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Technological Practice, Firms, Communities and Networks

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ABSTRACT

The purpose of this paper is to explore the notion of technology as a practice and a system of connections. The Hughesian tradition in the history of technology locates technological practice in transorganisational systems, involving a variety of different actors by a central figure or entrepreneur. The Chandlerian approach privileges the firm as site of development of idiosyncratic capabilities, appropriation and development of technologies. Alternative approaches regard technology as knowledge, associated with well-winnowed traditions of practice and clearly defined communities of practitioners, involving both individuals and organisations. Constant (1987) attempted to reconcile these different traditions, through a framework contemplating communities of practitioners as the locus of technological knowledge, firms as the locus of technological practice and technological systems as the broader context where technologies evolve. Whilst relying on Constant's insights, this paper argues that a more refined conception of technology as practice and knowledge as a system of connections needs to address junctions of user-producer interaction as the locus where technological is developed and shaped.

Keywords: technology, communities of practice, knowledge-based theory of the firm

Introduction

The purpose of this paper is to explore the notion of technological knowledge and the loci where technological knowledge is used and developed. Since Layton's (1974) pioneering contribution, technology has been looked at as a form of knowledge on a par with scientific knowledge albeit with significant differences and aims. In this paper we look at technological knowledge as practice as well as a dynamic system of connections rather than a substance or a body of universal principles. From the literature we identify three important loci of technological knowledge: firms, communities of practitioners and large-scale technical systems. These loci represent different strands of the same storyline about technological knowledge corresponding to different intellectual traditions. A second objective of this paper is to show that technology as a practice has to be understood at the level of formal and informal institutions and the interaction amongst different institutional arrangements. The focus should thus not on the loci of technological knowledge but on how institutions themselves are both constitutive of knowledge and preconditions for the development of knowledge.

The firm as a locus of technological knowledge is most closely associated with the work of Chandler. For Chandler, the firm as a managerial hierarchy is the point of departure for analysing how technological knowledge is appropriated, deployed and developed in the context of serving and developing markets. In the Hughesian history of technology tradition, the focus is on large-scale technical systems rather than on firms and system-building entrepreneurs combining both technological and organisational innovations. Firms are simply one type of actor that makes up these large-scale systems. To understand the dynamics of technological change, we must look beyond the confines of the firm and examine how a variety of actors (e.g. managers, engineers, funding agencies) establish and maintain connections amongst a variety of fields of knowledge, organisations and people. In industrial networks research, firms are important to understand technological change but only as one actor embedded in a network of relationships (Håkansson 1987, 1989).

A third strand of the same storyline is associated with the pioneering work of Constant (1984, 1987). For Constant, technology had to understood at the level of communities of practitioners who developed well-winnowed traditions of framing and solving particular technological problems in specific ways. Constant's (1984) inspiration as an historical study of the turbojet revolution and how a specific community of practitioners across a range of firms had evolved a broad set of principles to address the same design problems. In the literature on technological innovation, notions such as dominant designs, technological trajectories or paradigms are just some of the terms deployed to denote the fact that technological knowledge transcends the formal organisation level, even if the appropriation of this knowledge differs from firm to firm.

The structure of this paper is as follows: in the first section we attempt to define what is technological knowledge and what distinguishes it from other forms of knowledge. In the second part of the paper, we look at the framework devised by Constant (1984, 1987) to look at technology as embodied in both formal organisations and communities of practitioners. In the third section, we develop the notion advanced by Potts (2001) and Loasby (2002) that knowledge should be understood as system of connections and that those connections extend across different types of contexts, namely user-producer contexts. In the fourth section, we focus on the idea that institutions broadly understood as systems of rules and routines, should be understood as a form of knowledge as well as structuring the growth of specialist knowledge. In the final section, we offer some concluding comments and implications.

2. What is technological knowledge?

Since Layton's (1974) contribution, technology has been seen as embodying its own form of knowledge distinct from scientific knowledge. Layton viewed technology as a spectrum with the domain of ideas at one end, and the world of techniques and artefacts at the other, with engineering design somewhere in the middle. Rather than being hierarchically subordinate to science, technology is seen as autonomous form of knowledge interacting with science in a complex ways. But what defines technological knowledge?

