Lifetime learning, biased technological change and the evolution of wages in the U.S. 1960 - 1990

Klaus Wälde*, January 96

Stylized facts derived from wage pattern analysis in the U.S. point to the importance of non-standard explanations for changes of relative wage. Learning while working is predicted to be able to account for wage divergence so far unexplained. Increases in productivity differ among individuals due to heterogeneity in learning capabilities which excludes a group of workers from training. This selectivity can explain relative wage changes within as well as between groups. Wage divergence within groups is an equilibrium property in the 1970s. It was not observed before since other relative wage neutral investments were more profitable. The introduction of new production processes at the beginning of the 1980s leads to either a limited but permanent or unlimited increase in relative wages between groups. The latter happens if labor is substituted for by human capital and physical capital. It is shown how to empirically distinguish between these explanations.

1. Introduction

The evolution of relative wages in the United States during the last three decades has been the subject of many studies. Especially the apparent increase in the skill premium in the 1980s has caught the attention of many authors but longer time periods have also been covered. Most of the studies combine descriptive with explaining elements.

Probably the most "theory free" approach to a description of relative wage movements is to describe the *overall* distribution of real weekly or hourly wages. Juhn, Murphy and Pierce (1993) base their analysis on the March supplement of the Current Population Survey (CPS) and focus their attention on the distribution of real hourly wages of full time working men (for more precise information, cf. their paper). Measuring relative wages by the ratio of the 90th to the 10th percentile in this distribution, they show that wage ratios stayed fairly constant in the 1960s but then rapidly increased. The increase was caused, roughly speaking, by an increase of real wages which were above the median in 1970 and a decrease of wages below the median. Borrowing log wage differentials from Goldin and Margo (1992) shows that the 90th percentile of weekly wages was 2,9 times higher than the 10th percentile in 1950, increased slightly to about 3,2 times in 1960 and 1970 to then rise further to 3,7 and 4,3 times as much as the 10th percentile in 1980 and 1988. A more detailed way of describing the evolution of wages is to focus on wage ratios *between* and *within* groups, e.g. between men and women or between education and experience groups. Juhn, Murphy and Pierce (1993, fig. 5 and 6) show that the ratio of wages between experienced and inexperienced workers (21 to 30 years of experience vs. 1 to 10 years) increased from 1964 to 1988 by about 22% as did the wage ratio of college to high school graduates. The same figures show that also within groups wage dispersion has increased. Increases from 1964 to 1988 of the 90th to 10th percentile ratio range from about 25% for high school graduates to about 43% for experienced workers.

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* Tinbergen Institute and University of Amsterdam, Department of Macroeconomics, Roetersstraat 11, 1018 WB Amsterdam, The Netherlands. Email: k.waelde@sara.nl.
Financial support by the Human Capital and Mobility Programme of the EC is gratefully acknowledged. I would like to thank participants of various seminars for helpful comments, especially Casper van Ewijk, Paul Frijters, Cecilia García-Peñalosa and Sweder van Wijnbergen and Daniel Tsiddon for very helpful discussions and encouragement. I myself am responsible for remaining shortcomings.

A first step towards explaining or interpreting the data is usually to ask the most natural question of how much of wage changes can be explained by changes in supply. Katz and Murphy (1992) and Murphy and Welch (1992), e.g.[1], subdivide the labor force into subgroups distinguished by experience and education and test whether changes of supply and wage changes are negatively correlated. Both studies conclude on this point (Katz and Murphy, 1992, Table III; Murphy and Welch, 1992, p.309) that the change of relative wages between groups can until the end of the seventies indeed be reasonably explained by changes in the supply of labor groups alone. Afterwards, in the 1980s, a change in relative demand must have occurred. Juhn, Murphy and Pierce (1993, sect. 4) do a similar analysis. They decompose the evolution of the wage distribution under consideration into changes in the distribution of observables like experience or education, into changes of prices of observable skills and a residual which stands for all unobserved components. The central finding is that changes in *un*observed for the entire period and prices for observed characteristics in the 1980s are the major source of the increase in inequality. Hence, education biased demand sets in a decade after biased demand for unobserved variables, a fact which led them to conclude that these two phenomena are independent. Since similar demand shifts were also found by, among others, Bound and Johnson (1992), this first step of an analysis shows unambiguously that supply shifts alone are not enough to explain relative wage movements.

The next step consists in testing different hypotheses on demand shifts. Among the most common[2] are international trade, structural change, de-unionization and biased technological change. The extent to which increasing internationalization of the U.S. economy can be put forth as an explanation for wage divergence is subject of an ongoing debate (Burtless, 1995). Different points of view in this debate result from different opinions about how to best study the relationship between increasing international trade and domestic wages. On the one side are studies measuring the factor content of trade (Murphy and Welch, 1991; Borjas, Freeman and Katz, 1992; Sachs and Shatz, 1994; Wood, 1994). The idea is to decompose trade volumes into embodied quantities of labor and interpret these labor quantities as increasing or decreasing domestic demand. If a country is a net importer of low-skilled-labor intensive goods, domestic demand for low-skilled labor falls as trade expands and wages of low-skilled decrease. This approach is criticised for its weak foundation in trade theory and little information it provides for drawing conclusions on causality (e.g. Deardorff, 1994; Leamer, 1994). A different approach, based on the Stolper-Samuelson Theorem, is followed by Lawrence and Slaughter (1993). They relate relative wage changes between production and nonproduction workers to relative price changes of production worker intensive goods and technological change. Since they find that the relative price on nonproduction-labor intensive goods did not increase, no link between relative wages and international trade based on the Stolper-Samuelson Theorem can be drawn. One drawback of this approach (as criticised by Leamer, 1994) is the distinction between production and nonproduction workers which is far from representing a clear-cut distinction between low- and high-skilled workers. Despite these different approaches, a conclusion that can be drawn from these studies is that trade did contribute to some extent to a widening of U.S. domestic wage gap but is far from being the only source. Estimates range from virtually no impact of trade on wages of low-skilled to up to 50% reduction in the demand for low-skilled due to increasing international trade (Wood, 1994, as cited by Burtless, 1995, p. 813).

The hypothesis that structural change, partly an outgrowth of international trade, can cause demand shifts between education groups (Katz and Murphy, 1992) is motivated by their heterogeneous distribution across industries. Assuming that relative within-sector demand for factors is constant,

[1] Studies of this type have been done before, see, e.g., Freeman (1979), Welch (1979).

[2] For a first overview and further references to the literature, cf. the symposium in Economic Policy Review (1995) and the survey by Levy and Murnane (1992).

structural change leads to changing demand for factors. Katz and Murphy find, however, that shifts in the composition of the U.S. economy are not large enough to explain demand shifts that are necessary to account for observed relative wage changes. Hence, structural change alone is not enough to explain shifts in relative demand. Freeman (1992) considers the effect of de-unionization: since the variance of earnings among unionized workers is lower than among non-unionized workers, a decrease in unionization can be expected to increase wage inequality among workers. In fact, Freeman argues that 15 - 40 percent of the rise in the college premium can be attributed to de-unionization. He further stresses, however, that wage divergence was just as pronounced among union as among non-union workers. Hence, in terms of growth theory, unions do have a level effect, but cannot exert a growth effect.

The most common argument put forth to explain relative demand shifts is biased technological change (BTC). Bound and Johnson (1992) use CPS data to investigate structural change, union power, supply and technological change as possible explanations for relative demand shifts. They conclude, after having excluded other possibilities, that technological change in the 1980s must have been non-neutral, favouring high-skill workers. As they stress, the main difficulty with this result is that it is not based on directly observable phenomena. Berman, Bound and Grilliches (1994) do a similar analysis based on the Annual Survey of Manufacturers. They decompose the overall increase (starting in the 1960s) of the share of nonproduction workers in total employment and find that this shift took mainly place within rather than between industries. They thereby exclude international trade or the increase in defence expenses as a driving force for increased demand for nonproduction workers. They further argue to provide direct evidence for BTC by estimating the importance of investment in computers and R&D expenditure. Indeed, these two factors together account for 70 percent of the employment shift towards nonproduction workers. Further direct evidence is provided by Krueger (1993). A variety of estimations show a significant positive link between the use of computers at work and the level of wages. Letting computers represent technological change, this establishes a direct link between the introduction of new technologies and changing relative wages.

