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Vona, Francesco and Consoli, Davide

Manchester Business School

27 January 2009

SENTE Working Papers 27/2009

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Francesco Vona & Davide Consoli

University of Tampere
Research Unit for Urban and Regional Development Studies

www.uta.fi/sente

ISSN 1457-9995
ISBN 978-951-44-7600-6

Innovation, Human Capital and Earning Distribution

Towards a dynamic life-cycle approach

Francesco Vona [a]
Department of Economics, University of Rome "La Sapienza"

Davide Consoli [b, c]
Manchester Institute of Innovation Research (MIoIR),
Manchester Business School

Abstract. Empirical anomalies in the dynamics of earnings following the emergence of new ICT technologies are not consistent with various re-elaborations of the human capital theory. The first part of the paper reviews critically this literature and highlights an important gap concerning the role of institutional infrastructures for the systematisation and diffusion of new knowledge. The dynamic life-cycle approach elaborated in the second part provides a coherent account of the evidence, and indicates interesting implications for innovation and educational policies.

1. Introduction

One of the most striking effects of the large-scale adoption of Information and Communication Technologies (ICTs) is the impact that the new regime borne on the distribution of earnings. This is especially evident in the United States where under traditionally soft regulatory frameworks wages are mainly determined by market forces. Therein at the onset of the ICT revolution early in the 1970s the decline of the college premium was associated to a substantial increase in within groups wage dispersion, that is, the residual inequality not explained by observable characteristics such as qualification, experience, gender et cetera. Since the beginning of the 1980s, however, the trend reversed and the unexplained residual variance of earnings stabilized while the educational premium outgrew the initial decline and started to increase steadily.

The observed change in the relation between the dynamics of earnings and the distribution of characteristics across workers contrasts a key postulate of the standard human capital theory, namely the positive and linear relationship between formal education – calculated in number

a Francesco Vona is Post-Doc Research Fellow at the University 'La Sapienza' in Rome (Italy) where he obtained a Ph.D. in 2008 with a thesis on labour market inequalities, educational policies and technical change. Other research interests include skill dynamics and environmental sustainability. He is also visiting Research Fellow at the Manchester Institute of Innovation Research, University of Manchester (UK).

b Davide Consoli (Ph.D., MA, BA) is Research Fellow at the Manchester Institute of Innovation Research, University of Manchester (UK). His research focuses on the economics and management of innovation and, in particular, the emergence and development of new technologies; the role of organizational and institutional changes; and the relation between demand and innovation. His research is published on leading international journals including Research Policy, Journal of Evolutionary Economics, Technology Analysis and Strategic Management and Industry & Innovation.

c Corresponding author

of years – and earnings. Over the last two decades various re-elaborations have sought to make the theory consistent with the foretold empirical 'anomalies'. First, the adoption of an explicit distinction between components of the human capital aggregate, i.e. college graduates and high-school graduates, coupled with the conjecture that the higher college wage premium depends on the skill-biased nature of the new technologies (e.g. Acemoglu 1998, Krusell et al. 2000); a second group of works adds in further sources of heterogeneity to account for within-group wage inequality (e.g. Galor and Moav 2000, Aghion et al. 2002); finally, a third approach emphasises the connection between the large-scale uptake of ICTs and observed changes in the demand for tasks within occupations and, thus, for educational requirements within occupations (e.g. Autor et al. 2003). The first part of the paper examines thoroughly the foretold strands of research and argues that the proposed variants of the human capital theory fall short of a coherent account of the evidence because they disregard the role of the adjustment in the educational infrastructure. Arguably the conceptual foundations of the theory are ill-suited to analyse the relation between technological change and the dynamics of earning distribution.

The second part of the paper draws on the field of innovation studies and proposes a life-cycle approach to the analysis of skill dynamics. The central claim is that major technological discontinuities trigger a process of 'creative destruction' of skills, that is, the emergence of new skill requirements within existing occupations as well as the creation of whole new occupations and skills. The structural imbalance between job complexity and the existing educational supply is a key determinant of the observed empirical 'anomalies'. In the view proposed here the skill life cycle is uncertain and contingent to the process of knowledge systematisation. Thereby at the beginning of a technological transition the potential comparative advantages are unobservable because new knowledge and skills are mostly tacit and outside the domain of the extant knowledge; subsequently, as the new knowledge is codified and new skills become available in larger scale, the likelihood of technology transfer increases and diffusion unfolds. The crucial point is that the extent to which those technological opportunities generate new codified knowledge depends on the institutional conduits that facilitate learning. Conventional theories overlook these non-trivial matters and undervalue systematically qualitative changes in the supply of educational opportunities. By contrast, we argue, the transition to a new technological regime is neither automatic nor deterministic; the development of new cognitive patterns to absorb industry best practices and of appropriate channels to facilitate the diffusion of new knowledge require the appropriate adaptation of educational institutions through knowledge standardization and the creation of entirely new disciplines (Nelson, 1994; Rosenberg, 1998). Failure in either is an additional source of inequalities in the distribution of earnings.

The paper is structured as follows. Section 2 introduces empirical evidence on the increase of college premium; Section 3 overviews the modelling strategies that have been adopted to make the standard theory consistent with observed anomalies in the distribution of earnings; Section 4 looks at additional evidence on the mismatch between occupational complexity and educational requirements following the widespread uptake of ICTs. Section 5 presents a dynamic life-cycle approach to the analysis of wealth distribution cum technological change;

the purpose of this part is also to bring the debate to the attention of innovation scholars – who have arguably underinvested on the topic. The last Section summarizes and indicates promising directions for future research.