For Herschabach (1995) it is through activity that technological knowledge is defined; it is practical activity that establishes and orders the framework within which technological knowledge is generated and used. Technology makes use of formal, scientific knowledge but its application is interdisciplinary and specific to particular activities. The purpose of technology is praxiological rather than the pursuit of knowledge per se. Technology's aim is to control and manipulate the physical world, to accomplish things. In doing so, technology makes extensive use of formal knowledge, mainly from the sciences and mathematics, but does not constitute a discipline since it is primarily a manifestation of the selective use of other disciplines. Technological knowledge is created, used and communicated through such processes as observing, formulating, comparing, ordering, categorising, relating, inferring, applying, correcting and diagnosing. For Herschabach, technology is not only the content to be learned but also the vehicle through which the intellectual processes embedded in technological activity can themselves be learned.

For Vincenti (1990), the term engineering knowledge has usually been associated with knowledge used by engineers whereas scientific knowledge is customarily perceived as the knowledge generated by scientists. This conception perpetuates the notion that the split between science and technology lies in their respective roles as producers and users of knowledge. Vincenti goes on to identify a variety of knowledge generating activities associated with different types of engineering practice associated with design, production and operations. Vincenti (1990, p. 237) concludes that all engineering knowledge contributes in one form or another to the implementation of how things *ought to be*, usefulness and validity being the key criteria for assessing engineering knowledge. The implementation of how things ought to be requires both procedural knowledge (know-how) as well as descriptive knowledge (know-that), some coming from science but much of it generated through and within engineering practice itself.

Vincenti goes on to consider the social agents who embody these technological knowledge-generating activities and concludes that they can be divided into informal communities and formal institutions. Informal communities of practitioners are taken to be the central agency for the long-term accumulation and transmission of knowledge about specific problem domains. Vincenti's arguments follows in the footsteps of Constant (1984) who saw all technological practice as dominated by well-defined communities of practitioners which are co-terminous with traditions of practice. These communities are for Constant (1984) the central locus of technological cognition and progress since the bulk of technological change consists of incremental improvements in practice.

For Vincenti, communities of practitioners are essential to learning processes involved in technological progress, through a combination of competition and cooperation. Competition provides variety of alternatives to tackle difficult problems whilst cooperation provides mutual support and aid. Cooperation plays a key role in fostering the development of new knowledge through exchanges of knowledge and experience. Useful knowledge gets diffused through word-of-mouth, teaching and publications. Vincenti (1990, p. 239) concludes that engineering knowledge is the product of communities of practitioners bound together by allegiances to practice and having a sense of collective identity fostered by complex interactions based on shared problems and commitments.

Formal institutions represent the other leg on which the development of engineering knowledge rests. They provide the structure, support systems within which communities of practitioners can function. Vincenti includes within this category manufacturing firms and their suppliers as well as government research organisations, University departments, regulators and professional societies. Some of these institutions are primarily engaged in knowledge generation and transmission; others have a more prominent role in influencing the directions of knowledge development while others still cut across these categories.

The contribution of Hård (1994) provides a counterpoint to those who overemphasise the cognitive aspects of technological knowledge. For Hård (1994) technology like science is a contextually limited, practical activity that only partly includes universal and cognitive elements. Both science and technology include practical, embodied and locally delimited components. Hård pleads for an approach, which highlights the idiosyncratic, embodied, contingent and contextual character of technical work. Such an approach would take into account the existence of a codified literature and a set of methodical rules in both technology and science. However, such an approach would also to an even larger extent, focus on how technologies are shaped by locally rooted practices and routines. In Hård's (1994, p. 574) words: "A practice approach should bring forth the technician as tinkerer (following the 'logic of practice') rather than the engineer as theoretician and technology as *bricolage* (informed by 'practical sense') rather than engineering as knowledge production".

Hård's analysis of the development of Diesel engines at Cummins during the 1920s and 1930s highlights the interaction of elements of universal, consensual knowledge as well as piecemeal, iterative, trial and error problem solving to resolve anomalies. Cummins solution to the fuel system in diesel engine design was made within a limited and local network of practices, based on the experience acquired by Cummins and a number of closely related firms. In the Cummins story, problems were treated in a piecemeal manner and solutions are found in a pragmatic manner, following the path of easily accessible information and knowledge (Hård 1994, p. 575).

For Hård, engineers and technicians are socialised into their vocations through a mix of universal knowledge in the form of theoretical tools, common practices in terms of chosen design solutions and methods and global orientations, in terms of commonly adopted design goals. When engineering converges into the same, broad path of development we can refer to technological trajectories or dominant designs as the collective outcome of a consensus reached by practitioners in a field.

