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Abstract

This paper focuses on the complementary institutional and organizational adjustments that facilitate the routinization of technological opportunities. To address this issue we propose a life-cycle approach that accounts for the emergence, development and transformation of the conduits for the transmission of new knowledge and skills. While it is widely held that knowledge tends to get more organized as by-product of innovation, the purposeful absorption of practical know-how into formal education is another crucial, and arguably less analysed, intermediate step to bridge the beginning of the life-cycle, when new skills are closely tied to some novel technology, to later phases when the emergence of new disciplines and the diffusion of those skills elicit complementary developments in the technology. The paper connects themes that are central to the tangled policy discourse on skills impact innovation, namely: the institutional adjustments required to favour the re-absorption of skill mismatches; the systematization of knowledge underpinning the creation of new academic disciplines; and implications for dynamics of productivity and of the wage structure.

Keywords: Knowledge systematization; Skill life-cycle; Cognitive comparative advantage;

Technological paradigm.

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1. Introduction

The central concern of this paper is the relation between technological change and economic growth under the rules of capitalism, whereby modern societies attempt to advance technology and adapt institutions to extract wealth from continuous accumulation of knowledge. Therein the capacity of a system to replicate some initially circumscribed technology and to extend it to progressively interrelated, if sometimes unintended, domains of use is a crucial feature (Dosi, 1982; Freeman and Perez, 1988; David, 2001; Antonelli, 2008). It is often observed that after the advent of a new General Purpose Technology market mechanisms on their own do not warrant investments in specific skills and physical capital and a broad set of institutions and organizations become necessary (Brynjolfsson and Hitt, 2000; Bresnahan and Trajtenberg, 1995). By and large innovation emerging from a variety of behaviours acquires economic significance through complementary institutional adjustments and organizational innovations that facilitate collective learning and the routinization of innovative opportunities (Nelson, 1994; Baumol, 2002).

The notion that routinization is crucial to the full exploitation of latent innovative opportunities dates back to the dawn of post-industrial revolution capitalism, when science became progressively embedded in the design and organization of systems for production and distribution. History shows clearly that the ‘inventions’ of Watt, Marconi and Edison paved the way to new socio-economic paradigms because transformations in dynamically related areas of knowledge facilitated the exploitation of the associated latent opportunities (Noble, 1977; David, 1992; Wright, 1999). In these and other instances progressive knowledge diversification and division of labour goes hand in hand with renewal of knowledge and reorganization of the transmission mechanisms that allow coherence across specialized activities (Rosenberg, 1976). While it is widely held that knowledge evolves and tends to get more organized as by-product of innovation, purposeful absorption of practical know-how into formal education is yet another crucial, and arguably less analysed, element of technological revolutions. Following on this the present paper focuses on the institutional pathways that permit the systematization of practical knowledge into synthetic rules and usable instructions. In particular, we take skills as unit of analysis and elaborate a life-cycle heuristic to articulate the emergence, development and transformation of the content and the conduits for the transmission of new knowledge and skills. In so doing we disentangle the intermediate steps between the beginnings of the life-cycle, when skills are closely tied to some novel technology, and later phases when appropriate adjustments in education ensure the diffusion of those skills and elicit complementary developments in the technology. Accordingly we focus, first, on how technological change impacts the organization of work by inducing either new task configurations within existing occupations or the emergence of wholly new occupations (e.g. Autor et al. 2003), and, secondly, on the institutional responses that foster knowledge standardization and qualitative adjustments of education and training.

The perspective purported here draws on the seminal contribution of Nelson and Phelps (1966) on the relationship between human capital and innovation. In a nutshell, at early stages new technology is at most accessible to those possessing adaptable skills until technological diffusion lowers the threshold of skilfulness and enables adoption to less-skilled users, whose previous competences have become obsolete. The latter step is, however, contingent to adjustments within and between institutional domains that have been hitherto little explored (exceptions being Nelson, 1994; Rosenberg, 1998). The paper claims novelty in connecting themes that, despite an apparent fit, are seldom brought explicitly together. First it reflects on the dynamic two-way relationship between innovation and education that is crucial to the evolution of comparative advantage within knowledge economies. To this end, we use concepts from the literatures on knowledge economics and on cognitive comparative advantage (e.g. Cowan et al, 2000; Levy and Murnarne, 2004) to highlight new aspects of the interplay between technology and education (Goldin and Katz, 1999). Secondly, it calls attention to linkages between innovation and labour market dynamics that have been relatively neglected by innovation scholars. Third, the proposed framework seeks to operationalize the process of ‘knowledge systematization’ (Rosenberg, 1976) by looking explicitly at the changes in educational programs. Fourth, this essay addresses core issues of the tangled policy discourse on skills and innovation (e.g. Hall and Soskice 2001; Tether et al, 2005; Toner, 2011).

The remainder of the paper is organized as follows. The next section reviews different strands of literature concerned with the connection between human capital and technological change with a view to flesh out a unified framework on the skills’ life-cycle. Section 3 unpacks the black box of knowledge systematization by thoroughly reviewing the historical importance of new academic disciplines and training programs for technical change. Section 4 elaborates the implications of different adjustment mechanisms for innovation, productivity and income distribution. Section 5 summarizes and suggests an empirical agenda for future research.