2. Quantity vs. Quality of Human Capital

Recent empirical evidence provides compelling indications of the extent to which the ICT revolution has affected the requirement of skills across occupations. Empirical studies (e.g. Berman et al. 1998) on the observed returns to education, in particular, indicate a significant change in the composition of the workforce in favour of college graduates across OECD countries; in Anglo-Saxon Economies, where labour markets operate under traditionally soft regulatory regimes, this was accompanied by a robust increase of the college wage premium. Eckstein and Nagypal (2004) show that the ratio between the average weekly wage of workers with at least 16 years of schooling and of high-school graduates in the U.S. decreased between 1965 and 1975 (1.45 to 1.35) and subsequently increased steadily (1.50 in 1985 and 1.70 in 1995). A cross-country study by Martins and Pereira (2004) further shows that estimated returns to schooling are higher in the upper tail of the job distribution. Overall the evidence indicates a discrepancy with the basic tenet of Human Capital theory. A key postulate of the latter is the positive and linear relationship between educational attainment and workers' productivity; thereby, as the classical Mincer regression would have it (Mincer 1958), the expected level of earnings depends on the number of years of formal education and experience. It is worth noticing that alternative educational tracks, such as vocational courses, play no role in the theory. The data however seem to suggest that 'number of years of schooling' is not a good proxy for earnings and, furthermore, that differences across typologies of education – i.e. general or specific – matter.

A number of scholars (e.g. Acemoglu 1998, Krusell et al. 2000) sought to make the theory consistent with the evidence by building explicit discontinuities in the baseline model. A first step in this endeavour consisted in the explicit distinction between skilled/college graduate and unskilled/not-college graduate in a CES production function framework. Common across those models is the hypothesis that the degree of substitutability between physical capital and the two components of the workforce differs. Therefore under the assumption that the degree of substitutability between unskilled labour and machines is relatively higher than that between skilled labour and machines, Krusell et al. (2000) find that the observed acceleration of capital embodied technical change – measured by the decline of quality-adjusted prices of computer equipment – explains a large fraction of the increase in college wage premium. The latter is associated with both diminishing demand of unskilled workers and increased productivity of college workers following the take-up of new computer equipments. In other words, the college wage premium increases both because unskilled workers tend to be substituted by new computer equipments and, also, because the productivity of college workers increases the greater the number of computer equipments. Acemoglu (1998) proposes a sophisticated 2-skills endogenous growth model which accounts for the initial decrease of the college wage premium, and arguments that the increase in the supply of college graduates induces firms to build technologies that complement their skills. In the short run the new technologies are available with a lag and the increased supply of skilled workers induces a decrease of the wage premium. In the long run the equilibrium level of the wage premium grows together with the fraction of machines that are complementary to the skilled workforce.

By and large these works connect increases of the wage premium to changes in labour demand due to either capital-embodied technical progress (proxied by a decrease in the quality-adjusted prices of computer equipments) or to technological trajectories driven by an increase in the supply of college labour. Neither, however, explains the mechanism that connects the demand for college-educated workers to the advent of the new technologies.

Following the seminal paper of Nelson and Phelps (1966), a second, alternative, strand of literature incorporates a simple mechanism for explaining the comparative advantage of skilled workers in phases of intense technical change. The argument proposed by Caselli (1999) and Gould (2002) is that skills acquired through general education are more transferable across sectors and technologies, and therefore enable workers to operate more efficiently new technologies. Under this perspective general and analytical skills are crucial for innovative activities and technological improvements. This implies, on the one hand, that learning to use a new technology is less costly for college graduates compared to high-school graduates. On the other hand the competences of highly specialized workers are likely to experience significant obsolescence in periods of faster technological change. Overall the comparative advantage of skilled workers is contingent to the pace of technological progress.

An appealing feature of this approach is that the accumulation of different types of human capital is cast in a broader context, and wage inequality is analysed in conjunction with productivity dynamics and economic growth.[1] For example, the Nelson-Phelps approach contributes the debate on the observed differences in productivity, growth rates and degree of inequality/unemployment between the U.S. and Europe which mainstream economists articulate only in relation to differences in labour market institutions, namely minimum wage, hiring and firing costs and bargaining rules (e.g. Krugman 1994). In particular, Krueger and Kumar (2004) analyse differences across broad institutional frameworks, more specifically across countries which traditionally invest in skill-specific training, such as Germany, and others that support more significantly general higher education, like the U.S.. Their work shows that the former are likely to experience faster skill obsolescence and lower productivity due to progressive slowdown in the adoption of new technologies. In particular, the negative impact of quantitative components of labour market regulation, for example firing costs, is significantly lower than that of subsidies to higher education, like student aids. In this framework the transition towards new technological regimes is expected to generate relatively higher levels of wage inequality in countries with flexible labour institutions, like the U.S.. In fact, as long as such a country stays on its maximal productivity path the observed wage premium will reflect productivity differentials between innovative and non-innovative technologies.

1 There are few rigorous analyses of the impact of higher education on Total Factor Productivity and on growth rates. A study by the European Commission (2001) finds strong correlation between manufacturing productivity growth and education level of the workforce (tertiary education); a recent paper by Vandenbussche et al. (2006) indicates that tertiary education – including both vocational qualifications and college education – bears a stronger impact on TFP and growth in countries that are closer to the world technological frontier. This latter point is consistent with Nelson and Phelps (1968) and Krueger and Kumar (2004).