But, as Hård (1994. p. 575) points out, important parts of technological development have an irreducibly local character. Local trajectories based on idiosyncratic traditions as well as heterogeneous ways of appropriating global trajectories, highlight that engineering is a pragmatically oriented and contingently delimited activity. In the next section we will focus more specifically on the locus of technological knowledge.

3. The Locus of Technological Knowledge

Vincenti's (1990) discussion pointed to two sources of knowledge production, communities and formal institutions, even if he is rather silent on how these two sites interact and co-evolve. The literatures on the history of technology and business provide a complementary perspective to Vincenti's. The Hughesian tradition in the history of technology locates technological practice in transorganisational systems, involving a variety of different actors from firms to government laboratories coordinated by a central figure or entrepreneur. The Chandlerian approach to business history privileges the firm as site of development of idiosyncratic capabilities, appropriation and development of technologies.

For Chandler, firms are the important unit of analysis because they either develop new technologies internally or select and appropriate technologies from the market. Firms have pushed existing technologies to the limit through experimenting with new products, processes and managerial structures whilst on the other hand they have tried to ride on the coattails of Schumpeter's waves of creative destruction (Hounshell, 1995). Hughes, to a large degree, sees both technological and organisational innovation as derivative of higher-level invention of systems concepts. For Hughes, the focus should be on large-scale systems and superfirms rather than on firms. In his review of Chandler's (1990) *Scale and Scope,* Hughes writes: "…because he is focused on the firm, he does not analyse the spread of the firm-transcending enterprise that his narrative describes, and he does not consider the likelihood of their increasing importance in the future that his narrative implies" (Hughes, 1990, p. 700). He added further: "Chandler not only fails to acknowledge sufficiently the rise of firm transcending enterprises and to analyse their management systematically; he also neglects to consider how the rise of modern transportation, communication and energy utilities has shaped modern management". (Hughes 1990, p. 701). Chandler (1990 p. 742) reply is dismissive of Hughes's concerns: "…I cannot get a grasp on the shape of the post-modern, super-modern, enterprises that may replace the industrial enterprise whose history I tell in *Scale and Scope*".

Constant (1984, 1987) provides a useful and systematic attempt at bridging these two positions even if it is not without problems, as we will attempt to show later. For Constant, technological knowledge is embodied in both communities of practitioners and firms, and firms are inserted into broader level technological systems. Constant's main contribution lies in articulating a relationship between these levels of analysis as well as differentiating between institutional and individual dimensions.

For Constant (1984), well-defined communities of practitioners dominate technological practice and these communities are the central locus of technological knowledge. Such communities may be composed of either individual adherents to the tradition or organisations. Every high technology sector is dominated by a few firms who together form a highly visible community of practitioners, which map on to individual communities of practitioners. For example, turbojets are designed within and manufactured by a handful of large, complex organisations that are lumped together as an industrial sector.

Individual practitioners will also split into well-defined communities. For example, engineers will commonly share professional education and background but their insertion into organisational lives is likely to lead to a complex pattern of learning-by-doing and specialisation that will further decompose the community of practitioners into smaller subgroups. The proposed isomorphism between individual and firm level communities suggests that broad traditions of technological practice, over time, are appropriated and specialised within each firm developing into local and increasingly divergent traditions.

Constant (1987) develops the idea of technological practice as encompassing multiple, hierarchical levels with a modular structure. If a technological system is modular and decomposable it can be changed or improved with great efficacy. Subproblems can be isolated and changed independently, subject only to architectural level constraints. Whether a change is incremental or revolutionary depends on the hierarchical level. Complex, hierarchical levels imply multiple traditions of practice and multiple communities of practitioners. Each level, can be seen as the purview of a different community of practitioners; yet some traditions or communities may overlap at a number of higher or lower levels of aggregation – e.g. gas turbine practitioners are both a distinct community, part of a broader aeronautical community, but they also design gas turbines for offshore oil production platforms.

More controversially, Constant (1987) proposes that individual members of a given community of practitioners should be seen as vectors for a specific replication code, carriers of a set of programmes that together constitute and reproduce the relevant traditions of practice. The recipe for overcoming the problem of technological discontinuities is simple enough: "Slice open an organisation, insert the new vector and its programming and presto!, the organisation starts replicating turbojets rather than piston engines, turbosuperchargers or steam turbines." (Constant 1987, p. 228).

It is this dual aspect of technological knowledge expressed in large-scale formal organisations and in the career commitment of practitioners that creates Hughes's (1994) technological momentum, the propensity of technologies to develop along predefined trajectories unless or until they are deflected by external forces or plagued by internal problems. The successful parsing of technological systems and their problems enables specialisation, organisational and institutional development, which in turn further reinforce technological momentum.

