \sigma l_{it-2} + \sigma\beta l_{jt-2} = -ln\left(\gamma_{t-2}\right) + (\omega-1)\,a_{it}$$

Rearranging:

[8] the choice of production method is based on the information from two periods back

$$a_{it} = \frac{ln\left(\gamma_{t-2}\right) + \sigma l_{it-2} + \sigma\beta l_{jt-2}}{\left(\omega - \sigma\right)} \tag{8}$$

and putting back to the first condition (7):

$$\left(\sigma - 1\right) l_{it} + \sigma\beta l_{jt-1} + \sigma\frac{ln\left(\gamma_{t-2}\right) + \sigma l_{it-2} + \sigma\beta l_{jt-2}}{\left(\omega - \sigma\right)} = w_t$$

$$\left(\sigma - 1\right) l_{it} + \sigma\beta l_{jt-1} + \frac{\sigma}{\omega - \sigma} ln\left(\gamma_{t-2}\right) + \frac{\sigma^2}{\omega - \sigma} l_{it-2} + \frac{\beta\sigma^2}{\omega - \sigma} l_{jt-2} = w_t$$

Dropping the firm indices in the equilibrium (however not merging the terms in order to ease interpretation):

$$\left(\sigma - 1\right) l_t + \sigma\beta l_{t-1} + \frac{\sigma}{\omega - \sigma} ln\left(\gamma_{t-2}\right) + \frac{\sigma^2}{\omega - \sigma} l_{t-2} + \frac{\beta\sigma^2}{\omega - \sigma} l_{t-2} = w_t$$

As in the previous model (without endogenous choice of technology) there is a direct effect of spillover on skill premium (represented in the second term) taking place after first period (that may be 5 years). However if β is small this effect may be very limited and not even properly reflected in the data. In addition to the direct effect the spillover has also the indirect effect: since the returns to investing in skill-biased technology increases with how well this technology is utilized and this depends in turn on the density of skilled workers, increase in the relative skill supply will incentivise firms to invest more in skill-biased technology, thus providing additional factor that shifts skill premium. This effect will be however introduced only in the second period since two periods are required before the firm spots the increase in relative skill supply and implement new technology. Moreover the indirect effect of spillover (through incentivising skill-biased technology choice) might be stronger then the direct effect. If ω is not large and σ is not too far from unity the effect of spillover might show up only after second period.

4.2 Endogenous adoption of skill-biased technology.

Suppose that the technology choice mechanism does not work, each technological paradigm offers only one new production method and firms cannot choose between various production methods). Now imagine that new technology paradigm (e.g. Information and Communication Technology) and the (single) production method it offers guarantees higher productivity for both skilled, and unskilled workers however comparing to the previous technology is clearly skill-biased in the sense that it benefits skilled workers much more than the unskilled. However adoption of this technology is very costly (e.g. involves temporary loss of overall productivity) and not all countries want to immediately jump to the new production methods. We would expect that the first countries to adopt the new technology (and consequently move to higher skill-premium) were the countries that can benefit most, i.e. those with high stock of skilled labour. This could potentially explain the empirical results: countries with high growth of skilled labour supply could have accumulated a high stock of skills. Those countries would adopt the new, skill-biased production method more rapidly and thus increase their skill-premium more than other countries.

Furthermore the story may be continued beyond the first two periods: next period another new technology (even more skill biased) may appear and again countries that will adopt it first will be these with the biggest stock of skilled workers.

This hypothesis is in fact testable: it would imply that the skill premium increase should depend positively not only on the growth of skill supply but also on the level of skill-supply. Yet this is disproved by the regression in column 4 of table 1: there is no evidence that such positive association exist. The hypothesis would not be also able to explain the experience of Korea that has reported a decline of relative skill supply and a decline of skill premium.