2. Innovation and Skill Dynamics: pulling together different threads

2.1 – Skill formation and technical change

The seminal work by Nelson and Phelps (1966) is a classic starting point to articulate the mutual interplay between patterns of skill formation and technological change. As the argument goes, greater learning capacity possessed by highly educated individuals facilitates the adoption of innovations, especially at early stages when the knowledge relative to new technology is ill-defined and tacit. Eventually as learning lowers the minimal skill threshold, the realm of utilization of those new technologies expands. Further renditions of this stylized skill-innovation model differentiate types of human capital, namely general and specific in relation to, respectively, the adoption of radical innovations or the amelioration of existing ones (Krueger and Kumar, 2004). The key message is that human capital has several qualitatively different components whose individual relevance depends on the phase of development of the technology and on a broad array of circumstances of time and place[1]. Subsequent literature inspired by Nelson and Phelps emphasises three types of associations[2]: investments in higher education are crucial to the pursuit of innovation-driven growth by means of radical breakthroughs; broad availability of technical and vocational skills facilitates strategies based on incremental innovation; and finally, imitation-based strategies are the only feasible option for countries with an overall low- skill workforce and remote from the technological frontier. This conceptual posture arguably over-simplifies the mutual dynamics between the creation and use of knowledge and innovation. What is the role in these contexts of policies and institutions aimed at ensuring transition from low-skill/imitation to high-skill/innovation modes? It is plausible that the skill threshold falls mechanically *just because* new technologies diffuse? What, then, of the causality chain from skill to innovation?

For definitional purposes, let us propose that individual knowledge is a combination of innate abilities, formal education and of experiential learning. Conversely, when interacting, individuals share some form of correlated understanding generated by means of purposeful codification efforts and under the influence of social habits (Antonelli, 2008; Cowan et al, 2000; Cohendet and Meyer-Krahmer, 2001). Thus while we think of knowledge as the general ‘operating system’ of an individual, the notion of skill refers to a particular mix of capacity to learn and know-how applied to a specific task in a specific context. The 'life-cycle' metaphor, therefore, seeks to capture the dynamic and relational nature of skills, that is, the cyclical patterns of relevance and obsolescence which ability to learn and apply new knowledge undergoes as a result of changing economic and social conditions.

Various contributions in the economics of knowledge and innovation studies offer useful insights to open the black box of innovation-skills causality. Knowledge that enables new technology, especially if radical, is mostly tacit, sticky and likely to be confined, at best, on the frontier of the established cognitive domain (Baumol, 2002). In such cases only few especially talented and creative individuals enjoy the associated comparative advantages and knowledge transfer is circumscribed to the mobility of these skilled individuals. Depending on how radical the technology is, successive incremental improvements, clear task specification and the creation of routines may or may not progressively lower barriers of use. In these critical stages the pace of technology adoption and development depends on the existence of appropriate conduits for the diffusion of associated knowledge and, as Nelson (1994) suggests, on adjustments within and between complementary institutional domains. Indeed a key postulate of innovation theory is that the knowledge base continuously adapts to novelties stemming from new inventions. By triggering imbalances in the distribution of knowledge among agents and across space this process accelerates cognitive obsolescence and encourages the

1. Unified growth theory represents another theoretical framework where the importance of human capital changes at different stages of the development process (Galor 2005).

2. See Krueger and Kumar, 2004; Caselli, 1999; Aghion et al, 2002; Aghion and Howitt, 2004; Vandenbussche et al., 2006.

exploration of new paradigms (Feldman, 2000). The latter, in turn, requires dedicated efforts at knowledge systematization aimed at facilitating the widespread diffusion of relevant skills as well as encouraging a cascade of complementary inventive efforts (David, 1992; Antonelli, 2008).

The adaptation of educational programs based on the creation of new disciplines and teaching models as well as the revision of the attendant training programs plays an essential role in the systematization of knowledge. In particular, large-scale replication of new forms of knowledge and skills, which are idiosyncratic to particular location and often emerge outside the educational sector[3], can be very problematic without direct interventions aimed at restoring coherence between the training infrastructure and the attendant system of production. In principle, the tacit dimension of human capital renders its transfer difficult in the absence of personal interaction (Polanyi, 1967; Nelson and Winter, 1982), both at school and in the workplace. However, knowledge spillovers due to workers' mobility are slow and tend to be geographically concentrated (e.g. Feldman, 2000). Also, appropriate educational programs and codified devices complement personal interactions and practical learning by frame problems in a broader context. More in general, formal education is a key input for on-the-job and practical training, thereby the degree of substitutability between on-the-job and formal learning is limited (Bassanini et al., 2006).

The significance of newly established disciplines within emergent technological paradigms is a recurrent theme in the innovation literature. Rosenberg (1998) and Nelson and Rosenberg (1994) emphasise the co-evolution between science and technology, together with the emergence of new standards *both* in technology and in formal education. At early stages novel and ill-defined concepts are epistemologically remote from the attendant knowledge base. Subsequently new ideas are tested in practice, refined through learning-by-using and those that stand the test of selection eventually become the criteria for framing research trajectories and directing the transformation of training systems. At the same time, the displacement of old standard makes existing knowledge obsolete and generates both 'economic' losses and political resistance. A new life-cycle begins when a new paradigm is settled and begins to be challenged by new radical ideas (Dosi, 1982; Freeman and Perez, 1988; David, 1992). Innovation scholars frame the selection processes of new ideas in the context of dynamics of markets and institutions (Klepper, 1997). At the same time being focused on firms, top researchers and elite research institutions this literature neglects the role of skills' selection and development for capitalistic societies.