However, technological knowledge is never found in pure form, but is expressed through functional artefact oriented towards particular uses. It must be mixed and matched other varieties of technological knowledge implying the cooperation and coordination of multiple communities of practitioners. Thus formal organisation is necessary to provide a stable pattern of connections between multiple communities of practitioners and to aggregate various forms of technological knowledge towards the design and production of functional artefacts oriented towards particular types of users. As Loasby (1998, p. 149) noted: "Divided capabilities typically need to be used in clusters or in closely related sequences, if the improvements in each subskill which follows this division are to be guided in compatible directions and effectively used".

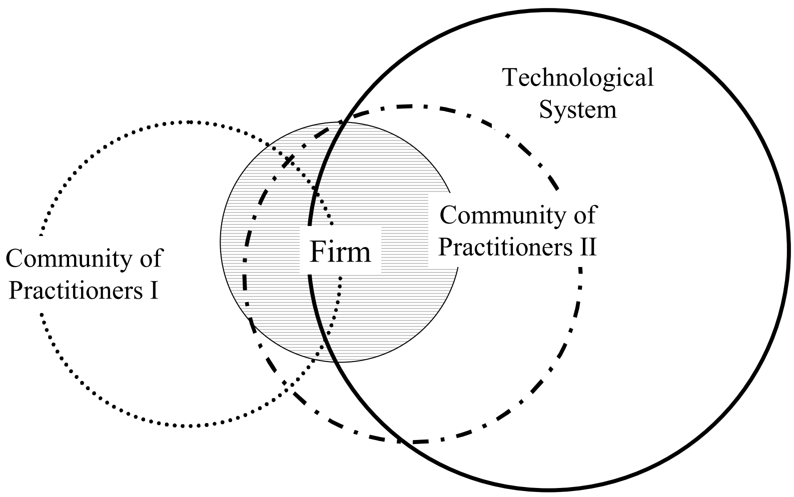
Formal organisation, as Vaughan (1999) remarks, can complicate and manipulate the knowledge production process. Organisations configure people, resources, technologies and work practices; set up motivational and incentive systems that facilitate the development of certain types of knowledge and discourage others; and establish relationships with third parties that both complement and reinforce particular logics of knowledge development.

Constant (1987) observes that each organisation within the same broad technological community fine-tracks its own technological approach to its own environment. A Honda Civic or a VW Golf is based on the same pool of international pool of technological capabilities, the same broad traditions of technological (e.g. internal combustion engines) and organisational (e.g. JIT, TQM) practices. Each of these traditions is represented by members of the same communities of practitioners and yet the technological knowledge embodied in each vehicle is also embodied in the complex, functionally differentiated organisational structure of the two firms.

In Constant's (1987) proposal each functional area in an organisation indexes a specific set of technological community knowledge necessary to perform that module's function within the organisation. More abstractly, each module or department could be considered as co-terminous with that organisation's insertion in a specific community of practitioners, as represented by individuals adherent to a broader technological tradition who happens to work for that organisation. If an organisation has a module populated by people who design say turbojets, this module does three things: it performs a design function for the organisation; it contains adherents of the turbojet community of practitioners; and it makes the organisation a member of the turbojet community, now defined at the organisational rather than the individual level.

For Constant (1987) each module in the organisation is a locus for potential change both for the organisational performance of that module as well as for practice in a broader represented community. Each of these modules also represents an environmental interface, a semipermeable membrane through which the organisation both receives information and acts on the external world. It is within through these modular interfaces that in the ideal case, Hughes' (1992) reverse salients are identified and resolved. It is also in these organisational modules (and through the individual practitioners who inhabit them and their connections to relevant communities) that technological frames or trajectories might be said to exist.

In summary, Constant (1987, p. 240) proposes to see communities of practitioners as the social locus of technological knowledge, organisation as the locus of technological function (with a modular conception of function used to portray the way knowledge and function are integrated in complex organisations), and socio-technical systems as the broader structural contexts of both – see figure 1.



Adapted from Constant (1987, p. 238)

Figure 1

Constant's proposals have the undoubted merit of providing a comprehensive and systematic framework for analysing the nature and loci of technological knowledge. But a number of issues remain unclear in this framework. First, the development of firm-level technological trajectories is underspecified. Constant mentions that each firm fine-tracks its own technological approach in response to its own environments and local contingencies but there is no indication as to how this process might unfold. Secondly, the modular conception of organisational structure underpinning the interaction between communities of practitioners and formal organisations elides some of the obvious issues relating the role organisations play in creating and processing knowledge rather than serving as mere loci where communities earn their living. Finally, the hierarchical conception of technological systems provides no means through which technological variety and architectural innovation can come from within as well as without the system.