Nevertheless elements of this mechanisms can be incorporated into the endogenous technology choice model. It may be that new technology platform offers a range of production methods that boost skilled workers productivity and only few that improves unskilled workers productivity (in the model this is simply captured by the increase in γ and modest increase in B) - indeed it is very likely in case of ICT. All countries in such case will shift towards more skill-biased technologies, however the countries that have large number of skilled workers and which before and after the change were operating relatively skill-biased technology will witness a large jump away from the old technology (since there are so many new opportunities in the corner for skill-biased technologies) and, analogously, will experience a high degree of adoption of new technoogy. Conversely, countries that had high number of unskilled workers and which always positioned themselves at the unskilled corner of technolgy choices will move very little away from their previous position (although they might move towards more skill-biased technologies they will still remain closer to the corner of unskill-biased technologies where not many new opportunities had been offered by the new technology platform).

Yet the model does not predict the effect of the stock of skills on the change in skill premium - this is because countries with high stock of skilled workers were using more skill-biased technology already before - and therefore if the technology platform nature becomes more skilled biased itself this will not have a higher effect on skill premium in these countries then in any other countries.

5 Tradeoff in Production Methods Menu.

In this section I elaborate in more details ideas drafted in section 2.1 - I present and formally discuss two arguments why we can expect the tradeoff between technologies that assign high productivity to skilled workers and technologies that assign high productivity to unskilled workers. The first argument is based on the presumption that adoption of each technology might be costly - a firm might find it not optimal to adopt technologies that increase productivity of unskilled workers if there are very few unskilled workers. The second argument is that random nature of production methods discoveries might generate the trade-off itself. Both arguments are described with the formal models.

5.1 Costly adoption

One implicit, though potentially problematic, assumption in the analysis presented so far is that technology is taken to be a single object associated with some productivities for skilled and unskilled workers. Instead in the world technologies devoted to skilled workers and technologies devoted to unskilled might exist separately. Mathematically this would imply that each technology is no longer characterized by a vector (A_s, A_u), but by scalars: technologies for skilled by a scalar A_s, technologies for unskilled - by a scalar. In such case firms will simply take the best technology available for skilled workers (buy fastest available PCs, apply best practices for HR management etc., i.e. maximize A_s) and take the best available technology for unskilled workers (purchase most productive machines, apply best practices in production line organization etc. i.e. maximize A_u). Why would purchase of better computers necessarily involve necessity to use worse production machinery?

Such trade-off might however arise if firms face adoption costs. Suppose that the more advanced is the technology firm aims to adopt the higher is the cost of adoption. Moreover progressing on the advancement of technologies devoted to skilled workers and technologies devoted to unskilled has different cost: $\frac{c}{\gamma}$ and c respectively. The firm optimization problem can then be stated as:

$$\max_{L_{is},L_{iu},A_{is},A_{iu}} \left[(A_{is}L_{is})^{\sigma} + (A_{iu}L_{iu})^{\sigma}\right]^{\frac{1}{\sigma}} - w_s L_{is} - w_u L_{iu} - \frac{c}{\gamma} A_{is}^{\omega} - c A_{iu}^{\omega}$$

subject to $A_s \leq \bar{A}_s$ and $A_u \leq \bar{A}_u$ where $\bar{A}_s$ and $\bar{A}_u$ are the frontier technologies.

Of course firms might hit the frontier for both technologies. However if the costs are high enough this will not happen and firms will find it not optimal to adopt technologies that increase productivity of unskilled workers if there are very few unskilled workers. In fact, if firm is not choosing frontier technologies, the first order condition will be exactly the same as before with γ rulling the tradeoff between optimal choices of A_s and A_u.

Another possibility is that firms face the credit constraints for adoption of technologies. In such a scenario, firms optimization will be given by

$$\max_{L_{is},L_{iu},A_{is},A_{iu}} \left[(A_{is}L_{is})^{\sigma} + (A_{iu}L_{iu})^{\sigma}\right]^{\frac{1}{\sigma}} - w_s L_{is} - w_u L_{iu} - \frac{c}{\gamma} A_{is}^{\omega} - c A_{iu}^{\omega}$$

subject to $A_s \leq \bar{A}_s$ and $A_u \leq \bar{A}_u$ and $\frac{c}{\gamma} A_{is}^{\omega} + c A_{iu}^{\omega} \leq B$ where B is the borrowing constraint for the firm. As long as B is not high enough firm will not be able to adopt best technologies for either skilled and unskilled workers and it will face a tradeoff between investing in the two types of technologies. In such case the first order conditions will be exactly the same as before.