The latter strand of works hints at a notion of skill life-cycle based on the close association between the paths of technological progress and productivity. However as technologies mature the heterogeneity of learning costs across skilled and unskilled workers fades away, and neither of those works accounts explicitly for the underpinning adjustment mechanisms. Such adjustments are implicitly ascribed to generalized reduction of learning costs across the whole population. As a result, wage inequality appears only as a temporary effect of the technological transition which is in open contrast with the permanent increase in the graduate and, even more, the post-graduate wage premium following the widespread adoption of ICTs (Eckstein and Nagypal 2004).

Our conclusion is that the distinction between skilled and unskilled workers proposed by those studies does not substantially improve the explanatory power of human capital theory. The dichotomy is not a sufficient proxy to capture differences in the quality of human capital and, moreover, does not address the critical issue of within group wage inequality. A closer look at data on wages distribution show that inequality has grown at an average rate of 1% in the upper tail (90/50) since the early 1980s, while lower tail (50/10) inequality has receded in the second half of the decade (Autor et al. 2005). Autor et al. report that between 1980 and 2005 up to 80% of the rise in the 90-10 wage inequality is explained by that in 90-50 wage gap. Since the fraction of graduates in the upper part of the distribution is substantial, one would expect relatively higher within-group wage inequality in this group. And, in fact, the latter has grown more in the upper tail of the wage distribution in correspondence to highly paid occupations where returns to formal education are relatively higher (Autor et al. 2005). The broader point is that qualitative differences emerge especially within the graduate workforce, where – as will be argued in Section 5 – the effects of technical change on earnings depend on adjustments in the knowledge base. This observation opens up interesting scenarios to which we now turn our attention.

3. Different Sources of Heterogeneity

The conjecture that a large fraction of inequality associated to the ICT revolution is driven by unexplained residual in the classical Mincer regression (Gottshalk and Muffitt 1994) adds a new dimension to the 'human capital *cum* inequality' literature. Two main orientations emerge in this context. The first connects with empirical evidence on increased variance of firms' characteristics and the wider theme of organizational changes; the second attributes the increase in within group wage inequality to the rising premium of unobservable individual characteristics, such as innate abilities. Let us review them seriatim.

The first approach casts the analysis in the broader context of the organisational changes that followed the ICT revolution over the last three decades (Brynolfsson and Hitt, 1997 and Caroli and Van Reenen, 2001), and in particular, the generalised reduction in the scale of production (Davis and Haltiwanger, 1991) and the consequent raise in the dispersion of productivity across firms (Dunne et al., 2004). Wage inequality enters this debate in relation to the issue of fairness. To fix ideas, fairness considerations are important to motivate employees and, accordingly, within-firm wage differentials among workers with similar characteristics are unlikely (Howitt, 2002). Under this perspective a reduction in the scale of production likely leads to the implementation of incentive schemes for rewarding unobservable workers characteristics such as motivation. As the downscaling of the production units would allow to sort together more productive workers (Kremer and Maskin, 1995) higher dispersion of productivity across firms triggers wage inequality among workers with equally observable characteristics. Not surprisingly, empirical work on matched firms-workers panel data find strong correlation between rising levels of wage inequality and of productivity dispersion (Dunne et al. 2004, Faggio et al., 2007), or of employers' characteristics (Abowd et al., 2001).

The latter point, however, does not substantiate a solid argument without proper consideration of heterogeneity across workers. Clearly under an orthodox perspective workers' striving for better occupations likely squeezes the extra rewards tied to higher productivity levels. Under an efficiency-wage perspective, however, the reduction of scale makes monitoring and control more efficient and increases the probability that workers are rewarded on the basis of individual characteristics – such as motivation. In the latter scenario unobservable heterogeneity among workers does indeed affect wage inequality within groups.

The second approach integrates explicitly heterogeneity within cohorts of workers with equal characteristics. This assumption is grounded on empirical evidence (e.g. Card 1994) showing that individual abilities – such as test scores or school marks – affect schooling decisions, earnings and the ability to operate new technologies (Bartel and Sicherman 1998). Following this, Galor and Moav (2000) propose a model featuring two types of human capital and, within each, individual efficiency units depending on abilities; both types of human capital are assumed to be technology-specific and, thus, tend to depreciate as a result of technical change. They show that high-ability workers can compensate obsolescence as opposed to low ability workers whose real wages decrease. Thereby faster technological change decreases the minimum ability threshold as more individuals endeavour to acquire high-level skills; this, eventually, generates higher wage dispersion across skilled workers. The foregoing warrants the conclusion that the speed of technical change is a key determinant for the relative returns to formal education with respect to innate abilities.

Whit respect to this point we observe that the acceleration in the rate of capital embodied technological change documented by Cummins and Violante (2002) is at odd with the decline and the subsequent stabilization of the within group component observed since the beginning of the 1980s. Moreover Blundell and Preston (1999) show that only a minor fraction of the increase in the residual earning inequality is an outcome of permanent, rather than transitory, factors. Overall Aghion et al (2002) argue that permanent factors alone, such as innate abilities or given unobservable skills, cannot account for wage inequality within-group. In contrast with the literature on innate ability, they introduce 'induced' heterogeneity workers by considering the accumulation of informal knowledge through experience. The argument goes as follows. The claim that innovations reduce the returns to job-specific or technological-specific experience does not apply to general purpose technologies, which are transferable across sectors or related innovations. This is the case of ICTs whereby the ability to operate, say, a new software can be transferred across jobs and sectors as well as enhance the probability of learning by using[2]. Accordingly individuals who work with leading-edge technologies should be able to transfer a greater fraction of human capital in future leading-edge technologies. In the absence of counter-balancing mechanisms this form of path-dependency is likely to become a source of persistent inequality between workers with similar initial level of human capital and different working history. Over the long-run this can consolidate inequality and reduce accessibility to new skills which, in turn, may hamper the diffusion of the new technology.