3. Knowledge as Practice

The dichotomy between firms and communities of practitioners has been pursued in the literature in different ways. If Constant conceives at firms as modular assemblages of representatives of practitioner communities, others have stressed that firms are essentially non-modular structures and should be themselves be seen as a communities. For Kogut and Zander (1996), firms are superior to markets because they generate patterns of communication, coordination and learning that are situated not only physically, but also mentally through the development of an identity rooted in the notion of a firm as a social community. The firm boundaries are largely determined by this discontinuity of knowledge generated inside, relying on coordination and learning based on shared identities. Identities are important because: "Through identity, individuals anchor their perceptions of self and others and attach meaning to a membership in a firm, as well as in the categories of skill that define a division of labour (e.g. "worker" or "accountant"). More importantly, through identification to occupation and firm, individuals are guided and motivated along coordinated paths of joint of learning" (Kogut 2000, p. 408).

Brown and Duguid (2001) provide a useful critique of the notion that firms as social communities and culturally uniform entities. Their starting point is the paradox that firms often find hard to transfer knowledge inside as much as they find it difficult to avoid leakiness of knowledge to outsiders. Brown and Duguid's approach to this paradox is that practice creates epistemic barriers among the different communities that make up a complex organisation. The suggestion is there is a need not only to look beyond explanations that take knowledge as a substance that can get stored and circulated, but also to look beyond explanations that take the cultural unity of the firm for granted.

Brown and Duguid make extensive use of Lave and Wenger's (1991) notion of communities of practice. The notion of community of practice focuses on how work context provides a platform for the construction of shared identities and collective outlooks on the world and work. Within these communities knowledge can easily be shared since shared perspectives and identities facilitate learning and the construction of common interpretations. This perspective embraces the possibility that organisations include many different identities and helps explain how different practices often create loosely coupled or balkanised organisations, where knowledge sticks to specific locations or segments of the organisation.

Brown and Duguid (2001) elaborate this argument by proposing that practice creates a common substance that aggregates different types of communities into “networks of practice”. The term “network” suggests a looser relationship than is implied by a community of practice, more appropriate for situations where members have extensive interactions and experience of dealing with each other.

Not unlike Constant’s (1987) vision, Brown and Duguid see disciplinary networks of practice cutting horizontally across vertically integrated organisations and extending far beyond the boundaries of the latter. While networks embrace people with a core of common practices, organisations embrace communities with fundamentally different practices, presiding over a particular division of labour, and hence, of practice and knowledge. Internal divisions within organisations help explain knowledge stickiness while the external connections help explain leakiness. Taken together, these observations suggest that a firm’s knowledge doesn’t falls within its boundaries but partly draws on the embeddednesss of the firm in broader community structures. The implication is that knowledge may flow out of the firm more productively than within it.

Brown and Duguid’s (2001) proposals suffer from much the same problems as Constant’s (1987) framework. The split between formal organisations and informal communities or networks of practice fails to recognise that practice requires an orientation towards a set of problems and contexts that cannot only be found at the junction between producer and user contexts. Brown and Duguid also fail to address the local, situated and embedded character of technological practices. This characteristic accounts both for variations in the way firms or even parts of firms develop idiosyncratic traditions as well as role of organisation in establishing connections amongst a set of dispersed, heterogeneous and often sticky local practices.

Hård’s (1994) story of the development of the Cummins’ engine portrays technical development as occurring within a local frame of reference and embedded in a series of relationships where first-hand experience played a key role. An iterative model of working allowed Cummins to design new engines, enrol new customers and made changes after the new engines went into operation. The development work took Cummins along a rather specific path and it followed a piecemeal, iterative problem solving strategy that incorporated both in-house and market-based experience.

Von Hippel and Tyre (1995) and Tyre and Von Hippel (1997) describe a similar scenario in their study of problem identification in field trials of novel process equipment. Field trials usually help expose a host of problems related to the interaction between machine and use environment in customer plants. Some of these problems emerge as a result of a lack of pertinent information about the use environment, while other problems emerge only as a result of user learning associated with using the machine in the field. It is the practical intricacies and emergent nature of this interaction between supplier, machine, and use environment that precipitates the appearance of problem symptoms and leads to design changes. In the process of getting the equipment to work within the use environment, the locus of problem solving may go through several iterative loops between the supplier and customer.