5.2 Random Discoveries

The purpose of this subsection is to demonstrate that if we are ready to assume that each technology is associated with a pair of productivities: for skilled and unskilled workers (rather then some technologies determining technologies for skilled workers and other technologies ruling productivity of unskilled) then the tradeoff can be derived easily simply by allowing for a random generation of production methods ideas.

Before we proceed we should first consider if the assumption of single technology for both unskilled and skilled workers is defendable. It is hard to justify the assumption if roles of skilled and unskilled workers are clearly defined and separated and when technologies are only used to help workers to perform in their duties better. Then we would probably observe two types of technologies - one devoted to skilled workers, one devoted to unskilled workers - and the two types are unlikely to be negatively correlated.

However what happens it the roles of unskilled and skilled workers are not independent of technology? If technology (especially if it is defined broadly, including management strategies, organization of production) itself determines the roles and their division between two types of workers it has to be treated as a unitary object - firms cannot choose technologies for skilled and unskilled separately and independently.

The logic above suggest that if tasks of workers are predefined and technology determines only on the division of these tasks between skilled and unskilled workers the trade-off between skill biased and unskill-biased technologies appears immediately: firms have to decide to adopt technology where skilled workers assist unskilled workers (key roles in production go to unskilled) or the technology with unskilled workers assisting skilled (the key roles go to skilled). However what if the set of roles is not predetermined but defined by technology? The technology might determine the duties for skilled workers independently of duties for unskilled. The model below captures this idea and shows how random generation of technology might explain the trade-off essential for endogenous technology choice hypothesis.

Imagine a Central Science University that has just devised a new civilizational milestone (such as power of steam, semi-conductors, or radioactive decay). The finding has been passed to Central Engineering University that will try to work out how to combine the new scientific disovery and two types of labour inputs to generate a final good. In fact they might have various ideas how to do it, each of the idea will involve some degree to which the newly discovered law of nature can compliment the work of skilled and unskilled humans. Thus each idea can be represented with the production function (1) with parameters (A_{is}, A_{iu}).

How the ideas look (what are the pairs (A_{is}, A_{iu}) that engineers could come up with) depends partly on chance, partly on the nature of the scientific discovery made in Central Science University. Therefore we might think about each idea, or rather a pair (A_{is}, A_{iu}) that characterize it as a draw from the bivariate distribution whose parameters depends on the nature of discovery (some discoveries might be skill-biased by nature in the sense that the explored law of nature compliment ideally with the effort of educated workers - then engineers have much higher chances of finding out production methods with very high A_s). Engineers have n ideas and thus n production methods (with n associated (A_{is}, A_{iu}) pairs) appear as possibilities to be picked up by firms.

As in the other parts of the paper the production function is assumed to take a CES from for all available technologies:

$$F_i = [(A_{is}L_s)^{\sigma} + (A_{iu}L_u)^{\sigma}]^{\frac{1}{\sigma}}$$

Suppose that we know that a representative firm uses the technology represented by a solid point on figure 3. An isoquant going through this point indicates that in the areas A and B there must not be any available technology (otherwise firm did not choose the optimal technology). Suppose now that the skilled and unskilled labour supply has change - in particular relative to