It is worthwhile to note that this line of argument oversees altogether the enabling role of institutions in the diffusion of new technologies and, in particular, the absorption of new knowledge by what Aghion et al. (2002) call less-lucky workers, that is, those who had not direct access to the new technologies. Our conjecture is that new technological opportunities generate new sticky and non-yet-codified[3] knowledge. Allied to this is the idea that the associated benefits are contingent to the institutional conduits underpinning knowledge systematization and learning (Rosenberg, 1998). The kind of learning we refer to here differs from conventional 'learning by doing' (Arrow 1969) in that it does not involve mere repetition of an activity but, rather, the development of new cognitive patterns to absorb practical experience, as well as the creation of new modules that enhance transferability of new knowledge. It also differs from 'learning through formal education' because the radical technological changes that are at the core of our analysis imply a redefinition of the existing stock of knowledge in order to make it available to a larger fraction of individuals.

The significance of such phenomena against the backdrop of the ICT transition stimulates our interest on the processes of non-linear knowledge creation and codification[4]. Across the range of theories overviewed thus far such gaps are a non-issue in that the human capital index and its changes due to technical progress are sufficient statistics for worker's productivity. However knowledge systematization, that is, the institution of educational packages and training opportunities is especially important to fill educational gaps opened up by radical technological changes. We will now overview recent studies that propose new metrics to measure skill requirements on the basis of changes in the characteristics of occupations. This conceptual step is crucial to elaborate a framework which resonates with the empirical evidence discussed thus far and that is, at the same time, suitable to overcome some of the shortcomings of the human capital theory.

4. The Mismatch between Job complexity and Educational attainments

The previous section hinted at the notion of (induced or innate) heterogeneity across workers as likely explanations for the observed trends in wage dispersion, both within and between

2 This might explain why returns to experience rose at the beginning of the ICT revolution (Weinberg 2003).

3 Implicit in this argument is the articulation of knowledge beyond the codified vs. tacit distinction (Ancori et al, 2000). Not-yet-codified knowledge is intermediary knowledge that stems from industry best practices.

4 A related issue concerns the impact of inherited characteristics, such as family background, on individuals' decision to acquire certain skills which, according to Galor and Zeira (1993), is an additional source of non-linearity and multiple equilibria.

educational groups. We argued that variants of the standard human capital approach provide only a partial account of the skill life cycle, mostly because they disregard the mechanisms that drive the synthesis, codification and diffusion of practical knowledge. In this section we propose a new notion of skill based on the gap between job complexity and educational appropriateness. This is a building block for the proposed dynamics life-cycle theory.[5]

Let us begin by observing that the existing notion of skills within the standard human capital theory does not allow a clear distinction between qualitative changes in labour demand and qualitative changes in labour supply. In turn, the unclear demarcation between skills and qualifications proffered by the standard theory leads to critical conclusions. One of them is that the system of formal education adapts seamlessly to the emergence new knowledge requirements, which is in open contrast with a large body of evidence on educational mismatches (e.g. Green and McIntosh, 2007). Our conjecture is that educational mismatches and qualitative adjustments in the supply of education system are all signals – rather than 'anomalies' – of the fact that radical technical changes, akin to the ICT revolution, trigger complementary changes across various layers of the institutional infrastructure. Accordingly if changes in skill requirements within occupations and the emergence of new occupations have been relevant, changes in the educational programs necessary to support the new occupations must have been important too. Under this perspective within group wage inequality is to be ascribed to poor, or not uniform[6], adjustment of educational programs.

Official dictionaries and guidelines of the task structure underpinning a number of occupational classes provide prima facie evidence of an emerging qualitative mismatch between education and technology. Actual changes in task requirements within occupations are tracked by assigning a score to each skill level, i.e. manual dexterity, analytical skills, communicative skills (Autor et al. 2003). The foregoing observations highlight the following three important stylized facts and, at the same time, bring out interesting weaknesses in the basic tenet of the human capital theory.

Stylised fact 1: The adoption of radical new technologies such as computers tends to displace jobs that consist mostly of routine tasks. This is what Autor et al (2006) call 'routinization hypothesis': machines are better suited for tasks that can be expressed in the form of rules while humans retain a comparative advantage in non-routine tasks that involve creativity, pattern recognition, expert thinking, complex communication and social interaction. The relative increase in the demand of skilled workers, according to the skill-biased technical change hypothesis, reflects the fact that ability for non-routine tasks can be acquired through general and higher education (Levy and Murnane, 2004). It is worth stressing that this is broadly consistent with Nelson and Phelps' (1966) view. Various other studies support[7] the foregoing hypothesis, and indicate that returns to intelligence (Ingram and Neumann 1999), expert thinking and complex communication (Autor et al., 2003; Levy and Murnane, 2004;

5 An early hint at a notion of skill life-cycle can be found in Tether et al (2005).

6 This suggests that a decentralized educational sector can respond faster to external changes in knowledge, but, at the same time, could raise the variability of educational attainments.

7 By contrast Howell and Wolff (1992) found no discontinuities in the requirement of cognitive skills following the ICT revolution; their work, however, does not consider the distinction between routine cognitive and non-routine analytical.