The aim of the above discussion was to see how much of wage dynamics in the U.S. can be understood by standard economic theories. Due to the apparent lack of adequate explanations, the notion of biased technological change has been frequently used and argued to be an important mechanism to be taken into consideration. Since well-defined concepts of BTC are missing in this context[3], however, no indications for further investigation into BTC as a source of wage divergence are available. In addition, empirical findings call for a consistent interpretation from which policy recommendations can be derived. It is the scope of this paper to construct a simple framework which (i) is capable to reproduce observed wage patterns, (ii) thereby identifies channels through which *biased technological change* acts, (iii) distinguishes it from "normal" wage divergence, to be termed *lifetime learning effect* and (iv) allows an evaluation of the necessity and consequences of policy measures. Hence, the intention is not to only contribute to economic theory itself. The building blocks of the model are well-known though the composition is novel. The main contribution lies in the application of theory to understand certain empirical regularities. This "translation from empirics to theory" leads to a sharpening of concepts, ideas and relationships used and stipulated in empirical work. Clearly, many other theoretical papers frequently refer to empirical findings but this is more often done for justifying assumptions rather than understanding these findings.

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[3] The direction of technological change was a major field of research in the 1960s (cf. e.g. Kennedy, 1964; Samuelson, 1965; a detailed overview is given in Binswanger and Ruttan, 1978). It was not concerned with distributional issues between different groups of labor but rather between labor an capital.

The next section explains the strategy followed in this paper, works out the stylized facts to be accounted for and sketches a theory. Biased technological change and the lifetime learning effect will be defined. The third section presents the model and discusses its properties. The forth section focuses on the relationship between savings, training and the evolution of wages and discusses important assumptions. The fifth section will give an interpretation of wage dynamics as observed in the U.S. in terms of the theory and relates concepts introduced in the paper to well-known growth models. Section six discusses empirical implications of this theory and works out predictions that have to be tested in order to allow for further development and refinement of the present approach. The final section concludes and points out remaining questions worthwhile being considered in future work.

2. The approach, stylized facts and a theory

Apart from a brief discussion in the final section, it is beyond the scope of this paper to discuss schooling decisions of households. The above short summary of empirical findings will be condensed to stylized facts that give a picture of the evolution of wages that would have taken place *if the share of more to less skilled labor in terms of years of schooling had been constant.* Clearly, this is contradicted e.g. by the increase of the average education level of labor input (e.g. Katz and Murphy, 1992, Table II). Supply effects on relative wages, however, are well understood and it is generally accepted that relative wage changes can not be explained by supply shifts alone. This is equivalent to saying that the model to be presented here wants to account only for changes in relative demand for factors of production. This does, of course, not mean that the model is incapable to incorporate supply shifts but will consider them to be exogenous. Given this approach, the stylized facts to be accounted for are the following: the sixties are a period of constant relative wages, both within and between groups. Starting in the seventies, overall wage divergence increased, though relative wages between groups stayed constant. In the eighties, divergence of wages within groups continued, now accompanied by wage divergence also between groups.

From this highly stylized picture, three main questions emerge: first, under what circumstances do wage ratios first remain constant and then diverge? In other words: why does demand at a certain point become biased? Second, what are the reasons for biased demand? Third, what is the driving force behind wage ratios that follow a different pattern between and within groups? The interpretation offered is the following: imagine a growing economy endowed with different factors of production. Such an economy can save in different ways, either by accumulating physical capital or by increasing the quality of its labor force. With respect to the first question, it will be argued that the *potential* for wage divergence has always existed but was not called on. Differentials between individuals come to light only when they gain in importance. Hence, a period of "sleeping divergence" will be argued to result from investment in other forms than increasing the quality of the labor force, e.g. in physical capital. At a certain point, however, the returns to invest in capital[4] can be expected to be too low, either because of increasing stocks and decreasing returns to capital or because of more sophisticated production technologies that could not be implemented profitably without the appropriate labor force. Then, skills acquired before working are no longer sufficient and training the labor force becomes profitable. The term training will be used here for all measures that increase individual productivity at the workplace, that are costly (e.g. in terms of forgone production or earnings) and take place while employed by a firm. Training includes formal courses but also simply time spent by an individual at his workplace acquiring new skills that are

[4] The term capital is sometimes used as an abbreviation for *physical* capital. Human capital will always be denoted by *human* capital.

required by a new technology or production process. When training takes place, changing relative wages due to shifts in relative demand are caused by two mechanisms: the lifetime learning effect (LTLE) lying at the origin of relative wage changes within groups and biased technological change causing wage changes between groups.

Starting with relative wages within groups, the simple reason for a diverging wage evolution lies in the selectiveness of training. Some workers or employees have higher learning capabilities, are faster in adapting to new and generally more sophisticated technologies than others. As a consequence of heterogeneity in their abilities to learn (whose origins and dependence on economic circumstances will be discussed below), only the "faster" group of workers will obtain (formal) training or be selected to work with new technologies. Hence, due to learning which can be expected to last an entire lifetime, productivity of this subgroup increases, whereas productivity of those obtaining no further education stays constant. This LTLE is defined as the ratio of effective hours worked of a fast-learner to the effective hours worked of a normal learner after a certain time span. It can be measured in percent as the ratio of hourly wages of individuals with identical education as a function of experience. BTC changing relative wages between groups comes in two guises. In a weaker form it leads to a change in relative training costs. Human capital biased technological change is then defined as a permanent decrease in the ratio of the cost of one unit of human capital to one unit of labor. If training for one group becomes more costly relative to another group, e.g. due to more complex concepts or techniques to be learned, only the group promising higher returns will be trained. The change in relative wages is persistent but limited. A second, stronger form of BTC leads to changes of relative wages between groups as a result of a restructuring of the production process. The restructuring considered here replaces labor by human capital and physical capital and, once implemented, leads to wage divergence between groups that does *not* peter out. These are the reasons for biased demand and answers question two. With respect to question three, shifting demand between groups occurring much later than shifting demand within groups is the result of introducing sophisticated technologies that were not available before. Under the changing training costs scenario, this "technology shock" leads to a limited divergence of between groups wage ratios, whereas a restructuring scenario predicts wage ratios between groups that increase at a constant rate.

Another way of viewing the central point of the selective feature of training on the job is to argue that experience is not as homogenous across groups as is usually assumed in wage regressions. It is reasonable to expect that on average years of experience are a good proxy for increasing productivity which implies higher wages; it should also be true that on the individual level increases in productivity due to learning-by-doing are a monotonic function of experience. The point here is that training on the job – as organized and financed by firms – is a zero-one decision: either one takes part in a programme (or less formal related activities) or one does not. Since the decision of being trained depends on abilities to learn, originally small differences in endowment can lead to very high differences in productivity. Further, one does not necessarily, as suggested by Rosen (1992), have to introduce higher order polynomials in experience to explain the recent wage evolution: to the extent that higher returns to experience are the result of higher learning possibilities or more intensive training while working, these effects can be captured by controlling for training on the job.

Individual heterogeneities in ability to learn and adapt to changing environments on their job, the central assumption of this paper, might to a certain extent be innate but are to a much bigger extent determined by the relationship between the quality of the education preparing for (and hence prior to) the jobs and the technological know-how required in office or on the shop floor. Since this paper takes supply decisions as given, the education induced differences in abilities to learn are also fixed. It therefore studies the consequences of heterogeneities in abilities to learn. The relation between the quality of an education system, ability distributions and technology will be the focus of future work; its basic relationships will be sketched in the Conclusion. For the arguments in this paper it is important to keep in mind that abilities are not exogenously imposed on individuals but are the result of economic decisions and can therefore be changed.