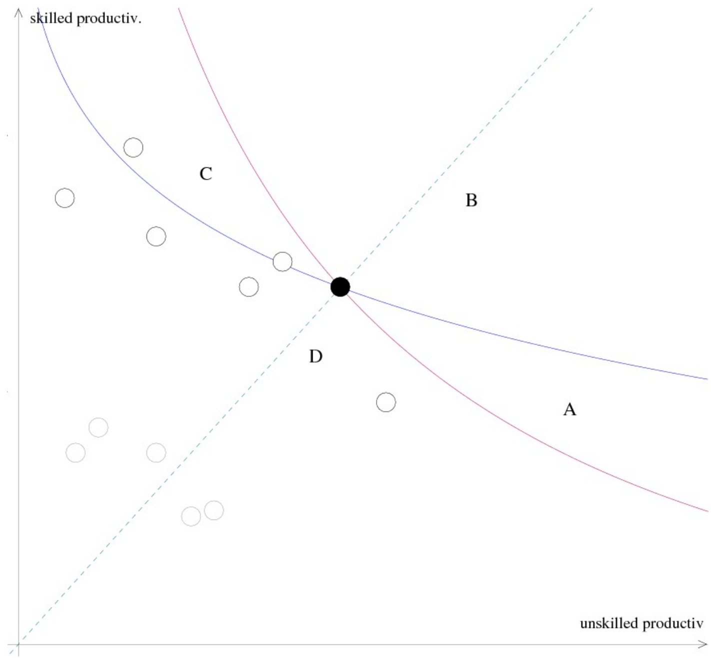

Figure 3: Optimal Choices of Technologies under changing relative supply of skills

the number of unskilled workers number of skilled workers has increased. This makes the isoquant flatter as illustrated on the graph. We know for certain that a firm will not jump to technologies in areas A and B because there are no available technologies there. It will also not choose technology from area D because it is suboptimal - it is better to stay with the current technology (represented with solid dot). The only possibility is then that firm might find other available technologies in area C - then it will decide to shift. There will be no jump to the technologies that lay below the dotted line. The proposition follows

Proposition 1. Upon a relative increase in supply of one of the types of labour the representative firm will never jump to technologies that disfavour this type of labour.

In fact we can tell much more about the changes of optimal choices of the company if we consider a particular bivariate distribution of technologies. We might assume that this distribution is a bivariate normal distribution with no correlation between A_s and A_u (to form a production method engineer draw first A_s from a normal distribution, then draw A_u from another normal distribution (but independent of the value of the first draw) and then put the two draws together). With this assumption we can phrase another proposition:

Proposition 2. If a pair (A_s, A_u) is drawn from bivariate normal distribution with no correlation between A_s and A_u then the most likely ex ante (i.e. before the realization of the draws) choice of technology (the mode of the optimal technology choice distribution) has to satisfy:

$$\log\left(\frac{A_s}{A_u}\right) = \frac{1}{2-\sigma}\log(\gamma) + \frac{\sigma}{2-\sigma}\log\left(\frac{L_s}{L_u}\right)$$

Proof: With the bivariate normal distribution with no correlation the equidensity contours in the take the (A_s, A_u) space takes the form $A_s^2 + \gamma A_u^2 = B$. Each contour is associated with some density level π (i.e. if point (A_s, A_u) lays on the contour k, the probability (or probability density) that a random draw from the distribution will be (A_h, A_l) is equal to π^k)

Suppose that there are n independent draws of inventions (and so n points (A_s, A_u) a firm can select from). Each draw will be indexed by i. Further, let $F^j = \left(\left(A_s^i L_s^j\right)^\sigma + \left(A_u^i L_u^j\right)^\sigma\right)^{1/\sigma}$ be the output of firm j if it picks the draw i.

Take any point in the (A_s, A_u) space, call it point P. The probability (or probability density) that this point ex-ante (before the realization of the draws) is the optimal point for firm j is given by the probability that the first draw happens to be at point P multiplied by the probability that the first draw is optimal for firm j among all the other draws plus the probability that the second draw will happens to be at point P multiplied by the probability that the second draw is best etc.

$$Pr\left(\left(A_s^P, A_u^P\right) \text{ is selected by country } j\right) =$$

$$= \sum_i Pr\left(\left(A_s^i, A_u^i\right) = \left(A_s^P, A_u^P\right)\right) *$$

$$*Pr\left(\left(A_s^P, A_u^P\right) \text{ is optimal for } j \text{among all the draws}\right)$$

If the point $\left(A_s^P, A_u^P\right)$ lays on the contour k then probability that a draw is exactly equal to $\left(A_s^P, A_u^P\right)$ is given by π^k . The probability that draw i is optimal for country j among all the other draws is in turn equal to probability that the use of any other technologies that popped out will give smaller output:

$$Pr\left(\left(A_s^P, A_u^P\right) \text{ is optimal for } j \text{among all the draws}\right) =$$

$$= \prod_{s \neq i} Pr\left(F^j\left(A_s^s, A_u^s\right) < F^j\left(A_s^P, A_u^P\right)\right)$$