Scholarly works on artificial intelligence and on cognitive comparative advantages (both related to the work by Herbert Simon, 1960) yield useful insights on the link between knowledge dynamics and the

3. In certain circumstances or historical phases, the opposite causal mechanism might operate: a change in the conceptual framework and cognitive categories within universities induces the appearance of a technological paradigm. Also in this case, however, knowledge systematization plays a major role as generally initial conceptual changes are idiosyncratically localized in a limited number of elite institutions. However the channel from innovation to education is fairly prevalent. Goldin and Katz (1999) maintain that: "technological shocks … swept the knowledge industry in the late 19th and early 20th century" (p. 39).

skill life-cycle. Labour economists, in particular, made significant contributions to the topic by framing the relation between humans and 'machines' on the dynamics of the skill-content of occupations (e.g. Autor et al. 2003). The main argument is that humans retain comparative advantage in elaborating new ideas and confront novel (i.e. unstructured) problems, working in teams, bridging different bodies of knowledge and to recognizing different contexts; conversely automated devices excel in executing efficiently and rapidly clearly specified instructions. As Levy and Murnarne (2004) aptly sum this up, humans are better endowed for either practical or cognitive non-routine tasks. Under this perspective the comparative advantage of humans does not rely on the usual definition of skills – e.g. know-how to do a well-established task which is not easily codifiable – but rather involves 'theoretical know-how', that is problem-search and -solving heuristics, codes for interpretation, framing of problems (Balconi et al. 2007). It then follows that tacitness is no longer the main attribute of human capital as at least a fraction of 'theoretical know-how' can be in principle codified and translated into propositional knowledge (see the classic analysis by Cowan et al., 2000). Ultimately, systematization can ease learning of certain skills up to the point of enabling the incorporation of cognitive and higher level skills into machines.[4]

2.2 – The skill life-cycle

Pulling together the different threads of literature outlined above allows us to propose a life-cycle perspective of skills and technical change. The seminal work of Langlois (2002) provides a connection between the literatures on technical change and on cognitive comparative advantage by suggesting that the lowering of skill threshold is a by-product of specialization and of the division of labour. Therefore at early stages of diffusion of new technology tasks are complex and 'ill-structured', they are exclusive knowledge of the few creative individuals involved in the inventive process and therefore not ready to be expressed though rule-based and codified languages (Simon, 1960; Levy and Murnarne, 2004). As technological development unfolds the fulfilment of the innovation potential carves a path of finer specialisation consisting of tasks' simplification and greater division of labour. 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. Eventually improvements reach a maximal threshold whereby tasks are fully standardized, productivity gains from specialization diminish and the process may likely give way to deskilling and narrowing of further innovation opportunities. In sum, the division of labour depends *ceteris paribus* on the extent to which tasks can be productively standardized.

4. The seminal paper by Autor, Levy and Murnarne (2002) on the organization of work in the banking sector provides a classic example of how intellectual skills were replaced by software in mortgage decisions. Another example is represented by the impressive development of the algorithms in chess playing, which are now as good as humans from a strategic point of view. Software such as 'Mathematica' can solve complex mathematical problems in symbolic language. Further examples not necessarily related to ICTs are provided in section 3.

Framed in a broader context this view challenges the assumption that the degree of substitutability between machines and (heterogeneous) workers – and thus the degree of routinization – is *de ipso facto* synchronic with the industry cycle. Rather the degree of substitutability between workers and machines increases with incremental technological developments so long as the division of labour facilitates the standardization of a higher fraction of tasks. It is therefore important to acknowledge the existence of a cognitive upper limit in the division of labour. Since specific skills yield productivity improvements mainly within an existing knowledge paradigm, the fulfilment of the innovation potential is contingent to widening, as opposed to deepening, of the knowledge base in phases where existing paradigms have been over-exploited. However, even this perspective neglects the role of educational institutions that is essential for both the routinization and the creative phases. In fact, we suggest, the extent of task standardization depends on purposive process of knowledge systematization that facilitates the diffusion of novel practice-based concepts and the emergence of specific applications.

The foregoing resonates with Baumol's (2004) observation that significant technological breakthroughs often stem from individual intuition and ability to think 'outside the box', while rigorous technical training is crucial for the exploitation of the latent benefits of invention through incremental innovations. As for the relationship between technology and complementary organizational change (Brynjolfsson and Hitt, 2000), endogenous productivity gains are not just the outcome of indefinite market expansion but also depend on complementary adjustments in the labour market – providing the incentives to accumulate specific skills – and in the educational sector. What is more, matching the supply of education to new technological requirements[5] need not be relevant only for knowledge-intensive professions, such as researchers, school teachers, engineers and science professionals. In the view presented here skill portfolios co-evolve with the array of technologies used and skills are often specific to a particular machine or organizational form, hence the adoption of a new vintage of that machine might render obsolete at least a fraction of the workers' competences (e.g. Chari and Hopenhayn 1991). Likewise, a valuable fraction of skills is occupation-specific as demonstrated by empirical research showing that income losses associated with change in occupation among displaced workers are much larger than income losses for those who stay in the same type of job (Kambourov and Manovskii, 2009).

General Purpose Technologies represent natural experiments to test the effect of technological change on changing the task requirement of several occupations. Using data of the Dictionary of Occupations and Titles (DOT)[6] Autor et al. (2003) examine the effect of ICTs in both high- and low-paid occupations in the U.S. and find that the degree of job complexity, measured by higher scores in non-

5. Again, our framework does not require that the causality nexus runs only from innovation to formal education. The broader point is that whatever new knowledge stems from industry best-practices or elite institutions should be diffused and the educational system plays a key role.