Other papers have also followed a theoretical approach to study the evolution of relative wages. Acemoglu (1995) bases his analysis on an imperfect matching framework and derives many interesting results with respect to the interaction between skill composition of the workforce, wage inequality, GDP growth and the impact of institutions. At various stages, Acemoglu shows how findings can be used to explain international evidence on the evolution of wages. Bertola and Ichino (1995) present a model where labor is subject to permanent productivity shocks. They characterize a flexible labor market by allowing wages to differ between high and low productivity firms and by allowing firms to fire employees. In a rigid labor market, institutions assure equalization of wages between firms and firing costs are prohibitively high. They then go on using this framework to interpret U.S. vs. European labor market experience. Neither of these studies, however, tries to account in a unified framework for the wage time-series evidence of the U.S. and give a precise interpretation of specific events such as the rise in overall inequality in the 1970s and the increasing inequality between groups in the 1980s as identified by the empirical literature. The present paper takes as a starting point empirical findings and translates them into a model tailored to understand the history of the U.S. labor market. This allows for further refinement of explanations proposed in the literature and a straightforward evaluation of the suitability of different policy options. Galor and Tsiddon (1994) develop a model that allows to analyze the interaction of technological change and the incentives to accumulate human capital. Though their main concern is a theoretical study of how human capital accumulation and technological change interact to determine the distribution of income, they argue at some point that their model can help to understand American wage dynamics in the 20th century. One of the driving forces in determining the evolution of income distribution is family background (cf. also Glomm and Ravikumar, 1992; Galor and Zeira, 1993; Galor and Tsiddon, 1995) which has strong empirical support. This relationship is neglected here in order to stress the importance of factors determining individual ability that are subject to economic decisions and are not as unavoidable as family background. The crucial difference is the focus of the present paper on abilities to adopt new technologies and to endogenously study who will benefit more from technological change in the form of increasing job complexity. Hence, human capital accumulation is considered that takes place while working, and not while young, hence when individuals usually have left the sphere of "parental spillovers".

3. The model

This section presents the general framework within which the evolution of wages will be discussed. It will first describe the different types of consumers in the economy and work out in what economically important dimensions they differ. It then presents the production technology and saving possibilities and finally discusses general properties of the model.

3.1. Consumers and labor supply

Utility of a representative household at time t stems from a stream of future consumption, discounted at the time preference rate ρ , and is given by

$$U(t)=\int_t^{\infty}\exp\left[-\rho(\tau-t)\right]u(\tau)d\tau. \quad (1)$$

Instantaneous utility $u(\tau)$ depends on consumption C of a homogenous final good and takes the form $u(\tau)=\left(C^{1-\sigma}-1\right)(1-\sigma)^{-1}$, reflecting an intertemporal elasticity of substitution of $1/\sigma$. All individuals have identical preferences but differ in the type of labor they supply. The labor force consists of N individuals of which N_H attended college, whereas $N_L=N-N_H$ attended high school before they enter the labor force. To relate these groups to standard notation, one can think of college graduates supplying human capital and high-school graduates supplying labor[5]. Each group can be divided into two subgroups consisting of high- and low-ability graduates which makes in total four groups. The easiest way to think about high- and low-ability individuals consists in dividing them into those leaving school with better and those with worse marks. Differences in ability reflect differences in how easily individuals acquire new skills or – more generally – how fast they are in learning. It is one of the scopes of this paper to study the implications of lifetime learning – learning that does not stop when leaving school but continues while working . Heterogeneities in speed of learning are captured by introducing parameters that represent cost differentials in training of certain subgroups. If, e.g., a high-ability college graduate (hence one with a good school report) receives training for some short time period *dt* and pays some investment costs *I* per unit of time, covering expenses for teachers or teaching material, her productivity increases by one unit, $d\overline{\Pi}=1dt$ (cf. Figure 1). If a low-ability college graduate receives training for the same length of time *dt* and with the same monetary support *I*, her productivity increases by $d\underline{\Pi}=b^{-1}\,dt$ only, where $b>1$. An identical relationship for training costs differentials will be assumed to hold between high- and low-ability high-school graduates. Comparing the productivity increase of a college and a high-school graduate who have the same ability to learn new skills required in their jobs and who receive identical training, it will be assumed that the productivity increase of the college graduate will be *d* times the increase in productivity of a high-school graduate. No a priori assumption is made on the value this parameter takes, apart from being positive.

	College graduates (Human capital)	High-school graduates (Labor)
High ability	$\overline{N}_H$, 1	$\overline{N}_L$, d^{-1}
Low ability	$\underline{N}_H$, b^{-1}	$\underline{N}_L$, $(d\,b)^{-1}$
Effective supply of hours worked	$H=h\,\overline{N}_H+\underline{N}_H$	$L=l\,\overline{N}_L+\underline{N}_L$

Figure 1: Number of workers and productivity increases per labor group

The amount of human capital H supplied inelastically to the economy is given by the effective or quality augmented hours worked of college graduates which is the sum of $\overline{N}_H$ high-ability college graduates and $\underline{N}_H$ low-ability college graduates, $H=h\,\overline{N}_H+\underline{N}_H$. The endogenous productivity differential between individuals is given by *h*. It can have any level when individuals start working, but it will increase over time, if training and learning while working takes place. The amount of labor, supplied

[5] The terms human capital and labor are used here instead of the terms high- and low-skilled, respectively, which are more frequent in the literature. This is to avoid confusion with the terms high- and low-ability to be introduced now.

inelastically as well, consists of quality augmented hours worked of $\overline{N}_L$ high- and $\underline{N}_L$ low-ability high-school graduates, $L = l\,\overline{N}_L + \underline{N}_L$. The productivity differential between low- and high-ability high-school graduates is also endogenous and given by l.

3.2. Production and investment technologies

The aggregate production function of the economy is characterized by constant returns to scale using physical capital K, human capital H and labor L as inputs. The amount of schooling an individual has obtained before going to work determines the type of job she obtains. This means that high- and low-ability individuals are perfect substitutes in the sense that e.g. one high-ability high-school graduate can be replaced by l low-ability high-school graduates (and vice versa) if the current productivity differential is given by l. Capital, human capital, and labor, however, can be substituted only imperfectly: there is perfect substitutability within groups but imperfect substitutability between groups. Due to the emphasis that will be put on increasing the productivity of all factors of production and the impact this has on relative rewards[6], a CES production function with an elasticity of substitution $\varepsilon = (1-\theta)^{-1}$ differing from unity is assumed,

$$Y = \left(K^\theta + H^\theta + L^\theta\right)^{1/\theta}, \qquad \theta < 1,\ \theta \neq 0. \tag{2}$$

The efficiency and distribution parameters usually appearing in such a function (Arrow et. al., 1961) have been normalized to unity and set equal to $1/3$, respectively, since they play no role in the following analysis of changes of relative factor rewards.

An economy can invest in several ways. It can e.g. accumulate physical capital, increase the quality of its labor force or of its capital stock or diversify final output. To give an interpretation of wage dynamics as observed in the U.S., only the first two aspects will be taken into consideration, accumulation of physical capital and improvement of the quality of the labor force. Simplifying, the latter can be divided into (*a*) education at school, university or during apprenticeships and (*b*) training or learning while working. Schooling leads to general knowledge and basic capabilities which does, however, not fully exploit learning capacities of individuals. Further more specialized schooling, however, is not optimal before individuals know which specific job they are going to work in. Once this decision has been made, further profitable investment in human capital can be made[7]. This improvement of the quality of the labor force while working, hence *after* a decision for a specific job has been made, will be treated here. It encloses formal training by firms, be it in-house or external to a firm, as well as non-formal training such as learning-on-the job[8].

Investment is a normal production activity and requires the allocation of factors to obtain an increase in the stock of capital or the quality of the labor force. To avoid unnecessary complications and without loss of generality, both the production of capital goods and the learning technologies are assumed to be identical to the technology to produce final output Y. Hence, the goods market clearing condition reads

$$\dot{K} + \dot{H} + d\,\dot{L} = Y - C. \tag{3}$$

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6 A comparison of the human capital theory with signalling theories of wage levels and differentials is provided by Weiss (1995).

7 Another interpretation of gradual building up of human capital over the entire life time bases on the trade off between working and learning (Ben-Porath, 1967).

8 A detailed discussion of enterprise-related training can be found in OECD (1991).

The specification for the accumulation of physical capital is the usual relation between investment and savings. The second possibility of this economy consists in increasing the *effective* number of hours worked by increasing the quality of college or high-school graduates. It will be assumed throughout the paper that all investment is irreversible, which means that a unit of capital can not be instantaneously be transformed into one quality unit of labor or vice versa. The accumulation constraint can be seen as a simplified version of Rebelo (1991) or Lucas (1988)[9].