De Wit et al (2002) introduce the notion of innovation junction to define the space where sets of heterogeneous technologies come to be mobilised in support a particular set of activities. As a result of the co-location and interaction of these technologies, specific patterns of innovation tend to emerge which create a need for coordination amongst these different technologies. The dynamics of innovation junctions such as the office can only be understood by focusing on the interaction between users and manufacturers, sometimes mediated by various kinds of intermediaries such as consultants. In industrial networks research, there is a plethora of studies showing how the dynamics of innovation is intimately related to a complex structure of relationships involving a multiplicity of actors (for a recent example see Håkansson and Waluszewski, 2002).

The implication is that a focus on technological practice needs to take into account how producer and user contexts are linked. Practices are always oriented towards a particular set of problems and carried within a particular disciplinary matrix, partly reliant on universal knowledge and global orientation towards particular solutions and methods. But this doesn't invalidate the observation that user-producer contexts embody location-specific, contingent and sticky knowledge that cannot easily be transferred or replicated. It is these contingent and local character of developing and applying technological knowledge at user-producer interfaces that allow firms to develop their own technological trajectories, based on path-dependent and cumulative learning.

4. Knowledge and Institutions

The above discussion leads us to look at the ways knowledge can be organised and developed in industrial systems. Loasby (2001) starts from the position that knowledge is structure, a system in the form of categories into which phenomena, concepts and ideas are grouped, or in the form of relationships between such categories. As in Hård (1994), these categories are not general purpose and universal but oriented towards loosely coupled systems of context-specific problems and solutions. These connections are always imperfect and incomplete – the knowledge possessed by any one individual is always a small fraction of the total knowledge available in any one domain. As Loasby (2002, p. 8) puts it: "We make sense by making patterns and we stick to apparently successful patterns and seek to enlarge their scope, perhaps with modifications at the periphery; sometimes we perceive apparently successful patterns in another business or another discipline and try to import them; and sometimes we create a link between two patterns and produce an innovation".

The generation of novelty is accomplished through processes variation and selection but against a background of stability – variation and selection are meaningless unless both the variants and the selection environment are stable for a while. Potts (2001) conceives of knowledge as sets of connections between ideas and can be represented by a system of rules. This knowledge is not abstract and disembedded but consists of solutions to problems that have been satisfactorily resolved and carried forward as a generative system of connected elements. In short, all knowledge requires a system, a set of frameworks that connects disparate elements of knowledge, both practical and theoretical. New knowledge and economic evolution proceeds through the creation, maintenance and destruction of connections.

Institutions are a response to the limitations of the incompleteness and dispersed nature of knowledge; they are also an important supplement to the structure of internal cognition. As Loasby (2002, p. 1235) puts it: "”Knowledge itself is organisation, produced by trial and error, and always subject to challenge, including changes in its form and its relationships to other bodies of knowledge; it is the product as well as a precondition of decisions. Knowledge lies in the particular connections between elements rather than the elements themselves…"

Economic activities rely on different types of mechanisms to connect agents and dispersed knowledge. Stable clusters of connections are required for some processes whilst other processes benefit from more variable and flexible connections. Firms and business relationships provide stability to economic systems whilst markets contain much greater variability going from fleeting transactions to longer-term trading patterns. An economic system is thus a patterned network of connections combining stability and a structure to facilitate repeated transactions as well as an experimental space where new knowledge is created through the creation and destruction of connections. Some of these connections are best handled through modular type structures whilst others require more interactive interfaces and closer management of interdependencies (Araujo et al, 1999). Our argument is that firms, markets, networks and communities all play a part in both stabilising economic systems and creating the potential for new connections.

The key characteristic of firms is to allow for this embedding of sets of specialised and complementary capabilities where specialisms can be pursued without the need to continuously negotiate and clarify their mutual relationships. The Penrosian perspective on the firm was that it should be seen as "…a collection of productive resources the disposal of which between different uses and over time is determined by administrative decision" (Penrose 1959, p. 24). This view encapsulates two important arguments. First, the productive resources the firm controls are regarded as a bundle of possible services, rather than a fixed set of attributes available as public knowledge. As Penrose (1959, p. 75) remarks, it is the heterogeneity rather than the homogeneity of both human and material productive services that makes firms unique. Secondly, as Penrose (1995, p. xiv) acknowledges, the administrative structure of the firm provide not only the platform for deciding how the existing stock of knowledge is to be mobilised but also constitute a framework for the creation of new knowledge.