Spitz-Oener, 2006[8]) increase together with the progressive uptake of new machinery (e.g. computers) in the workplace. Widespread adoption of computers entailed a sharp decline of demand for jobs consisting in routine tasks such as bookkeepers, secretaries, middle-managers and non-specialized blue collar workers. In turn, as most of these are associated with non-college qualification, the demand for unskilled workers has been decreasing. Conversely demand for college graduate and a fraction of non-college graduate jobs (e.g. mechanics, bus drivers) has relatively accelerated because the associated tasks cannot (yet) be performed by computers. The 'routinization hypothesis' captures also the emergence of substantial job polarization, especially in Anglo-Saxon economies characterised by soft regulatory frameworks. Therein increase in the relative demand of non-routine tasks benefits professions at the top (i.e. scientists, managers) and at the bottom (i.e. bus drivers, waitress) of the pay scale more than middle-paid clerical occupations.

Stylised fact 2: The use of radical new technologies such as computers induces changes in the structure of task requirements within both high- and low-paid occupations. Indeed the degree of job complexity, measured by higher scores in non-routine analytical and communicative tasks, increases also for low-paid jobs in workplaces where computer adoption has been faster. To give an idea of the magnitude of such within-occupation changes, between the 1978 and 1990, 73% of occupations listed in the U.S. DOT (Dictionary of Occupations and Titles) have been revised on the basis of new emerging job requirements. In addition, as the skills needed to perform non-routine analytical and interactive tasks are mostly acquired through formal and higher education, 40% of the increased demand for educated workers in last two decades "… is due to a shift in task composition within nominally unchanging occupations" (Autor et al. 2003: 1321). The latter paper shows that the relation between intra-occupational task changes and computerization does not vary if one controls for the simultaneous change in the fraction of college graduate workers employed in this specific occupation. In other words, task changes *within* occupation are not affected by an increase in the fraction of college graduates. This proves that during the more intense phase of diffusion computerization has borne significant effects on both the educational attainments and the nature of occupations. From this perspective it can be further argued that the initial decline of the educational premium signals an initial mismatch between the complexity of jobs and the quality of educational programs.

Stylised fact 3: The use of radical new technologies such as computers stimulates the emergence of wholly new occupations. Arguably the standard human capital theory does not pay much attention to this aspect, or at least considers it far less important (Goss and Manning 2007). This, however, is in contrast with the significant revision of the U.S. DOT which after 1991 lists computer-related occupations under a newly added section. Moreover economic historians have long since stressed that the creation of new occupations is critical to accommodate the imbalances stirred by significant technological transitions (see e.g. Rosenberg, 1979; Hughes, 1983).[9] The next section will articulate the latter remark in a broader context. For the moment

8 Notwithstanding minor differences Spitz-Oener (2006) and Goss and Manning (2007) find similar patterns respectively for Germany and the U.K..

9 See e.g. a study on the shift to steam engine technology in sailing showing that new occupations accounted for 46% of overall employment on steam vessels compared to sail ships (Aimee et al., 2004).

suffice it to say that significant increase in the demand for postgraduates indicates that the emergence of new occupations should be matched by complementary transformations in the supply of learning opportunities. Empirical evidence lends support to this idea. Eckstein and Nagypal (2004) observe that both the persistent increase of the graduate wage premium and that of wage dispersion in the college cohort (or higher) are highly correlated with a substantial increase of the post-graduate wage premium. The steady growth of post-graduate wage premium in computer-related jobs after 1974 – which is commonly considered the 'Year Zero' of the ICT revolution (Greenwood and Yorukoglu 1997) – through to 2002 confirms that the types of qualification which best accommodate skill requirements are contingent to the characteristics of a technological paradigm. Eckstein and Nagypal (2004) further report on the divergence between college graduate and the postgraduate wage premium: over the last forty years the ratio of earning of postgraduate (college graduate) to high school graduate increased from 1.4 (1.3) in 1963 to 2.6 (1.8) in 2002. A similar argument holds for professionals with high levels of educational attainment – for example managers, physicians, lawyers, scientists, engineers, computer specialists and college professors. Overall the emergence of a new variety of highly paid occupations is likely to call for appropriate adjustments in the supply of learning opportunities.

Combined together the three foregoing facts indicate non-negligible changes in the distribution of wages and jobs following the wide uptake of ICTs. Framed in a broader context such recognition challenges the assumption that the degree of substitutability between machine and (heterogeneous) workers – and thus the degree of routinization – is *de ipso facto* synchronic with the cycle of industrial development. Rather, we suggest, the degree of substitutability between labour and machines increases with incremental technological developments *so long as* the division of labour facilitates the routinization of a higher fraction of tasks. This is not a trivial remark. Clearly, the foregoing 'new empirical evidence' is not at home in the standard orthodox tenet where the inputs of the production function – either heterogeneous labour or different tasks – are fixed, and the distinction between skill requirement of an occupation and educational supply is not clearly specified. In particular, changes at the 'intensive' margin, i.e. within occupations, are not connected to changes at the 'extensive' margin, i.e. the emergence of new occupations and skills. Our conjecture is that the emergence of educational mismatches and the qualitative changes outlined above are structural features – rather than 'anomalies' – of radical technological change. The next section will bring together the issues discussed thus far, and will articulate the role of the educational infrastructure in the systematization of new knowledge.