3.3. Solution of the model

The socially optimal allocation of factors is achieved by maximizing a social welfare function obtained from summing over utility functions of individuals as given in (1) subject to the constraint (3), given the production technology (2). Given the absence of any technological or pecuniary external effects or other distortions, this outcome will be identical to factor allocation in a decentralized economy. The optimal sequence of investment allocations is dictated by returns to investment. Many different sequences of investment decisions are possible in this model (six in total), depending on the relative scarcity of factors and relative training costs as captured by parameters b and d. This subsection will assume that initially physical capital is the most scarce factor of production, hence, a situation in which the return to an additional unit of capital is higher than the return to an increase in the quality of workers. The criterion to distinguish returns of different investments is how much they increase total output. Given some investment I for some short time period dt in a factor that can be accumulated, the productivity of labor and human capital would increase by an amount as shown in figure 1 and the stock of capital would increase by[10] 1. This increase in the stock then increases total output. More formally, returns to investment are given by

$$\frac{\partial Y}{\partial I} = \frac{\partial Y}{\partial V}\frac{\partial V}{\partial I},$$

where the first term captures the scarcity of the factor and the second one its training or accumulation costs. Hence, returns to investment are Y_K, Y_H and $d^{-1}Y_L$ for physical capital, human capital and labor, respectively. Returns to accumulation of capital exceed returns to training labor if labor is relatively abundant compared to capital, given relative training costs,

$$\left(\frac{K^\theta + H^\theta + L^\theta}{K^\theta}\right)^{\frac{1-\theta}{\theta}} > d^{-1}\left(\frac{K^\theta + H^\theta + L^\theta}{L^\theta}\right)^{\frac{1-\theta}{\theta}} \Leftrightarrow L > d^{-1/(1-\theta)}K. \qquad (4a)$$

The analogous condition for human capital reads

$$H > K. \qquad (4b)$$

Whenever condition (4) holds, the model reduces to a CES version of a standard Ramsey growth model, since $\dot{H} = \dot{L} = 0$. The solution of the central planner then yields a decreasing consumption growth rate of $g \equiv \dot{C}/C = \sigma^{-1}(r - \rho)$, where the market interest rate r is given by the marginal productivity of capital Y_K. Eventually, returns to investment in capital must equalize to returns to investment in one of the education groups. Taking as an example human capital, $Y_K = Y_H > d^{-1}Y_L$, this

[9] The lab-equipment model version of Rivera-Batiz and Romer (1991) has a similar accumulation constraint, allowing for an increase in the capital stock and the number of firms in an economy. Barro, Mankiw and Sala-i-Martin (1995) also have a similar accumulation constraint but do not consider transitional dynamics and ask different questions.

[10] Consistency of figure 1 with equation (3) requires normalization of I to unity.

equalization condition reads $H = K$. As a consequence, a second period (which is one of two theoretically possible second periods) will be characterized by investment in the productivity of human capital *and* in physical capital, whereas $\dot{L} = 0$. Returns to investment in physical and human capital continue to fall, whereas returns to investment in labor increase. This convergence of returns continues until complete equalization is achieved at the moment where $K = H = L\,d^{\,1/(1-\theta)}$. Capital accumulation is accompanied by training of all labor groups and the economy is on its long-run balanced growth path. The production function (2) becomes (cf. appendix)

$$Y = K\left(2 + d^{-\theta/(1-\theta)}\right)^{1/\theta}, \qquad (2')$$

the change of the quality of labor is related to capital accumulation by $\dot{K} = \dot{H} = d^{\,1/(1-\theta)}\dot{L}$ and the goods market clearing condition (3) simplifies to

$$\dot{K} = \left(2 + d^{-\theta/(1-\theta)}\right)^{-1}(Y - C). \qquad (3')$$

In that case, assuming that the utility function is bounded which is given if $(1-\sigma)g - \rho < 0$, where g is the long-run consumption growth rate, maximizing subject to the goods market clearing condition yields a time path of consumption growing at a constant rate g of $g = \sigma^{-1}(r - \rho)$, where $r = \left(2 + d^{-\theta/(1-\theta)}\right)^{1/\theta}$. By solving for the time path of capital and applying the transversality condition of the maximization problem shows that on the balanced growth path, the capital stock grows at the same constant rate g, as does total output.

The model leads naturally to a positive long-run growth rate without introducing linearities justified by learning by doing, public stock of knowledge or other externalities. It further does not have the sometimes lamented scale effect of the growth rate and is not characterized by the knife edge properties with respect to the specification of external effects as most endogenous growth models. Investment is a constant share of total output and is divided between capital accumulation and augmentation of the quality of the labor force. The interest rate is constant on the balanced growth path and transitional dynamics can easily be analyzed. Clearly, the long-run growth rate is positive since all factors of production can be accumulated, as was emphasized by Rebelo (1991).

The behaviour of this example economy can be summarized by the phase diagram in figure 2, where for simplicity only two periods are covered, a first one in which no training takes place and a second in which both labor groups are trained. This is identical to assuming that the returns to investment in both labor groups are identical, i.e. $H = L\,d^{\,1/(1-\theta)}$ already from the beginning of the accumulation process. Assume the economy starts at t_0 with a capital stock K_0. The growth rates of both capital and consumption then exceed the BGP growth rate but decrease over time. Wages increase and the interest rate decreases. The economy follows the usual Ramsey timepath until the capital level $K = H$ is reached where training the labor force becomes profitable. The figure is drawn for agents who anticipate changing investment possibilities which allows them to choose a consumption level at t_0 such that no jump in consumption takes place when training sets in. Such a jump could be expected if training came as a surprise. At this point, defined by $Y_K = Y_H$, the economy starts a linear path on which growth rates of consumption and capital are identical and constant. The initial consumption level C_0^{II} is proportional to the initial capital stock $K_0^{II} = H$. By (2') the zero motion locus for capital accumulation also becomes a linear ray (starting from the origin) whose slope is larger than the one of the growth path as long as there is a positive growth rate.

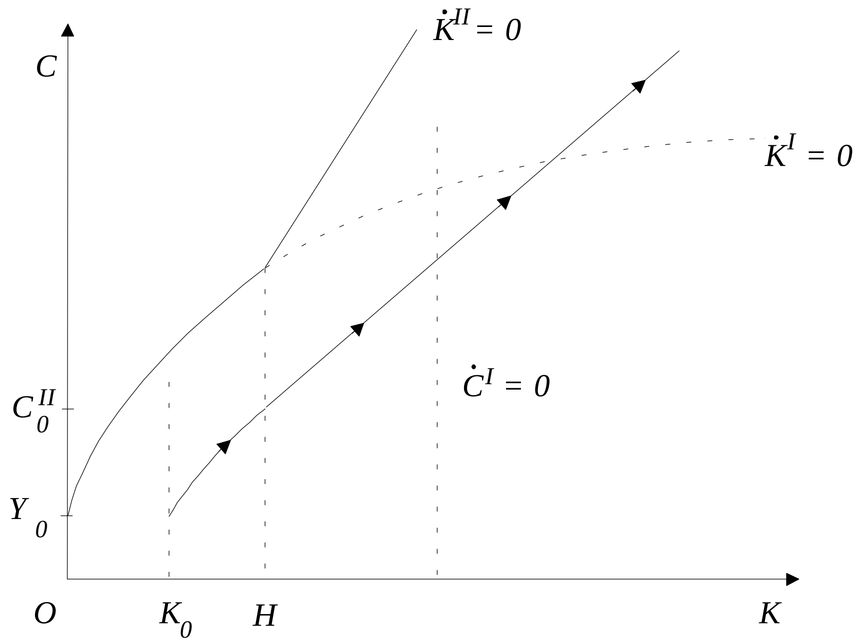

Figure 2: Investment sequence and capital accumulation

4. Capital accumulation, training and wages

So far the description of the model has concentrated on the sequence of investment decisions. A first subsection will now look at the implications of investment in capital and training on wages. The discussion will be formal and not refer to the U.S. labor market. An easily accessible discussion of the American wage evolution will follow in the next section. The second subsection discusses central assumptions and implications of the theory.