What is specific to a firm is thus not the collection of resources and specialisms it aggregates but the connections amongst them which allows to be oriented towards a range of different purposes, namely in the form of different product and service offerings as well as new methods of delivering them. In short, as Richardson (1999) remarked, what is distinctive about firms is not just the professional knowledge and skill its members bring with them but the complex pattern of relationships and "local knowledge" derived from teamwork and continued interaction. Richardson (1999, p. 29) credits Penrose (1959) to "… leading us to understand firms, more fully than before, as embodying and transmitting through time attitudes, habits, experience, knowledge and skills, both general and specific, without which no economy can work successfully".

Firms cannot thus be reduced to loci where communities of practitioners converge and are organised in modular-like assemblies, as Constant (1987) proposed. The identity of the firm is defined not just by its commitment to the continued development of a range of specialisms but to the architecture that connects and mobilises these specialisms in particular directions. Coordination amongst specialisms requires compatible routines, frameworks and decision mechanisms whilst their continued development is stimulated by diversity and differences amongst specialisms. The advantage of firms is that they are able to connect and give coherence to a variety of local practices and user-producer contexts. Productivity gains stem from capturing similarities amongst activities and reusing existing knowledge in the form of economies of scale and scope (Langlois, 1999). Overlapping knowledge boundaries with other parties also create the opportunity to develop new knowledge. Through selective interaction, firms can combine their respective knowledge of how products are designed, manufactured and used.

This takes the form of what Håkansson (1993) calls joint learning and Lundvall (1993) interactive learning. Joint or interactive learning often requires stability and a degree of continuity of association to take effect, in the same way that continuity of association with a firm helps specialise and glue generic resources to a firm (Richardson, 1999). In order to evaluate what a counterpart can offer, a firm will need to interact with that counterpart over a period of time. If a measure of stability is an important pre-condition for joint learning, the existence of a degree of variety in the structures within each firm operates is also an important ingredient in joint learning (Håkansson, 1993). There may be important systemic effects when each party in a business relationship is involved in a range of other relationships, which may provide important pointers and guideposts for the joint definition of needs and solutions. As Loasby (1998, p. 156) puts it: "The development of a specialised skill depends on a variety of experiences, but a variety that can be encompassed within a network of connections".

Loasby (1999) alerts us to the facts that the growth of knowledge within any firm requires a degree of closure and agreement, which limits the range of variations that can be successfully pursued. The overall growth of knowledge in an economy requires further sources of variety, allowing for a broader set of combinations and recombinations that can be successfully accomplished within firms. Marshall (1920, p. 115) identified three institutional mechanisms for development knowledge in a community of practitioners – that of a single business, that of various businesses in the same trade and that of various trades in relation to one another. Beyond these there are institutions that guide the practice of specialised communities of practitioners and facilitate transactions between members of these communities.

Businesses within a single trade by acting and thinking in different but readily comprehensible ways, provide access to vicarious experiments and learning. Networks of complementary trades, linking dissimilar but complementary or closely complementary types of knowledge, through markets and cooperative relationships (Richardson, 1972), provide multiple opportunities for knowledge development. Young's (1928) vision of industrial dynamics, which anticipates some of the key research themes in industrial networks research, is one of continuous generation of value as a consequence of rearranging connections both within and across firms. For Young the progressive division and specialisation of labour is the process through which increasing returns are realised. Increasing returns apply to the individual components of industrial systems and to the connections between them. The dynamic processes Young illustrates require a variety of learning processes encompassing firms, relationships between firms and network structures that gradually transform an existing structure through a series of small but interconnected changes.

Finally, communities of practitioners play an important role in the growth of knowledge in a number of ways. First, communities of practitioners facilitate the diffusion of technical information and provide channels for know-how trading. Larsen and Rogers (1984) study of emergent industries in Silicon Valley suggests that in the growth phase of an informal and densely patterned networks between communities of practice based on professional allegiances and reciprocity of information exchanged provide an efficient and rapid source of learning. Saxenian's (1994) study of the evolution of the computer and semiconductor industries in Silicon Valley and Route 128, ascribes the comparative success of Silicon Valley to these rich and dense information networks that continuously cross firm boundaries and contribute to the diffusion of technical knowledge.