Now consider particular point E that lays on the contour k depicted on figure 4. Probability that a draw happens to be exactly at point E is π^k. Probability that this draw is the best option among all the other draws is the probability that no other draw appears in the shaded area above the isoquant passing through point E - if it does, then selection of that alternative draw (and the associated production function) would result in a higher output and selection of point E would be suboptimal. Observe that point H has exactly the same probability that it will appear as an optimum as point E: it lays on the same contour k and it has exactly the same probability that no other draw will give higher output (i.e. the probability that the shaded area remains empty). Now notice that if we consider any point on the contour k between points E and H, say point F, again they have exactly the same probability they will be drawn in one of the

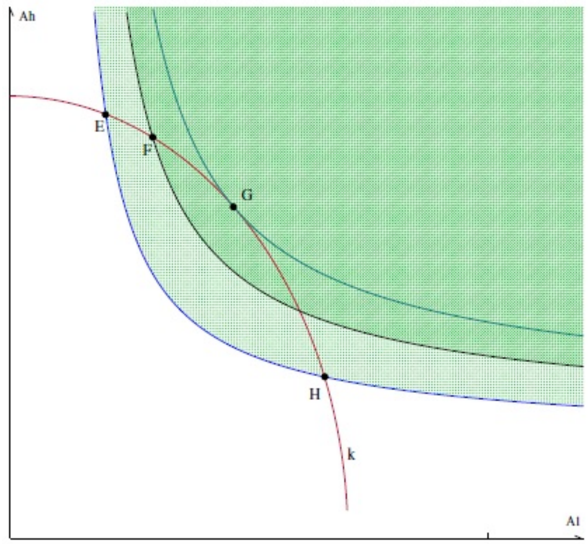

Figure 4: Derivation of density distribution of optimal technology choices

draws (they lay on the same contour) but they have strictly higher probability that no other draw will give higher output. This is because the probability that there exist other draw that will give better output than point F is the probability that this draw will appear in the double shaded area. This area is strictly contained within the single shaded area. Thus the probability that poin E is outperformed has to be higher than the probability that point F is outperformed. The only point on the contour k that for which we cannot find a point with higher probability of being and optimum (among other points on contour k) is point of tangency of the contour with the isoquant. Therefore point G has the maximum probability of being chosen among all the points on contour.

A simple algebra - analogous to the one from Caselli and Coleman model - shows that the point of tangency between equidensity contours and isoquants has to satisfy

$$\left(\frac{A_h}{A_l}\right)^{2-\sigma} = \gamma \left(\frac{L_h}{L_l}\right)^{\sigma}$$

Notice that this condition does not depend on which contour we consider. This means that the mode - the point in (A_h, A_l) space that is most likely to be selected has to satisfy this condition. The condition might be rearranged to the form in the proposition. □

Now consider a bivariate distribution of optimal choices of technologies (ex ante - i.e. before we know which technologies are available to firms). Since proposition 1 tells us that none of the firms will move towards technologies disfavouring skilled workers after they became more numerous (relative to unskilled) and proposition 2 tells us that at least some mass of the distribution of optimal technology choices has to move towards choices that favour more abundant factor we arrive to the final proposition of the paper:

Proposition 3. Consider a bivariate distribution of optimal choices of technologies (ex ante - i.e. before we know which technologies are available to firms). The expected optimal choice must shift towards more skill biased technologies after increase in supply of of skilled labour

6 Concluding Remarks and Policy Implications

The purpose of the paper was to decompose the increase in the college premium growth across the OECD countries into growth caused by global forces (such as skill-biased change in global technological paradigm, the new ICT) and growth driven by local, country level forces related to supply of college workforce. I propose an empirical model which uses both cross-section and cross-time variation in the data to isolate out global from local factors. I find that countries with higher growth of college workforce experience substantially higher college wage premium growth a decade later. Given that the independent variable of interest is lagged ten years it is unlikely that the result is driven by reverse causality.

The results of the regression that includes various control variales suggest that the dependence is not caused by falling importance of trade unions, globalization forces, or endogenous adoption of ICT technology. In this light the most plausible candidate to explain this result is the endogeneuty technology choice: if number of college workers increases firms have an incentive to choose production methods (technologies) that are better suited for skilled workers. This, after some time, drives up demand for educated workers and thus leads to increase in college wage premium. Using the results of the regression we might conclude that country-level mechanism driven by supply of skilled workers (most likely endogenous technology choice at the local level) can explain 30% of the increase of college premium in the OECD countries.