4.1. Wages and investment

The implications of investment allocations on wages can most easily be seen when considering a more detailed version of the production function (2) that takes heterogeneity within groups explicitly into consideration,

$$Y = \left(K^{\theta} + H^{\theta} + L^{\theta}\right)^{1/\theta} = \left(K^{\theta} + \left(h\,\overline{N}_H + \underline{N}_H\right)^{\theta} + \left(l\,\overline{N}_L + \underline{N}_L\right)^{\theta}\right)^{1/\theta}.$$

With profit maximizing firms, labor income of an individual is given by the value of her marginal product, $\overline{w}_L \equiv \partial Y / \partial \overline{N}_L = Y_L\, l$ and $\underline{w}_L \equiv \partial Y / \partial \underline{N}_L = Y_L$, where Y_L denotes the marginal productivity of labor as a whole. Wages for college graduates are given by $\overline{w}_H = Y_H\, h$ and $\underline{w}_H = Y_H$, hence within groups wage ratios are

$$\overline{w}_H / \underline{w}_H = h \quad , \quad \overline{w}_L / \underline{w}_L = l. \tag{5}$$

These expressions point to the basic mechanism that will be used here to provide a possible explanation for the evolution of wages. The ratio of factor rewards of high- to low-ability workers *within* a group changes only if the endogenously determined productivity parameters l or h change. If the latter are constant, the level of wages of both groups can increase through physical capital accumulation that increases the marginal productivity of the labor force as a whole, with relative wages staying constant. The wage ratio *between* groups can be derived from weighted averages of wages within groups. With $w_H = \left(\overline{w}_H \overline{N}_H + \underline{w}_H \underline{N}_H\right)/N_H = Y_H\, H/N_H$, $w_L = Y_L\, L/N_L$ and $Y_V = (Y/V)^{1-\theta}$, $V = H,\ L$, it reads

$$\frac{w_H}{w_L} = \left(\frac{H}{L}\right)^{\theta} \frac{N_L}{N_H}, \tag{6}$$

hence, it decreases when there are more college graduates N_H but increases in their quality H.

Wage dynamics *between* groups can be easily analyzed since they are monotonically related to the economy's factor endowment with human capital and labor (6). Following the same investment pattern as in the discussion of the solution of the model in the last section, a first period of investment allocated exclusively to physical capital accumulation witnesses an increase of productivity of both labor groups at the same rate. Hence, absolute wages increase and relative wages (6) remain constant. When returns to investment in physical capital equalizes to returns to investment in human capital, this second period will be characterized by training of college graduates *and* physical capital accumulation. This is equivalent to saying that human capital is accumulated and that by (6) the wage ratio increases. Eventually, training labor becomes profitable and the economy finds itself on the balanced growth path. The stocks of all factors of production increase at the same rate and the college-high school wage ratio (6) is constant again and reads, after inserting the equilibrium condition $H = L\, d^{\,1/(1-\theta)}$,

$$\frac{w_H}{w_L} = d^{\frac{\theta}{1-\theta}} \frac{N_L}{N_H}. \tag{6'}$$

In order to understand relative wages *within* groups, it is useful to rewrite the accumulation constraint (3) in more detail as

$$\dot{K} + \dot{\overline{H}} + b\,\dot{\underline{H}} + d\left(\dot{\overline{L}} + b\,\dot{\underline{L}}\right) = Y - C.$$

Again, assume that the economy finds itself with a factor endowment that makes training of college graduates profitable. Since they differ in ability to learn, $b > 1$, it is more costly to increase the quality of low-ability individuals than the productivity of their high-ability colleagues. As a consequence, all training will be concentrated on high-ability individuals and $\dot{\underline{H}} = 0$. This leads to an increase of the relative productivity measure h which implies increasing within group wage divergence (5). A similar argument can be made for labor.

The long run implications can be most easily seen when considering the balanced growth path where the economy eventually ends up. It is characterized by constant relative wages between groups (6'). Factor rewards for both college and high-school graduates with low ability are constant whereas high-ability individuals' wages increase at a rate higher than (but asymptotically approaching) the economy's GDP growth rate g. Constant real wages for low-ability individuals are the result of two opposite effects. Taking as example labor, investment in the quality of high-ability labor reduces demand for low-ability labor, since they are perfect substitutes. Investment in physical capital and human capital increases productivity of low-ability labor. These two effects exactly offset each other on the balanced growth path. An immediate implication is that the income share of low-ability workers in total human capital and labor income decreases over time and approaches zero. On the balanced growth path, the share of labor and human capital income in GDP is constant.

The crucial difference between wage ratios within and across groups is that an increase of the latter is constrained by decreasing returns to accumulation of one factor of production and hence is a transitional phenomenon, whereas the former can grow with much less technological constraints and will eventually be limited only by individuals leaving the labor force.

4.2. Discussion

This subsection focuses on three aspects. First, the central difference to the literature treating heterogeneities of learning capabilities will be stressed. Second, the role that capital accumulation plays in this model is worked out. Finally, an interpretation of an important empirical finding is given.

There are two crucial aspects characterizing the above interpretation, heterogeneity of individuals and the financing by firms of learning while working. The fact that some individuals learn faster than others though they have obtained the same education is quite obvious and its consequences have often been analyzed in the literature. The second aspect that a training investment is preceded by a deliberate decision of a firm, or in general of investors, with respect to whom to train might also seem natural but this is precisely the difference between this model and the literature that treats heterogeneity of individuals of one sort or another. The literature on optimal human capital accumulation builds on the work of Becker (1962; 1964) and Mincer (1958; 1974). Ben-Porath (1967), Blinder and Weiss (1976), Heckman (1976) or Killingsworth (1982), consider self-financing of human capital accumulation and do not examine the *selection* effect of heterogeneity of individuals in learning capabilities. If heterogeneous learning abilities are taken into consideration, higher ability is predicted to lead to longer years of schooling and thereby higher wages and human wealth (Willis, 1986) or they are used for comparing different outcomes of saving decisions as a function of ability (Heckman, 1976). The issue that small differences in ability are crucial for the decision of whether to receive training *at all* has not been taken into consideration.

This paper adopts the view that in an economy with a labor force characterized by an invariant quality, growth must eventually peter out when the marginal product of capital approaches the time preference rate. Hence, a positive long-run growth rate requires a continuous increase of the quality of labor accompanying the increase of the capital stock. While it is true that positive long-run growth rates can be explained e.g. by labor augmenting technological progress or increasing productivity of capital, there should be no doubt that increasing the education level of the work force is one crucial aspect of increasing economic prosperity. A reading of this relationship between capital accumulation and education is that an ever increasing capital stock per worker can take on two forms. Either capital accumulation simply means (*a*) an increasing stock of generally useful investments like roads, buildings, railway, infrastructure in general, or simple investments that increase the quantity of capital controlled by a worker or (*b*) it increases the quality of machines, thereby their complexity and the complexity of a job. Capital deepening is usually not referred to as being equivalent to increasing job complexity. In this paper, however, it is argued that the moment when it becomes profitable (or necessary) to increase the quality of the labor force delimits the end of simple increase in quantities of capital in an economy and the beginning of a period where new investments imply better machines, higher quality and bigger complexity. This *capital-deepening-cum-complexity-increase* allows an endogenous study of who adopts new technologies and thereby who profits from them. It gives a rationale why wages of two individuals, that are perfect substitutes according to characteristics that are standard ingredients of individual datasets but differ in abilities to learn, continue to diverge over time and why decreasing returns to learning will set in only very late. One might object that wage divergence in this model is simply the consequence of the permanent advantage of high-ability individuals in learning $(b = \text{const.} > 0)$ and that with decreasing returns to learning, within groups divergence would peter out. There are three answers: first, continuous increases in within group wage divergence is what the data shows. Second, a more sophisticated version of learning with decreasing returns can be constructed where both high- and low-ability individuals are permanently trained, but high-ability individuals learn faster. Finally, and most importantly, the effect of previously accumulated knowledge on the ability to further accumulate knowledge is a priori far from clear. It can easily be imagined that a worker who has learnt to produce with some sophisticated machine will have an advantage in learning to work with the next generation over a colleague who had not adopted that technology.

Another way of interpreting the above process is to think of careers. Simple rewriting of the production function shows that high-ability persons will over time command over more capital and more colleagues as their productivity increases through training, hence they "make career" in contrast to low-ability persons who do not progress. While it is true that it would be completely unrealistic to argue that there were no careers to be made before 1970, it is the systematic *change* in opportunities resulting from higher job complexity which is highlighted by the model. Any CRTS production function $Y(V)$, where V is a vector of factors of production, can be written as $Y(V) = \sum_i Y(\lambda_i V)$, where $\sum_i \lambda_i = 1$. Setting $\lambda_i = h_i / H$, the production function (2) reads

$$Y = \sum_i \left((h_i\, K/H)^\theta + (h_i\, H/H)^\theta + (h_i\, L/H)^\theta \right)^{1/\theta}$$

$$= \sum_i \left((h_i\, K/H)^\theta + h_i^{\,\theta} + (h_i\, L/H)^\theta \right)^{1/\theta}. \qquad (2'')$$

Since capital to human capital and labor to human capital ratios are constant (on the balanced growth path which, for simplicity's sake, we limit our attention to), an individual i whose productivity h_i increases, will have an increasing amount of capital $h_i\, K/H$ and colleagues $h_i\, L/H$ at her disposal in contrast to an individual j whose productivity h_j stays constant. Hence the assumptions of the model imply a complementarity between capital and skills (here ability to learn), a frequent finding in empirical work.