Kreiner and Schultz (1993) study of the Danish biotechnology industry found what they termed a barter economy, an infrastructure of interaction between individuals working for a variety of firms and research institutions involved in the exchange of favours and services. Powell et al's (1996) study of R&D alliances in the US biotechnology industry suggests that when knowledge is widely dispersed and its potential sources diverse networks of formal and informal relationships tend to develop as a means to accelerate learning. Liebeskind et al (1996) stress the role of social networks in facilitating access to valuable scientific knowledge in the US biotechnology industry but emphasise instead the role of hierarchy in supporting and channelling those exchanges. Almeida and Kogut (1999) show that the interfirm mobility of engineers influences the spillovers of knowledge in a regional labour network.

Studies by Hamfelt and Lindberg (1987), Von Hippel (1987), Carter (1989), Schrader (1991) and Von Hippel and Schrader (1996) also suggest that informal practices of information exchange on a routine basis between rival organisations also occurs in mature industries. Von Hippel (1987), for example, studied the existence of information trading of process-related knowledge in the US steel mini-mill industry and discovered that when process knowledge is not found in-house, an engineer can either proceed to develop it in-house - which is costly and time consuming - or else, in the absence of publicly available information, contacts his or her peers in rival organisations who may have faced a similar problem.

Secondly, communities of practice provide a context for multiple and alternative forms of relationships, coexisting with other, more formal and institution-based relationships. Communities can, for example, provide the platform for the organisation of technical committees, task forces, standard-setting bodies which may play an important role in guiding technological development. Rosenkopf and Tushman (1998) study of the flight simulation industry demonstrates how communities of practitioners can serve as loci for consensus building and negotiation particularly during eras of technological ferment.

Thirdly, communities of practitioners can play an important role as outsiders in technical development (Van de Poel, 2000). Outsiders may be able to acquire a role in technological development if gaps appear in the expert division of labour that sustains a particular technological regime leading to opportunities for newcomers. One such possibility is illustrated by the development of turbojet engines (Constant, 1987). Since the 1920s aerodynamic theory suggested that conventionally propeller engines would be inadequate for powering aircraft to known attainable speeds. Turbojet engines were known to be capable of delivering higher power at higher levels of efficiency than were previously thought possible. These insights combined to introduce what Constant (1987, p. 226) called a presumptive anomaly that eventually led to a major change in both the community of practitioners involved in and the tradition of technological practice associated with aircraft engine design.

Conclusions

At the beginning of this paper we identified technological knowledge with practical activity and conceived it a system of connections between ideas, people, materials, artefacts, etc. rather than a well-defined substance or a universal and easily accessible body of knowledge. The main function of economic systems is to provide mechanisms of coordination that can help organise, generate, test and modify knowledge.

A focus on technological knowledge as practice and as a system of connections leads us to focus on how the institutional forms through which knowledge is constructed and carried forward in the form of rules, solutions, technical artefacts, etc. But, as Potts (2001) and Loasby (2002) have stressed, rearranging connections in knowledge systems cannot be understood as a mere reconfiguration of a static body of knowledge. Instead, knowledge is created through reconfigurations of connections and new forms of knowledge creation pose new problems of coordination. Rather than seeking to locate knowledge in firms or communities of practice, we would be better advised to look for how different institutional forms support different types of connections and how knowledge development itself reconfigures these connections within and across firm boundaries. Economic systems need both stable clusters of connections and latitude for experimenting with reconfigured connections.

The conception of knowledge as practice and as system of associations has a number of implications for the study of industrial networks. First, there is a need to be clearer in what circumstances and how business relationships contribute to the development of knowledge. Relationships provide an arena to confront complementary but dissimilar knowledge, as Richardson (1972) highlighted, and for producer and user contexts to interact. But not all relationships lead to the development of new knowledge and relationships are more often than not characterised by well-honed routines rather than hotbeds of innovation.

Secondly, there is a need to develop further the notions of how economic evolution proceeds through the growth of knowledge conceived as creation, maintenance and destruction of connections (Potts, 2001). The concept of friction introduced by Håkansson and Waluszewski (2002) is one important advance in this direction. Friction captures the notion that movement of knowledge involves both transfer and transformation when different types of knowledge interact. Friction is seen as having two important effects on knowledge development (Håkansson and Waluszewski 2002, p.230). One effect relates to the idea that the rearrangement of connections is not a merely a problem of coordinating static pieces of knowledge, but contributes to the transformation of those different pieces of knowledge. The second effect is concerned with the notion that development proceeds along paths of least resistance, weaker or more flexible associations that allow for experimentation and tinkering. This last observation brings us back to the logic of practice, and the extent to which innovation requires both black-boxing of some issues and concentrated focus on others.

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