5. Rethinking Human Capital: a Dynamic Life Cycle approach

5.1 Conceptual foundations

The last section emphasised the extent to which the transition to the ICT paradigm touched upon the broad institutional infrastructure. This section elaborates a conceptual framework for the analysis of skill dynamics through the lenses of innovation studies. The objective is to illustrate how changes in the systematization of knowledge base and, more specifically, the updating of educational programs contribute to the absorption of the 'creative destruction' of skills – both at the intensive and the extensive margins – following a major technological discontinuity.

Recall our claim that such adjustments involve quantitative and qualitative transformations, and that these are equally important for the viability of technology diffusion. The various re-elaborations of the standard human capital theory avoid these complications and present a rather linear analysis of how knowledge is produced and used. In so doing however the impact of qualitative adjustments in the supply of education are systematically undervalued. On the whole empirical works on wage inequality dismiss the role that qualitative differences across universities can bear on the persistence of wage dispersion within graduates.

Research on innovation and technological change offers an alternative view of the relationship between knowledge and technical change. Innovation scholars refute the notion that new knowledge is *sic et simpliciter* the source of generalised – yet elusive – positive externalities. Rather, they propose, the emergence of new opportunities due to the growth of knowledge sets in motion a non-linear process of adaptation of the existing structure of know-how (Rosenberg, 1976; Nelson and Winter, 1982). Strong emphasis is placed on the pivotal role of discoveries originated in the context of problem-solving activities rather than basic research (Rosenberg and Birdzell, 1986).[10] Allied to this is the claim that the ability to reap the benefits of new knowledge is contingent rather than automatic: uncertainty, irreversibility and path-dependency play a significant role in either stirring or thwarting the potential of new knowledge (Arthur, 1989; David, 2001).

Most scholars focus on the benefits and the challenges of tacit and localized knowledge (see e.g. Cowan et al, 2000) and more, in general, how firms acquire new knowledge and implement it in their operations. An equally important question concerns the systematisation of not-yet-codified knowledge, that is, of knowledge originated from application-oriented fields (Nelson, 1994). A number of empirical works illustrate the extent of this process in areas as diverse as chemical engineering (Rosenberg, 1998); electrical engineering (Ryder and Fink, 1984); environmental engineering (Anderson, 2002)[11]; computer science (Mowery and Langlois, 1996); and medicine (Geljins and Rosenberg, 1998; Consoli and Mina, 2009). They all concur in the claim that such disciplines, each in a different time, acted as converters of emerging industry best practices into standardized training programs.

A full appreciation of not-yet codified new knowledge is relevant especially to those technologies that bear potential for application across several sectors. General Purpose

10 As Pisano remarks (1996: 1117): "In environments like chemical pharmaceutical which are characterized by deep theoretical knowledge and a significant accumulation of practical experience, the role of the plant in development may not be critical…In emerging technologies, like biotechnology, which are typically characterized by less mature theoretical underpinnings and less accumulated practical knowledge, the plant may be a critical venue for development. Difficulties to anticipate the locus of development competencies within organizations may be technology life-cycle dependent".

11 Preliminary research on the relation between skills and environmental-friendly innovation reveals interesting insights. This involved a series of interviews with engineers to assess the extent to which standard analytical tools within graduate programs (e.g. optimization algorithms) were perceived as conducive to environmental innovation. It emerged that the common perception of issues like emission abatement as constraints within an optimization process actually hampers the search for alternative solutions. A bias towards end-of-pipe technologies (i.e. filters), which simply redirect waste from a media to another, limits alternative solutions and desirable associated outcomes, such as overall reduction requirement of energy and raw materials (Vona, 2008b).

Technologies are a good case in point. Their widespread adoption entails a wide range of intangible investments correlated to increasing capital intensity, namely educational attainments, skill qualifications, training programs and inter-firm reorganization and retraining. The associated adjustments costs grind on a wide variety of institutional processes and are likely to be substantial, especially for what concerns intangible goods such as learning (see e.g. David, 2000; Breshnan et al., 1999). As Foray (2004, p.23) remarks "[during the last 30 years] the professionalization of R&D and the development of research structures in firms are relatively minor events, from the point of view of general economic change, compared to the discontinuity perceived in education and training".

David and Foray (1998) articulate this issue in relation to redistributive issues and claim that tacit knowledge, mainly embodied in human capital, might be a bottleneck and hinder the full realization of productivity potential. This is because firms can expect great benefits from knowledge codification inasmuch as it facilitates the re-absorption of the rents associated to tacit knowledge. Indeed, both the value and the distribution of innovative rents depend on the type of knowledge at root of such rents. Zucker et al (2001) contribute this debate with an analysis of the stock values of biotech companies, and shows that profits and capital gains are highly related to the quality of scientists employed. In relation at the distribution of such rents, they observe "… a sort of natural excludability that this tacit dimension bestows on knowledge. This represents a temporary source of intellectual capital, producing rents for scientists who have the know-how" (Op cit: 97); another passage reads "… the top scientist making the key discovery have a major strategic advantage in exploiting their commercial applications, particularly where they need for tacit knowledge of the new techniques creates natural excludability of scientists who have not worked at the bench level with the scientists or are incapable of reverse-engineering their methods from the published articles" (ibid: 99).