Juhn, Murphy and Pierce (1993, table 3) point out that increasing wage dispersion in their sample is not simply the result of increasing dispersion among new market entrants, which could result from an increasing dispersion of the quality of general education. Wage dispersion does increase over time as workers' on-the-job experience rises. The above theory interprets this as human capital accumulated on the job that changes the wage distribution within groups. This interpretation contrasts the one given by Juhn, Murphy and Pierce themselves, since they argue it is not *more of* but *higher returns to* unobservables. They base their argument on the observation that wage dispersion has also increased for new market entrants. This, however, in the light of the present theory, does not constitute a contradiction. The decomposition of the production function in (2") shows that the capital endowment of jobs filled with high-ability college graduates (note that an identical decomposition can be done for high-school graduates) increases, whereas the capital per capita ratio of low-ability jobs is constant. Hence, the economy observes a divergence into well-endowed, high-wage jobs and low-wage jobs with constant endowment. Arguing that jobs are more persistent than workers filling these jobs, in other words, one job is carried out over time by many workers[11], new entrants face high-capital jobs and low

[11] This view is supported by job turnover studies. This "churning" phenomenon is made explicit in Burgess, Lane and Stevens (1994).

capital jobs. Hence, the initial salary depends crucially on what job individuals are employed for. Since relative capital endowment of jobs diverge over time, so does the wage distribution of market entrants, as emphasized by Juhn, Murphy and Pierce. Of course, parallel movements of increasing job complexity and increasing human capital inequality of market entrants can be imagined[12].

Note that changing endowments of jobs with capital and changing capacities of individuals can be seen as a step towards endogenizing the evolution of jobs who differ in complexity and workers who differ in skills. So far, studies of the relation between job and skill heterogeneity in the assignment model tradition (e.g. Sattinger, 1975) study the allocation of heterogeneous skills to heterogeneous jobs but take the distribution of skills and complexity as given. Applying these models to an empirical analysis of wage distributions, however, shows (e.g. Teulings, 1995) that measures of degrees of skill and complexity differentials change over time. No hint is given, however, what are the driving forces of these developments. The above approach suggests that the ultimate determinant for both job complexity and productivities is differentials in individual learning abilities resulting from education.

5. The evolution of wages in the U.S. and the nature of BTC

This section offers two scenarios which qualitatively reproduce the stylized facts as worked out in section 2. The difference of the scenarios lies in the reason suggested for wage divergence between groups in the 1980s and the prediction for future wage development. The explanation of biased technological change based on changing training costs and proposed in the first subsection comes closest to views expressed in the empirical literature and turns out to be a very simple and intuitive. The second one – restructuring of the production process – is more "sophisticated" but also more extreme in its prediction. Both are illustrated in figure 3 which plots timepaths of relative wages; solid lines refer to the changing training costs scenario, whereas broken lines represent the impact of restructuring. The section concludes by investigating to what extent the concepts of increasing complexity and BTC used in this model can be related to standard notions of technological change.

5.1. The evolution of the U.S. wage distribution and changing training costs

A first period (the early transition period) is characterized by the accumulation of physical capital alone which increases productivity and hence wages of all workers or employees to the same extent. Relative wages within as well as between groups are constant. This was a period in which capital deepening was identical to accumulating more of the same type of capital. Operating of machines or production processes by workers did not require particular skills that were difficult to learn or would otherwise lead to a distinction between workers. To put it a bit sharply, education received before working was generally sufficient to fulfil job requirements. This is the situation the U.S. economy found itself in in the 1960s. Due to decreasing returns in physical capital, the returns of this type of investment fell over time and reached a point, where it became necessary to train the labor force in order to keep the economy growing. The decision to train someone depends on the scarcity of the labor group he or she belongs to (the marginal productivity of human capital compared to labor) and his or her learning capabilities. Since the 1970s, in terms of the stylized facts, were characterized by stable wage ratios

[12] Cf. Glomm and Ravikumar (1992) for a theoretical study of the relation between public and private schooling and the distribution of human capital and Card and Krueger (1992) for an empirical investigation into the relation between the quality of a school and the returns to education.

between groups, the necessity to train the labor force developed fairly simultaneously for both labor and human capital. The adjustment period IIa (the late transition period) that the model predicts, if marginal returns to training human capital and labor differ, was therefore either very short and barely identifiable in the data or returns to both labor groups were indeed identical. When both human capital and labor receives training in period IIb (the balanced growth path), wages between groups were stable but diverge within groups due to the natural difference of learning capacities of individuals having the same education. This represents the 1970s.

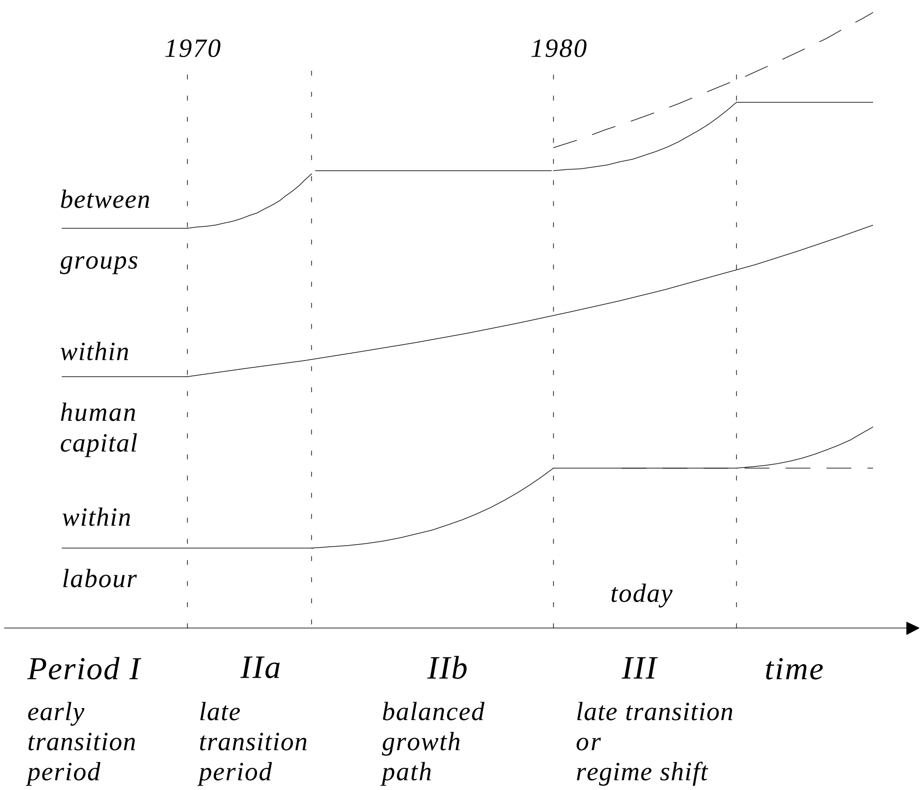

Figure 3: Qualitative evolution of between and within groups wage ratios

How can the sudden occurrence of between group wage divergence at the beginning of the 1980s be captured? It is the introduction of a new technology beyond complexity increasing capital deepening which affects the costs of training and starts period III (in terms of relative wage changes a late transition period). This is one possible formalization of the mechanism cited frequently in the empirical literature to explain between group wage divergence in this period. The argument is based on the comparative advantage of college compared to high-school graduates in coping with new technological requirements. The difference in the costs of (further) educating these groups, as captured by the parameter d, is a function of the complexity of a technology. The introduction of a new technology implies that the learning advantage of human capital increases compared to labor, which, in terms of the model, means an increase of d [13]. Such an effect increases the costs of training labor (compared to

[13] Empirical work shows (cf. e.g. the conclusion in Krueger, 1993) that highly educated workers use computers more frequently. Computers are probably *the* prototype of technological change requiring additional training for productive use. Arguing that any technology is generally available and can in principle be used by everybody who finds it

accumulating capital or human capital) and leads to permanent long-run increase of the human capital-labor wage ratio as can be seen from (6'). This constitutes a definition of biased technological change. It is measured by the percentage increase in *d*. Note the importance of the elasticity of substitution between factors for how strong a change in relative training costs translates into relative wage changes. If human capital can be substituted easily for labor (which means a high elasticity of substitution $\varepsilon = 1/(1-\theta)$ which is equivalent to a high value of $\theta/(1-\theta) = \varepsilon - 1$ in (6')), a small increase of training costs of labor leads to a strong shift of demand towards human capital and a high change in relative wages. As is clear from (6), the introduction of a new technology does not have an instantaneous impact on relative wages. Only smoothly does human capital of those adopting the new technology increase. In the course of the adjustment process, relative wages of college graduates increase but this wage divergence between groups comes to an end and wage divergence restarts within labor. Under this scenario, wage con- or divergence between groups is limited by imperfect substitutability, but divergence within groups is perpetuating; in other words, changes of between groups wage ratios are a transition phenomenon, whereas changes of within groups wage ratios are a property of both transition and the long-run equilibrium.