6. The DOT contains detailed information for several years on how categories of skills and tasks score within professions and sectors (see, e.g., Autor et al. 2003).

routine analytical and communicative tasks, increases also among low-paid occupations with observed fast rates of computer adoption.[7] Consistent with the notion of cognitive comparative advantage, several studies also find that widespread computer adoption is associated with a sharp decline of demand for jobs based on routine tasks such as bookkeepers, secretaries, middle-managers and non-specialized blue collar workers.[8] But computerization also stimulated the emergence of wholly new occupations, as confirmed by the addition of a dedicated 'computer-related occupations' category in the post-1991 revision of the U.S. DOT. This resonates with evidence about the importance of new occupations in accommodating imbalances associated to large-scale technological transitions (see Rosenberg, 1976, Hughes, 1983).[9] As a matter of fact the impact of computers on labour markets shares commonalities with the deskilling that followed the first industrial revolution as recounted by Marxian economists and economic historians (e.g. Braverman 1974).[10] Atack et al. (2004), for example, show that the shift from artisanal to factory work organization enabled the substitution of skilled craft workers with unskilled ones during the second half of the XIX Century. Similar insights stem from studies by Lazonick (1990) and Chandler (1977) apropos of the rise of managerial paradigm in the US and the displacement of skills from the shop floor. Conversely historical evidence on early XX Century growth in the US provides richer, and less immediate, interpretation. For instance, Goldin and Katz (2008) show that demand for formal skills was relatively higher among establishments that used intensively steam power. On the other hand Gray (2010) finds that the diffusion of electrification between 1880 and 1940 corresponds to a reduction in the demand of high-skill blue-collar workers with respect to both unskilled workers, as the standard 'deskilling argument' would predict, and, consistent with the skill-biased hypothesis, to white collar clerical workers. The general lesson is that patterns of deskilling in bottom and middle occupations and of upskilling among high-level employees are common features of large-scale technological revolutions rather than 'anomalies' peculiar to ICT technologies.

The life cycle heuristic elaborated thus far draws attention to another important question: what types of institutional adjustments match the demand for skills emerging as a consequence of radical technological change? The next section will explore this issue.

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7. To give an idea of the magnitude of within-occupation changes, between 1978 and 1990, more than 2/3 of the occupations listed in the U.S. DOT have been revised on the basis of new job requirements.

8. See Autor et al. (2003); Autor et al. (2006); Spitz-Oener (2006); Goos and Manning (2007); Goos et al. (2009). The so-called 'routinization hypothesis' (Autor et al. 2006) stemming from this stream of literature states that computers 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.

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

10. Modern studies in economic history distinguish between two phases of the Industrial Revolution. Initially, new technologies were deskilling and required minimum amount of formal education. Subsequently the demand for human capital increased as basic literacy and numerical skills became a requirement in basic factory jobs (see Mokyr, 1990; Galor, 2005).

3. Adjustments in the skill supply and the role of educational institutions

3.1 – Background

The empirical evidence discussed above lacks a conceptual framework that accounts for the re-absorption of structural mismatches between educational supply and task requirements. In standard theorizing, both in the growth and in the labour literature (e.g. Pissarides, 2000; Aghion and Howitt, 2004; Acemoglu and Autor, 2010), differences between occupational skill requirements and educational supply are blurry, and both mismatches at the 'intensive' margin, i.e. within occupations, and mismatches at the 'extensive' margin, i.e. the emergence of new occupations and skills, are not considered. Our conjecture is that the emergence of skill mismatches and the qualitative changes outlined above are structural features – rather than 'anomalies' – of the necessarily diachronic adaptation between technology and education (Amendola and Gaffard, 1988). In addition, the unclear demarcation between skill requirements and qualifications proffered by the standard theory leads to misleading conclusions. For one, that the system of formal education adapts seamlessly to the emergence new skill requirements[11] which stands in open contrast with evidence on phenomena like educational mismatches and over-education (Green and McIntosh, 2007; OECD, 2009), often interpreted as transitory phenomena due to frictions and lags in finding an appropriate occupation. Instead if changes in skill requirements within occupations and the emergence of new occupations have been relevant, the role of educational programs in supporting the nascent occupations must have played a more prominent role than what the existing literature acknowledges. Our life-cycle approach acknowledges these structural mismatches and suggests that they are difficult to reabsorb because the gap between existing and new knowledge requires an effort of systematization from specialized institutions, i.e. modern Universities.

A careful distinction of the qualitative characteristics of occupational content and of educational programs affords, first, a partial exploration of the black box concerning the sources of the skills that are crucial to societal development and, second, allows the life-cycle heuristic to come full circle. The key question is: what are the institutional mechanisms that provide society with the skills that are needed to produce, utilize and further develop new technologies? In the remainder of the section we address this question by distinguishing between (i) institutional adjustments in presence of skill mismatches at the intensive margin, mainly associated with routinized fine-tuning between supply and demand of skills and (ii) institutional adjustments in presence of skill mismatches at the extensive margin, mainly radical adjustment involving the broad redefinition of the content of educational programs.

11. This is what characterizes models following the seminal paper of Nelson and Phelps (1966). See e.g. Caselli (1999) and Aghion et al. (2002). A recent work by Iacopetta (2010) elaborates a full-fledged growth model that includes innovations in formal education enabling the diffusion a new type of human capital. The model however does not address institutional issues regarding the characteristics of innovations in education.