Let us bring together these threads in a coherent view of the skill life-cycle. At the beginning of a technological revolution new knowledge and skills stemming from innovative processes are sticky and tacit mostly outside of the established knowledge domain; accordingly, the related comparative advantages are retained by few early users and, thus, are empirically unobservable. High knowledge tacitness limits technology transfer only to inter-firm mobility of early users of new technologies and, thus, generates initially a higher earning premium. If the new knowledge is successfully codified and the new skills become available in a larger scale the likelihood of technology transfer increases with diffusion. The latter step however is contingent to adjustments within and between complementary institutional domains (Nelson, 1994). Inasmuch as opportunities for knowledge codification are fairly distributed across society, competition among workers with similar educational attainments will squeeze unexplained earning dispersion. But the changes that are necessary to accommodate the impulse of a technological transition are not automatic, and failure is an additional source of inequalities in the distribution of income.

Our life-cycle approach echoes Langlois' (2003) analysis of the process of division of labour in relation to mechanization and routinization. At an early stage of a technological revolution tasks are by definition 'ill-structured' in that they cannot be synthesised by rule-based and codified languages (Simon, 1960; Levy and Murnane, 2004). Thus, only highly creative individuals can deal with these tasks often characterized by complex activities such as organizational design, projecting and "the exercise of judgment in situation of ambiguity". As technological development unfolds the fulfilment of the innovation potential carves a path of finer specialisation due to further simplification of tasks. On the one hand increasingly specialised workers enjoy higher productivity levels as they acquire further dexterity; on the other hand as repetition deepens the comprehension of each task new opportunities of improvements emerge. Following on this, the division of labour depends *ceteris paribus* on the extent to which tasks can be productively standardized. Eventually refinement reaches a critical point where tasks are fully standardized and the process can actually reverse with likely deskilling and narrowing of further innovation opportunities. Our additional conjecture is that the extent of task standardization depends on purposive adjustments of educational programs aimed at facilitating the diffusion of new practice-based learning.

An important aspect of the suggested approach is the articulation of a cognitive upper limit in the process of division of labour. Since specific skills do no ensure *automatic* productivity improvements the fulfilment of the innovation potential is contingent to widening, as opposed to deepening, of the knowledge base. As Baumol (2004) remarks, significant technological breakthroughs often stem from individual intuition and ability to think 'outside the box'; at the same time, rigorous technical training is a key pathway for the exploitation of the latent benefits of innovation. This is also consistent with the broader observation that the emergence of wholly new professions and qualifications is both a joint effect of radical technological change, as well as a necessary consequence of the division of labour (Amendola and Gaffard 1988). The implication is that endogenous productivity gains are not the mere outcome of indefinite market expansion but depend on intermediate adjustments in the labour market. In both cases latent productivity improvements due to the new technologies can be achieved by adapting the educational infrastructure to emerging skill requirements, especially at the upper end of the job distribution where knowledge intensive profession tends to be concentrated. It is at the top of the job distribution, where formal education pays more, that the effect of technical change on earnings depends more on sticky adaptation of the knowledge base. Accordingly as changes in educational programs are slow and not uniform, the increase in dispersion has been more persistent at the top of the wage distribution.

5.2 Broadening the view to further applications

Thus far the discussion has been limited to the connection between skill creative destruction and wage inequality. Clearly the implications of the proposed view touch upon a wide range of issues. Let us focus on two: the dynamics of productivity and the policy aspects of education design.

The issue of earning distribution is closely associated to the dynamics of productivity. Over the skill life-cycle the variance of the wage distribution can be seen as a movement around the productivity trend. Thereby at the onset of the technological revolution educational mismatches – due to qualitative changes within occupations and the emergence of new varieties of occupations – limit the effective realization of potential productivity increases. Appropriate investments in knowledge systematization and educational policies should ideally ensure that the system escapes a low productivity attractor. In this light, the productivity slowdown observed in the 1970s appears as a structural phenomenon due to a shift of resources from production to learning activities (Greenwood and Yorukoglu 1997). Different from the standard 'productivity paradox' argument our approach shows that effective exploitation of new opportunities hinges upon the design and implementation of appropriate policies. These should facilitate the restructuring of the knowledge base and, eventually, sustain the process of technology diffusion[12].

As the division of labour and job standardization reduce the opportunity for improvements along the existing technological paradigm, labour productivity is likely to decelerate in the face of a cognitive bottleneck. To escape the latter and assist the technological transition policies should stimulate the emergence of heterogeneity in the knowledge base by supporting pluralism of the kind that is typically observed in university-firm interactions, communities of practitioners, innovation platforms (Metcalfe, 1995; Antonelli, 2008; Consoli and Patrucco, 2008). Further, as anticipated by Vanderbugghe et al. (2006), the closer the system is to the technological frontier, and thus to the exhaustion of opportunities, the higher the need for investments in explorative activities. At the opposite end of the spectrum, latent innovation potential is better exploited by increasing absorptive capacity, for example, by favouring the homogenisation of school quality and skill levels.

The outlined argument is also consistent with the observation that incentives and capabilities vary significantly across countries, sectors and individual firms. Thereby in considering how different innovation systems develop and change it is especially important to identify an institutional design that provides coherence to the extant ecology of learning attitudes while, at the same time, stimulating the growth of new variety. The route of a diachronic policy strategy seems best suited vis-à-vis the heterogeneity that characterises economies; that is, policy interventions should spur, or smoothen, heterogeneity between educational and research institutes when heterogeneity is relatively low, or high. Overall public investments should sustain knowledge-creation throughout the life cycle process, from creation to synthesis of new knowledge.