5.2. The evolution of the U.S. wage distribution and restructuring

The second scenario proposed to explain wage divergence between groups is based on organizational change of the production process. The new organizational structure of production introduced here captures the often expressed concern that work done by many some years ago (the old production structure) can nowadays (the new production structure) be done by one individual, provided she or he has the right equipment. It will be show that an ever increasing wage gap between college and high-school graduates can be the result of restructuring that substitutes labor with human capital and capital. It is a well-known argument (e.g. Blanchard, 1995) that one can expect technological change, which, after all, is endogenous, to correct for wage divergence and tend to substitute expensive human capital[14]. Here, it is shown, however, that under such a regime shift scenario, the market itself will not correct for relative wage divergence but rather cause it, though accumulation and technology adoption decisions are endogenous. The regime shift is characterized by a change in the production structure from a situation where relative wages between groups were determined by relative supply and limited by imperfect substitutability to a situation where relative wages grow without bound.

As in the last subsection, the starting point is a balanced growth path of an economy (period IIb in figure 3) characterized by a production function (2) and an accumulation constraint (3). Organizational change, the regime shift, is captured here by the introduction of a new production process in addition to the traditional way of production (2). The modern production function, capturing the substitution process of labor through human capital and physical capital, reads

$$Y^m = \left(\left(K^m\right)^\theta + \left(H_1^m\right)^\theta + \left(H_2^m\right)^\theta \right)^{1/\theta}. \qquad (7)$$

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profitable, the fact that computers are more intensively used by highly skilled can be interpreted to result from the fact that this group learns easier. Generally speaking, the assumption that more education on average implies a more flexible way of thinking and trains the ability to learn should be without controversy. Hence, if there is some truth to this very frequently cited argument that the introduction of computers was such a shock, this is an example of an increase in *d*.

14 A similar argument (or in this case concern) with respect to labor saving technological change was expressed by Hicks (1932).

Note the similarity to the traditional technology (2). Both technologies are used to produce an identical good, but the modern technology has replaced labor with human capital and capital[15]. The economy will employ both technologies[16]. Since factors can move freely between different firms, factor rewards must be identical for factors employed in a modern plant and those employed in a traditional one, characterized by

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

Factor market clearing requires $K^m + K^{tr} = K$ and $H_1^m + H_2^m + H^{tr} = H$. The equilibrium allocation of factors between technologies is given by $K^m = K(H-L)/(H+L)$, $K^{tr} = K2L/(H+L)$, $H_1^m = H_2^m = (H-L)/2$, $H^{tr} = L$. Reinserting them into the production functions, gives the economy's aggregate production function,

$$Y = Y^m + Y^{tr} = \left(K^{\theta} + 2^{1-\theta}(H+L)^{\theta} \right)^{1/\theta}. \qquad (8)$$

This function has striking similarities to the production function (2) used to analyze wage divergence within groups. The crucial difference, of course, is that the aggregate production function (8) has as arguments factors of production which were imperfect substitutes in the traditional technology. The combined use of the traditional and the modern technology makes college- and high-school graduates perfect substitutes and therefore leads to the same ever increasing wage ratio as within groups. A low cost differential *d* that led to a limited change in wage differentials between groups (6') now leads to wage differentials growing without bound at a constant rate.

Changing wages between groups in the 1980s are caused in both scenarios by capital-skill complementarity (Grilliches, 1969) which means that total earnings of skilled (here human capital *H*) increase relative to earnings of unskilled (*L*) as capital is accumulated. Such an increase was found by Berman, Bound and Grilliches (1994, sect. 3) to be particularly fast in the 1980s. Capital accumulation alone accounts for little of the increase of nonproduction workers' share in the wage bill. Adding the share of investment in computers in total investment in the 1980s (cf. their table 7), however, thereby taking the *type* of capital investment into account, strongly increases the explanatory power of their model. This can be nicely interpreted by the model here: it is the type of capital that leads to either higher training costs or a restructuring of the production process and to the advantage human capital draws from this change. In the 1970s, capital accumulation led to divergence of wages within groups "only", in the 1980s, the technology shock changed relative wages also between groups. Note that the model also predicts that the 1970s are a period of stable demand within sectors, i.e. input changes within a sector could entirely be explained by changes in relative wages (6'). In the 1980s, demand shifts within sectors took place and relative factor inputs changed more than would have been expected by changes of relative factor prices (6), due to the change in relative productivities H/L.

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[15] At first sight, it might seem that labor is replaced by human capital only. A decomposition of the aggregate production function (8) following the lines in section 4.2., however, would show that human capital indeed has more capital at its disposal than labor.

[16] Note that an endogenous adoption of the modern technology can be studied in the present framework. As can be seen from the equilibrium factor allocation below, the new technology is adopted only if the supply of human capital is sufficiently high. By including the fact that the supply of college graduates increased over time, the seventies could receive an alternative interpretation in the form of an extended late transition period (cf. (6) and figure 3). Then the start of wage divergence between groups was endogenously triggered by $H = L$ in 1980. This would be a refinement of the theory that would not change the basic conclusions and is therefore conserved for future work.

The type of BTC that has affected the U.S. at the beginning of the 1980s has (if unanticipated) no consequences for time paths of wages before 1980. Hence wage ratios in the early and late transition period in this subsection are identical to the one discussed for BTC as changing training costs in figure 3. The crucial difference lies in the prediction for today. BTC as a restructuring of the production process leads to an ever increasing college high-school graduate gap that does not come to a halt as indicated by the broken line in figure 3. The other consequence is that wage ratios within labor should remain constant, other influences being excluded.

5.3. Capital deepening, increasing complexity and biased technological change

In order to facilitate an understanding of the lifetime learning effect through increasing complexity and biased technological change as used here, it appears useful to briefly relate them to standard growth models. Neoclassical growth theory explains increasing per capita output by increasing stocks of per capita capital. The basic model as developed by Solow (1956) stipulates a CRTS production function, where capital is the only factor of production that can be accumulated. Since there are decreasing returns to capital accumulation, the economy ends up in a long-run steady state where output per capita is constant. To reconcile this counterfactual finding with evidence, Solow considered a production function characterized by a steady increase of total factor productivity. This exogenous rate of technological progress determines the long-run growth rate of output per capita. The recent counterpart to this model was developed by Romer (1990) who endogenizes technological change by introducing differentiated capital goods and stipulating a public stock of knowledge. This guarantees, together with suitable linearity assumptions in the creation of knowledge, a constant long-run growth rate of output per capita which replaces the exogenous rate of technological progress. Both models have constant stocks of labor or human capital and do not consider changes in the productivity of the labor force per se. These models are characterized by a permanent capital deepening but neglect capital-deepening-cum-complexity-increase.

The role of what is called technological progress in these models, labor augmenting technological change or stocks of knowledge or differentiated capital goods, is played here by increasing complexity which allows and requires individuals to increase their productivity through human capital accumulation[17] which, via the LTLE, leads to wage divergence. The objection to the present model that there is no technological change would therefore be invalid. There is no general agreement what technological change is and differentiated capital goods or labor augmenting variables are one possibility to interpret residuals that remain unexplained in growth accounting. In this respect, growth accounting in a world as described in the present model would result in identical residuals. Hence, the above model does explain total factor productivity growth. The nature of BTC as it is often, though in various ways, used in the empirical literature can in terms of the present model be described as a unique, permanent shock. In the changing training costs scenario it is a simple shift in one of the model's parameters and therefore easily incorporated in standard literature. In the organizational restructuring scenario, however, the economy was hit by a shock (which can be endogenized as discussed before), that goes far beyond usual technological change as total factor productivity growth. If empirical support for the second scenario can be found, many interesting theoretical questions open up.