3.2 – Institutional adjustment for Mismatches at the 'intensive' margin

A large literature points to market failures preventing optimal change in the skill supply and hence appropriate responses to changing skill requirements. Examples include borrowing constraints preventing households' to invest in child education (e.g. Galor and Zeira, 1993), hold-up and poaching issues discouraging both workers and firms from investing in specific skills (e.g. Acemoglu and Pischke, 1999). The latter issue is even more prominent in the context of uncertainty concerning the skills actually possessed by workers. In this case the certification of competences and skills acquired on-the-job or in special training programs increases portability and workers' incentives to invest in occupational-specific skills (Busemeyer, 2009). On the firm side, more or less explicit cooperation among competitors in the provision of industry-specific skills defines appropriate standards of training and allows sharing both the cost of these specific investments and information on the emerging mismatches. The relevant example is the German apprenticeship system characterized by a high degree of non-market coordination, regulated through consensus among employers, trades unions and the government. In general, as pointed out by the literature on Variety of Capitalism (e.g. Estevez-Abe et al, 2001), it is a set of complementary institutions that prevents under-investment in specific skills.[12]

Incremental adjustments in training programs are continuously required to meet changing patterns of skill demand among firms. Coherent with the notion that the skill life-cycle unfolds in the context of adaptive learning systems (Lundvall and Johnson, 1994; Nelson, 1994) these pathways of skill development have gained currency in recent years and in specific institutional configurations. Vocational Education and Training (VET) and Life-long learning programs (LLL) involve practical forms of training within firms or in the context of inter-industry organizations.[13] Such technically-oriented programs are typically offered at secondary level though increasingly they are included in tertiary education across countries in the context of hybrid organizational forms such as multi-purpose Universities of applied science (Dutch hogescholen, Finnish polytechnics, German fachhochschulen) or paraprofessional, sector-specific institutions (e.g. Austria and Switzerland, see Kyvik 2004). The emergence of binary higher educational systems, characterized by the coexistence of specific institutional types, has its roots especially in Europe during the early 1960s owing to close collaborations between local governments and firms. Clearly, the skills developed along these pathways are tailored around the needs of incumbent firms within particular industries or geographical areas, and therefore idiosyncratic to the specificities of the attendant innovation system. It is unlikely, however, that the fruits of this cooperation can effectively promote new educational standards and

12. For instance, collective bargaining restrains external wage offers reducing the possibility of poaching, while employment protection, e.g. firing costs, increase the expected duration of the work relation together with the gains from relationship-specific investment. Besides, more or less explicit coordination between firms and unions, on the one hand, and within competing firms, on the other, enable to share the cost of specific training among all interested parties.

13. VET programs normally are designed for and used by young people at the beginning of their careers and commonly before entering the labour market, while LLL programs are mainly designed to contrast skill obsolescence of incumbents' workers.

conceptual categories to the point of opening up the potential of radical new technology. Economies of scale associated with high fixed costs of codification prevent private organizations from actively promoting knowledge systematization, at least when the cognitive gap between existing and new technologies is considerable.[14] In particular, codification of what we called theoretical know-how is not feasible within a generic firm in view of limited appropriability of the associated investments.

3.3 – Institutional adjustments for radical mismatches and new skills

For what concerns the generation of novel skills that are deemed necessary for using and developing new technologies, we argue that knowledge systematization and the related emergence of an "engineering paradigm" plays a central role.

At the institutional level, the first, obvious, candidate is the transformation of university education including new courses as well as changes in existing programs that will set the standard for curricula at lower level education. University is a crucial organizational innovation that internalizes positive feedbacks from research to teaching and from different research domains (Goldin and Katz, 1999). One of the key missions of higher education institutions (and hence of the scientific community itself) is developing new cognitive patterns and categories to absorb practical experience in rapidly evolving technological contexts. As a by-product newly established cognitive categories also enhance the transferability of knowledge by facilitating learning of less-talented individuals.

New universities and new technical training are central in several recounts of the waves of industrial innovations and sustained growth that took place in the U.S. at the end of the XIX Century. Different from the traditions that dominated in Europe, American higher-education institutions were modelled around the practical needs of local industries and priorities of state legislatures (Rosenberg and Nelson, 1994). As part of this process professional schools became embedded within universities in the US beginning the twentieth century (Goldin and Katz, 1999).

The role of University as key component of technological change is a recurrent theme in historical accounts of the transition to factory production wherein systematic efforts at codification and incorporation of useful knowledge sought to accommodate the demands of large-scale production (Noble, 1977; Rosenberg, 1976; Wrigley, 1986). Notable examples in the US include mining and mineral processing industries benefiting from new engineering training at the end of the 1800s (Wright, 1999); chemical and electrical engineering developing in symbiosis with respectively chemical, electrical and telecommunication industries (Rosenberg, R. 1983; Rosenberg, N., 1998); the speciation of training pathways stemming from and supporting the nascent computer industry in (Langlois and Mowery, 1996; Rosenberg and Nelson, 1994). The common thread across these stories

14. Perhaps only very large firms might be immune by the risk of poaching by recasting new training programs into idiosyncratic languages and codes.

is the ascendancy of engineering-type disciplines as conduits for knowledge systematization and the emergence of cognitive paradigms that bridge technical change and skill formation.