More in general, how processes of knowledge systematization affect the dynamics of skills and wages obviously deserves further investigations. This issue concerns political mechanisms. As Foray (2004) remarks, knowledge codification generates substantial indivisibilities and non-rivalry which, in turn, trigger changes in the prevailing social coalitions. New skills, complementary to the new technologies, can be considered akin public goods: individual firms have no incentives to finance or settle educational programs where the new skills can be attained without the cooperation of competitors (Vona, 2008a). A study on the emergence of public education during the first industrial revolution by Galor et al. (2008) shows that the entrepreneurial class actively sustained the expansion of public expenditures for education against the landowners. Also demographic structures will affect the propensity to invest in public goods, such as education: given the long-run rewards of these investments older individuals are less likely to support an increase in educational expenditures. Either way it is clear that these kinds of institutional adjustments are highly sensitive to political processes (Cohen and Noll, 1981).

12 For a more detailed discussion on the role of policy in a context where technological change induces productivity slowdown see Amendola et al. (2005) and Amendola and Vona (2008).

Careful consideration deserves also the issue of designing an educational systems vis-à-vis the challenges outlined above. From the foregoing discussion it follows that the structure of education supply is indeed a potential source of inequality, especially when the degree of homogeneity across universities is low. Although evidence on the relation between university quality and earnings is limited (e.g. Brewer et al. 1999), and results are sensitive to measures of university quality (Zhang, 2005), recent works show that the fraction of the graduate wage premium explained by university quality has increased sharply between the 1970s and the 1990s (Brewer et al. 1999, Zhang, 2005)[13]. This is consistent with the framework presented in this paper. Moreover if cycles of knowledge creation and systematization are limited to elite institutions, i.e. those that collaborate closely with highly innovative sectors, a gap in the quality of education is likely to increase within-group wage inequality. Proximity between elite institutions and innovative firms is a key source of qualitative advantage; in periods of intense technical change this advantage tends to grow together with the 'unexplained' wage inequality among graduates.

A last remark is that the capacity of educational institutions to adapt their knowledge depends crucially on the degree of decentralization of educational system. A highly decentralized educational system such as that of the U.S. has, in principle, provided larger room for experimentation and, thus, better conditions to accelerate the transformation of educational supply in elite institutions. The key organizational issues hinge upon the dynamic trade-off involved by the adoption of either centralised or decentralised structures. Decentralized schooling encourages experimenting and seems better geared to support changes in the structure of relevant knowledge (e.g. Murnane and Nelson, 1984), but at the same time carries the risk of thwarting social mobility. For example in Anglo-Saxon systems increasing returns to attendance of high-quality schools are positively related to higher intergenerational inequality: therefore growing heterogeneity in the quality of schools entails that residents of wealthy neighbourhoods have easier access to better education. A number of studies (e.g. Dale and Krueger 2002) indicate that returns to attending elite institutions are lower if one explicitly considers student talent, i.e. test scores. However in systems like the U.S. it is very likely that differences in pre-university level of human capital are due to huge variance in high-school quality. This lends support to the idea that the equalization of learning opportunities can be achieved through interventions at each level of the school hierarchy.

6. Concluding remarks and challenges ahead

This paper proposed an appreciative reading of recent empirical evidence on the dynamics of earnings and wealth distribution against the backdrop of the emergence of new Information and Communication Technologies. The central focus was on the effects that the new techno-economic paradigm borne on the systematisation and diffusion of new knowledge vis-à-vis empirical evidence on increasing earning inequality.

13 For a cohort who graduated from high-school in 1972 (resp. 1982), the top college premium, defined with respect to the bottom public college wage, was 0.15 (0.39) in the 1986 (1992) (Brewer et al. 1999). Moreover, the experience premium for those who attend top institutions seems to be much steeper than the experience premium for middle institutions (Thomas and Zhang, 2005).

The first part offers a critical review of the standard human capital theory and concludes that the latter undervalues systematically the role of the institutional adjustments required to coordinate technology development and education. Under the linear view implicitly adopted by the basic tenet the educational infrastructure adapts seamlessly to the emergence new knowledge. Empirical evidence on the emergence of new job requirements within changing organizational domains indicates a far more complex picture, one in which the adaptation of education and training that is needed to accommodate radically new technologies cannot be taken for granted. The second part of the paper draws on the field of innovation studies and provides the basis for a dynamic life-cycle approach which articulates the institutional changes that can support effectively the systematisation and diffusion of new knowledge. It is observed that both traditional educational practices and entrepreneurial action are of great value for innovation in different, yet complementary, ways along the life-cycle; lack of institutional intervention may turn one as obstacle for the other. This is a first step towards an alternative analysis of earning distribution cum technological change.

The dynamic life-cycle proposed here suggests an interesting theoretical and empirical research agenda ahead. For what concerns the former, the elaboration of a task assignment model with imperfect skill substitution across job types seems a natural step; a key challenge in this exercise, coherent with the foregoing framework, is the inclusion of institutional adjustments in the formal framework (Consoli and Vona, 2008). For what concerns the empirical aspects the impact of institutional heterogeneity, such as differences in school quality, on within group wage inequality deserve deeper analysis. For example, more precise evaluations of teaching capabilities across educational institutions should complement the assessment of research; institutional-specific labour market effects, such as the wage premium or index of the social utility of jobs, can provide useful information for the assessment of teaching capabilities. In relation to such matters the paper suggests a rule-of-thumb to assess the balance between research and teaching capacity which is contingent to the country's technological gap.

Acknowledgements

The authors would like to thank Cristiano Antonelli and Dick Nelson for stimulating remarks and suggestions on an earlier draft of this paper. The comments of Mario Amendola, Dick Langlois and Paolo Naticchioni are also gratefully acknowledged. All remaining errors are our own.

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