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[17] The same is true for Rebelo (1991) though he does not discuss this effect and is not concerned with distributional issues.

6. Empirical implications

There are several implications which have to be tested in order to find some support or indications calling for a refinement or rejection of the above theory. First, returns to investment in physical capital and the labor force can be estimated from National Account and CPS data and compared. The main hypothesis of the above model is that returns to investment in capital are higher than returns to investment in training in the 1960s but tend to equalize afterwards. It would further have to be tested to what extent it can legitimately be argued that different returns to investment in subgroups of labor are at the source of diverging wages. Since these returns depend, among other, on relative training costs, such an approach would give a quantitative measure of the bias in technological change.

The second main implication is – in general – the timing of within and between group divergence and – in particular – that wage divergence in the 1970s began with between group divergence (period IIa, late transition in figure 3) before only within divergence (period IIb, balanced growth path) could be observed. These predictions receive some support from Katz and Murphy (1992, Table III), who find that the period from 1965 to 1970, hence not only the 1980s, seems to indicate some biased demand between groups. More clarity, however, is needed on this point.

A further question to be investigated is the change of relative wages between groups. Does this increase in relative wages tend to peter out, once corrected for supply shifts? This would provide evidence on which of the two scenarios being qualitatively able to reproduce wage divergence is more likely. In addition, firm evidence on restructuring of the production process and substitution of labor through human capital and capital would yield insightful information[18]. Two aspects make such an investigation especially interesting: first, it comes very close to public concerns of the effects of job-consuming technological progress and second, despite its potential importance, fairly little theoretical work has been done on job heterogeneity, technological change (beyond factor productivity growth) and the effects on the labor market. The latter could be encouraged by empirical evidence.

A fourth implication is the prediction concerning the incidence of training on the job. This is probably the most direct way to obtain evidence on the above suggested hypothesis. The basic prediction is that training is not uniformly distributed over employees but concentrated on a subgroup of otherwise identical workers. Effects of training on the job have been investigated by Groot et.al. (1994), in Lynch (1994), by Booth (1991) or in the studies cited in OECD (1991). No evidence is available at this point – to my knowledge – on the distribution of training on the job over a longer time period. Bartel and Sicherman (1995) is a very interesting study that investigates the relation between technological change and the incidence and distribution of training for different labor groups. Unfortunately, the time period covered is fairly short (1988 - 1992) and does not coincide with the period of interest here. Further only averages over the entire time period are considered and the effect of training on wages is not studied.

[18] The author is currently involved in such a study. The basic difference between restructuring and changing training costs scenarios is that the former is characterized by changing elasticities of substitution, whereas the latter is not.

7. Conclusion

The challenge described at the beginning of this paper was to contribute to the understanding of changing wage patterns over time by investigating into possible reasons of biased demand. Many mechanisms have been discussed in the literature but non (neither any combination) is regarded to be sufficient to explain this phenomenon. This paper argues that the combination of lifetime learning and heterogeneous learning capacities is the link through which a changing technological environment affects the distribution of wages. The crucial point is the selection mechanism of training caused by financing through third parties. The central policy variable is the distribution of individual learning abilities which depend on their general education.

The model starts from the simple observation that per-capita output of an economy grows due to increases in the stock of physical capital and the quality of the labor force. If either of these mechanism comes to a halt, the economy's growth rate approaches zero. Though there are other theories explaining long-run growth without an increasing quality of the labor force, there is little doubt that know-how of individuals increasing over time as capital is accumulated or technology improves is *a* if not *the* crucial component of economic growth. When no on-the-job training takes place, relative wages within and between groups are constant. If training for a specific activity is planned, only those that, ceteris paribus, learn faster than others will be chosen. As a consequence, only productivity of this subgroup increases. Since learning while working becomes increasingly important and the model indeed focuses on learning during one's entire active (productive) life span at work, this driving force of changing wage ratios within groups was termed lifetime-learning effect. Relative wage changes between groups due to biased technological change take two forms: changing relative training costs or reorganization of the production process. Hints on which form (or which combination of types) of biased technological change, as observed at the beginning of the 1980s, has taken place can be derived from the future evolution of relative wages between groups. If widening of this wage gap tends to peter out, it would be evidence in favour of the hypothesis of an introduction of technologies that change relative training costs. It results from the advantage a certain group draws from the introduction of new technologies by being predominantly endowed with skills enabling them to mastering and adopting the new technology. If the between group wage gap widens continuously with no signs of a slowing pace, a reorganization of the production process appears a more probable explanation. The use of new sophisticated production technologies allowed to substitute labor by human capital and capital which triggered divergence of wages between groups that will not come to a halt. Biased technological change is a unique permanent shock, whereas the effects of this shock become visible through permanent learning of individuals.

To put it loosely, labor was homogenous before the seventies, became diversified through job requirements afterwards – where the quality but not the type of education became increasingly important – and was further diversified in the eighties where also the type of education gained in importance. Since this interpretation builds on heterogeneities in abilities to learn, it is important for future work to analyze origins of these differences. The idea behind this paper is to give an interpretation of wage dynamics in the U.S. in terms of "goodness of fit" of the education system on the one hand and technological, or more general, organizational requirements in the working world on the other. The central question is how well an individual's education prepares her for time after schooling. The value of a certain amount of human capital is not an absolute but a relative quantity, relative to the skills demanded on the job, it is less the quantity of skills acquired but the endowment with flexibility, with ability to learn, that counts. To give a precise example think of a manufacturing plant. If a certain group of individuals who have received no preparation for this particular type of work have to start working in this plant, some will find it easier to adapt to conditions and requirements on the job than others. If all receive some amount of training before starting to work, the average output at every point in time should be higher than without formal education (efficiency effect) *and* differences in productivity of individuals should be lower (distribution effect). Only if this distribution effect is important, the concept of ability differentials as used here is a meaningful one since then differentials in abilities to adapt to new production environments are not beyond the influence of economic decisions. There will always be differentials between individuals in their ability to analyze, understand and learn to work with new techniques, but these differences are smaller the more preparation individuals had obtained. This implies that wage divergence should be lower for groups that have obtained general preparation for a certain occupation (e.g. through apprenticeships) than those that acquired skills through learning-on-the-job. Taking this mechanism and its foundation in education systems into account is of major importance if distributional as well as efficiency issues are important for formulating policy measures.

Appendix

The model is solved by maximizing (1) subject to (3), given (2). As long as $\dot{H} = \dot{L} = 0$, the solution is a standard optimal control problem. The situation where either $\dot{H} = 0$ or $\dot{L} = 0$ is similar to the balanced growth path whose solution will be given here. On the BGP, $K = H = L\, d^{\,1/(1-\theta)}$ and therefore (2) becomes $Y = \left(K^{\theta} + H^{\theta} + L^{\theta}\right)^{1/\theta} = \left(K^{\theta} + K^{\theta} + \left(d^{\,-1/(1-\theta)}K\right)^{\theta}\right)^{1/\theta} = \left(2 + d^{\,-\theta/(1-\theta)}\right)^{1/\theta} K \equiv AK$ and (3) reads $\dot{K} + \dot{H} + d\,\dot{L} = \dot{K} + \dot{K} + d\, d^{\,-1/(1-\theta)}\dot{K} = \dot{K}\left(2 + d^{\,-\theta/(1-\theta)}\right) = Y - C \Leftrightarrow$ $\dot{K} = \left(2 + d^{\,-\theta/(1-\theta)}\right)^{-1}(Y - C) \equiv B(Y - C)$. The present value Hamiltonian then reads $H = \left(C^{1-\sigma} - 1\right)(1-\sigma)^{-1} + \eta\, B(AK - C)$ with f.o.c. $C^{-\sigma} = \eta B$ and $\dot{\eta} = \rho\eta - \eta B A$, which can be summarized to $\dot{C}/C = \sigma^{-1}(r - \rho)$, where $r = A = \left(2 + d^{\,-\theta/(1-\theta)}\right)^{1/\theta}$. Since this is a constant, (3) can be explicitly solved by taking the transversality condition $\lim_{t\to\infty} K(t)u'(C(t))\exp[-\rho t]$ $= \lim_{t\to\infty} K(t)\exp[-r\,t] = 0$ into account.

8. References

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