By and large public universities established at the beginning of the twentieth century offered more courses in engineering disciplines than existing private ones (Noble, 1977; Goldin and Katz, 1999). From a functional viewpoint the ascent of engineering sciences in higher education reflects the growing interdependence between scientific knowledge and economic organization (Rosenberg, 1976). We draw attention here to the translational nature of ‘engineering-type’ processes, that is, of a broad class of task-oriented activities aimed at devising criteria and procedures for a specific goal (Arthur, 2009). The dominant heuristic of such activities consists in the manipulation of physical, biological or chemical properties for constructing artificial systems through which deliberate design and control can be achieved. Therein ad-hoc feedback mechanisms are crucial for recursive problem-solving inasmuch as scientific knowledge needs be complemented with practical know-how, and especially lessons learned from failure. Our proposition is that rather than the framing of a particular body of know-how within some disciplinary boundary, the growth of engineering into an assortment of specialized branches is the reflection of a generalized process of knowledge systematization that is central to the skill life cycle heuristic proposed here.

Consider the transition to factory production, a process that entailed the development of specialised know-how to meet newly emerged standards for ensuring precision (i.e. controlling, measuring and correcting) of mechanized operations that is crucial for the viability of large-scale production (Rosenberg, 1976; Paulinyi, 1986; Metcalfe, 2002). In that particular context two things went hand in hand: a responsive machinery-producing industry to correct for technical imbalances *and* an adaptive system of education and training to compensate for skill deficiencies. Looking at a more recent example, the advent of the information paradigm relied on a nascent industry in parallel with the proliferation of disciplines that, by channelling practical know-how into specialised realms of application, magnified the roundabout potential of computing (Langlois and Mowery, 1996; Mowery, 2010). Thus the framing of repeated practice with stored-program computers within algorithm theory led to computer science in the early 1940s. Later, in the mid-1960s, improving the teaching of ill-defined principles became the key priority for the association of computing machinery (ACM) as well as of the few elite universities that pioneered training on computer sciences. [15] In spite of the impressive pace of technological improvements potentially disruptive for newly established curricula, the ACM succeeded in favouring the establishment of computer science throughout a trial-and-error process based on experimental teaching practices and progressive standardization by means of peer-

15. See the Babbage institute (http://www.cbi.umn.edu/) and issues of the ACM Computing Surveys (e.g. Vol. 28, No. 4, December 1996) for instructive material on the history of computer science. As history goes the growth of computer science triggered sub-disciplines aimed at specialized applications of the computing paradigm. An interesting example is that of Information System with the goal of adapting the ICT paradigm to organizations. The knowledge required in this field of applications is inter-disciplinary in that it combines organization and management theory, core computing skills and capacity to design and work with datasets.

review (e.g. Davis et al., 1996). Still in the computing paradigm the contribution of Stanford University stands out for its support to the refinement of the Integrated Circuit by timely adaptations of the electrical engineering curriculum (Harayama, 1998; Rosenberg, 2003).[16] Yet another relevant example, in the field of aeronautic engineering, is the systematization of operative standards in the early 1920s into a pilot training module known as Control-Volume Analysis. The latter stemmed from the systematic elaboration of specific routines for airplane control that could not be inferred from generic aerodynamics. The codification of these routines, in turn, relied on recursive practice within a community of specialists that was not limited to aeronautic engineers but included a larger group of specialized technicians (Vincenti, 1990).

The foregoing shares broad similarities with developments in other areas. A good case in point is the reorientation of psychiatry teaching due to the development of the Diagnostic and Statistical Manual of Mental Disorders (DSM). The systematic collection from multiple sources of medical records containing information on symptom observation led to the first edition of this manual in the pre-World War II period. Partly reflecting lack of heterogeneity in understanding (and accepting) mental disorders, the growing importance of this taxonomic catalogue led to the progressive abandonment of Freudian therapy and imposed a new style of practice. The influence of the various editions of the DSM is most apparent in the teaching of psychopathology and of mental status examinations both strongly focused on the detection of standard clinical symptoms and the selection of the associated treatment plan based on DSM diagnosis (Houts, 2000). This is true of several other areas of medicine where the evolution of teaching curricula reflects the growing importance of learning in practice. This is to say that the broad characteristics of the outlined ‘engineering-type’ of processes, namely strong reliance on experience, heuristics and case illustrations and a tendency to develop integrative forms of practical knowledge, are similar across disciplines as diverse as e.g. Finance (Noorgard, 1981), Design (Filippetti, 2010) and Business Studies (Whitley, 1988) – each unfolding along a specific trajectory but all sharing the bottom-up processes from practical know-how to formal knowledge. In general, new disciplines arise as academics either adapt their professional identity closer to the frontier with the real world (Ezkowitz, 2008) or, conversely, when industry experts become involved in academia. Clearly the payoffs are associated to either having access to a rich pool of experimental data that may facilitate basic research or, in the other direction, leveraging the reputation of academic institutions to improve visibility of new successful technologies or business models.

The systematization of practical knowledge into codified instructions and goals along the tracks described above generates two top-down trajectories. The first typically aims at deepening the nascent engineering knowledge through embodiment in new tools and artefacts (e.g. the dynamo or chemical plants) that allow efficient scaling up of production. A second, occasional, route is the discovery of

16. The complement to this process was the commitment by industry firms to make computers available at heavily discounted prices and provide complementary inputs that were necessary among academics (Rosenberg, 2003).

previously unknown natural phenomena that give way to novel bodies of basic scientific knowledge. Take by way of example the widespread adoption and use of electricity initially relying on basic science, especially physics, but progressively giving way to a more independent and specialized body of know-how namely electrical engineering (Noble, 1977). The latter, in turn, enabled the construction of measurement tools that facilitated the discovery of new physical phenomena and the creation of novel areas of basic science. A similar reasoning applies to several areas where the recombination of existing knowledge and routines leads to the growth of new disciplines such as in the case of Bio-informatics (Ouzounis and Valencia, 2003), Management Information Systems (Davis, 2006) or Biotechnology (Arora and Gambardella, 1995). The observation of this kind of process led Rosenberg (1998) to associate Chemical Engineering to a General Purpose Technology: for the character of 'generality' refers to the learning possibilities opened up by the systematization of knowledge rather than to the physical features of any physical technology.