To draw a policy implications we need to consider all effects predicted by the model. The framework presented in section 2 (and supported by empirical evidence from section 3) predicts that an increase in college workforce will first lead to drop of college wage premium (due to diminishing returns to skilled labour) and later (approximately in a decade) to its growth (due to the fact that technology choices of firms will be adjusted to higher supply of skilled workers). The latter growth will be smaller then initial drop, thus the net effect of college workers supply on their relative wages will be negative.

One important lesson policy makers can learn from the model is that a negative effect of increase in college workforce on wage inequality is smaller then predicted by the previous studies based solely on the short-term analysis. The second implication is that any increase in college workforce will produce a substantial fluctuation of college wage premium (it will first drop, later grow). Such fluctuations might lead to suboptimal educational choices of workers. An advise for the policymakers might be therefore to implement policies increasing number of college graduates gradually rather than rapidly.

In the theoretical part I explore the microeconomic foundations of the endogenous technology choice. The heart of the hypothesis is the presence (at any point in time) of a tradeoff: firms might choose between technologies that assign higher productivity to skilled workers and those that assign higher productivity to unskilled workers. The derivation of this tradeoff is therefore vital for entire model. I present a model that demonstrates how the R&D process in which researchers invent a finite number of production processes might generate the trade-off between two types of technologies.

References

1. Acemoglu, Daron, 1998. "Why Do Technologies Complement Skills? Direct Technical Change and Wage Inequality", Quarterly Journal of Economics, 113, 1055-1090.

2. Acemoglu, Daron, 2000. "Technical Change, Inequality, and the Labor Market," NBER Working Papers 7800, National Bureau of Economic Research, Inc.

3. Acemoglu, Daron, 2007. "Equilibrium Bias of Technology," Econometrica, Econometric Society, vol. 75(5), pages 1371-1409, 09.

4. Aghion, Philippe, 2002. "Schumpeterian Growth Theory and the Dynamics of Income Inequality," Scholarly Articles 3350067, Harvard University Department of Economics.

5. Bandiera , Oriana and Imran Rasul, 2006. "Social Networks and Technology Adoption in Northern Mozambique," Economic Journal, Royal Economic Society, vol. 116(514), pages 869-902, October.

6. Berman, E., J. Bound and Z. Griliches (1994): "Changes in Demand for Skilled Labor Within US Manufacturing: Evidence from the Annual Survey ofManufactures", Quarterly Journal of Economics, 109:2, pp.367- 97.

7. Caselli, Francesco and Wilbur John Coleman, 2006. "The World Technology Frontier," American Economic Review, American Economic Association, vol. 96(3), pages 499-522, June.

8. DiNardo, John, Nicole Fortin and Thomas Lemieux, 1995. "Labor market institutions, and the distribution of wages, 1973-1992: A semiparametric approach," Econometrica 64, (1995).

9. Katz, Lawrence F and Kevin M Murphy, 1992. "Changes in Relative Wages, 1963-1987: Supply and Demand Factors," The Quarterly Journal of Economics, MIT Press, vol. 107(1), pages 35-78, February.

10. Leamer, Edward E. 1995. "Trade, Wages and Revolving-Door Ideas," NBERWorking Paper No. 4716 (1995).

11. Peri, Giovanni, 2009. "The Effect of Immigration on Productivity: Evidence from US States," NBER Working Papers 15507, National Bureau of Economic Research, Inc.

12. Samuelson, Paul A., 1965. "A Theory of Induced Innovation along Kennedy-Weisecker Lines", Review of Economics and Statistics, Vol. 47, No. 4 (Nov., 1965), pp. 343-356.

13. Wood, Adrian, 1994. "North-South Trade, Employment and Inequality: Changing Fortunes in a Skill Driven World", Oxford, Clarendon Press, 1994.

14. Van Reenen, John, 2011. "Wage inequality, technology and trade: 21st century evidence," Labour Economics, Elsevier, vol. 18(6), pages 730-741.