The general lesson stemming from the joint reading of the literatures above is that different systems of innovation can feature substantial differences in the array of mechanisms that are implemented to assist the replenishment of the skill base, and that these differences might lead to substantial macro-effects in phases where rapid technical change requires a more radical adaptation in the knowledge base.

4. Discussion and Macro-implications

This section sketches out some macro-implication of the proposed life-cycle framework, and indicates the contours of an agenda for empirical research.

A key aspect concerns the extent to which differences in knowledge systematization affect the dynamics of productivity and the evolution of labour market inequalities. With regards to the relation between our heuristic and country performance, it is worth noticing that each country retains relative advantage by relying either on an institutional configuration that favours the re-absorption of routinized mismatches, like Germany's combination of vocational and on-the-job training and a regulated labour market, or on a configuration that relies on quick and decentralized responses on the part of the formal education system, like in the US. An even more important feature of these differences among educational systems is associated to the country's capacity to carry out radical rather than incremental innovations. The conventional wisdom stemming from seminal works by Nelson and Phelps (1966) and, more recently, Hall and Soskice (2001) suggests that institutional mechanisms favouring the development of general skills lead to successful radical innovation compared to systems whose workforce is characterised by specific skills. The empirical evidence on this point, however, is mixed. At macro-level Vandenbussche et al. (2006) show that tertiary education – including both post-secondary vocational qualifications and college education (OECD, 2007) – is especially important for productivity growth in countries that are closer to the world technological frontier. The impact of different endowments of graduate workers on productivity growth is proved to be empirically relevant in a comparison between productivity levels in the U.S. and U.K. (Basu et al., 2003). In spite of similarities both in labour market institutions and in the paths of ICT adoption, a comparative analysis of the dynamics of the total factor productivity shows that the country with the relatively larger cohort of college graduates, i.e. the U.S., maintained a higher rate of productivity growth in the 90s with respect to the country with the smaller cohort of college graduates, i.e. the UK. Interestingly, David and Wright (2003) reach similar conclusions by comparing the diffusion of electrification in same countries in early 1900s. At the micro-level there is robust evidence that new technologies tend to be adopted by firms with highly skilled workforce (e.g. Bartel and Lichtenberg, 1987) but the hypothesis that general skills spurs radical innovation more than specific skills is not supported by data (e.g. Akkermanns et al., 2009).

These studies coincide in acknowledging primacy to the U.S. capacity in generating radical innovation and in triggering virtuous skill-innovation dynamics, as the recent experience of information and communication technologies confirms. Some of these arguments resonate with our remark on the importance of adaptive education systems. Baumol (2004) calls attention to flexible and diversified teaching styles to explain differential productivity among scientists in the US and Europe, while Aghion et al. (2009) emphasises the governance of tertiary education. Storesletten and Zilibotti (2000) emphasize the trade-off between an egalitarian school system and excellent elite institutions. Thereby a highly decentralized system such as that of the U.S. provides, in principle, larger room for experimentation and, thus, better conditions to accelerate the transformation of educational supply in elite institutions. A key organizational issue hinges upon the dynamic trade-off involved by the chosen degree of centralization: decentralized schooling encourages experimentation and seems better geared to support changes in the structure of relevant knowledge (Murnane and Nelson, 1984) but at the same time might increase the effective degree of heterogeneity in the quality of schools and, hence, of skills.

Also consistent with this is the evidence of a relatively fatter tail in the right-hand of the US skill distribution (Freeman and Schettkat, 2001).[17] Likewise it may be that only high-end skills, like those acquired in top universities, are crucial for innovation in phases where the scope for technological change is greater. Possibly, a decentralized, stratified and willing to experiment educational system, like that of the US, would speed up the process of knowledge systematization at the cost of a higher heterogeneity across educational institutions. As a result of this asymmetric adjustment of training programs to new technological requirements skill dispersion would increase more in highly decentralized educational systems. Note that our life-cycle heuristic suggests policy implications on this that differ from those offered by works in the Nelson-Phelps (1966) tradition, e.g. Aghion and

17. Empirical evidence based on the standardized skills of the workforce (IALS survey) shows that the average skill level is remarkably higher in Germany than in the U.S., and that in the U.S. the variance of the skill distribution is characterized by two fat tails around the 25 and 75 percentiles (Freeman and Schettkat, 2001).

Howitt (2004). In fact fully taking into account adaptations in the supply of education sheds light on the trade-off between the speed and the heterogeneity of this adjustment.

Moreover our appreciative theory resonates also with recent evidence on the evolution of the wage structure in the US following the advent of ICTs (Autor et al., 2008).[18] Looking dynamically at the structural imbalances between job complexity and the existing educational programs, in particular, elucidates two empirical 'anomalies' in the dynamic of the wage inequality. First, 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 qualifications, experience, gender et cetera. Since the beginning of the 1980s, the trend reversed and the college wage premium outgrew the initial decline and started to increase steadily. At the same time, however, within-group residual inequality did not decrease back to the pre-ICT level, especially in top occupations and for high educational levels (Autor et al., 2008). Thus the initial decrease of the college premium reflects an obsolescence effect associated with the decreasing usefulness of existing educational programs vis-à-vis new skill requirements, and especially highly paid jobs whose skill-content has been relatively more affected by the uptake of ICTs (Eckstein and Nagypal, 2004; Autor et al., 2008). To reiterate the life-cycle metaphor, 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 importance of formal education is reduced and the relative comparative advantages in using new technologies is circumscribed to few early users and, mostly, empirically unobservable. In turn the persistent increase in within group wage inequality, especially among graduates, likely stems from the heterogeneous adjustments in the supply of higher education that underlies the US´ leadership in innovative capacity.[19] Two complementary pieces of evidence support this argument. First both the persistent increase of the graduate wage premium and of wage dispersion in the college cohort (or higher) are highly correlated to a substantial increase of the post-graduate wage premium (Eckstein and Nagypal, 2004); and, second, evidence on the relation between university quality and earnings (e.g. Brewer et al., 1999) shows that the fraction of graduate wage premium explained by university quality has increased sharply between the 1970s and the 1990s.[20] This is consistent with the framework proposed by this article: capacity of frequent adjustments in the supply of education in top Universities ensures a relatively larger skill advantage especially during phases of intense innovation. Moreover if cycles of knowledge creation and systematization are limited to elite institutions, i.e. those that collaborate

18. The US is a good example since in unregulated labour markets the wage is expected to depend more directly on effective workers' skills.

19. Notice that, unless opportunities to access new educational programs are unfairly distributed across individuals, competition among workers with similar educational attainments would eventually squeeze the unexplained earning dispersion.

20. However, Black et al. (2005) found constant wage premium for elite institutions between 1987 and 1998. The same constant returns have been observed for *grandes écoles* in France by Gurgand and Maurin (2007). To summarize, the empirical evidence on returns to University quality is still scant, problematic and mainly based on the US studies, hence identifying a clear trend is not possible.

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.

Obviously the relation between knowledge systematization and the dynamics of skills and wages is a complex phenomenon that involves several other aspects that are not addressed here. As Foray (2004) remarks, knowledge codification is a public good as it entails substantial indivisibilities and non-rivalry; therefore, as long as changes in the provision of codified knowledge affect established interests, political support for this change is not warranted. For instance, firms can expect great benefits from knowledge codification inasmuch as it facilitates the re-absorption of the workers' rents associated to tacit knowledge and know-how[21]. Similar issues emerge at the macro-level concerning the approval of public policies for education. In a study on the emergence of public education during the first industrial revolution, Galor et al. (2009) show that the entrepreneurial class actively sustained the expansion of public expenditures for education against the landowners. Other recent analyses stress the conflict between incumbents and new innovative sectors in supporting the formation of skills that are complementary to their productions (e.g. Bertocchi and Spagat, 2004; Di Gioacchino and Profeta, 2010). Ceteris paribus, incumbent firms' capacity to affect the direction of educational policies depends on their market power, which, in turn, depends on entry barriers and product market regulation. In particular, one should expect that incumbent firms privilege a high-quality system of post-secondary technical training rather than the formation of creative and adaptable skills that may likely challenge existing technologies and encourage spin-offs. The policy complementarity between educational policies and product market regulation, yet still unexplored, is evident when looking at the recent evolution of Scandinavian countries where over the last 20 years product market deregulation has been accompanied by a substantial increase in tertiary education expenditures. Incidentally, these joint reforms consent to Scandinavian countries to exploit new ICT technologies much better than main central European countries (Amendola and Vona forthcoming). Either way it is clear that these kinds of institutional adjustments are highly sensitive to the balance of political interests in several domains.

5. Concluding remarks

This essay has covered a lot of ground across literatures in economics and history in search of clarifications on the tangled relationship between skills and technological change. In so doing

21. 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). Clearly, what Zucker et al. (2001) mean by tacit knowledge is probably more similar to theoretical know-how than technical and practical knowledge.

it calls attention to a number of important issues that both the human capital tenet and the innovation studies literature seem to have overlooked. In particular, the former ignores the emergence of skill mismatches in a dynamic context where technology and education mutually adapt, while the latter lacks a thorough articulation of the role of human capital and of labour market dynamics in the process of technological change.

Rather than reiterating the main argument we would like to conclude by suggesting some items for a future research agenda based on the framework elaborated here. Two directions seem immediately promising to the effect of operationalizing our life-cycle heuristic. The first is focussing on fine-grained occupational characteristics (provided by Dictionaries of Occupations and Titles) and track changes in the skill requirements of occupations within different sectors. This exercise would go a long way in elucidating both cross-sectoral specificities as well as the longitudinal changes of the skill bases within sectors affected differently by technological change. Some steps in this direction have been made in relation to the knowledge base of Professional Services Sectors (e.g. Consoli and Elche-Hortelano, 2010). The second direction of future research along this track is our work in progress on the skill-content of 'Green' occupations, that is, the reconfiguration of task structures and job content due to new criteria for environmental sustainability. Further down the line stand other cogent questions. For example: how do academic disciplines evolve as a response to the impulse of technological change? And how do changes in course content within universities associate to the quality of higher education institutions – as measured by i.e. patents and publications? We hope that the present essay has laid some solid conceptual foundations for the pursuit of such an agenda.

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