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Understanding the role of the technical in the build-up of sociotechnical constituencies

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Abstract

This paper aims to advance the systematic understanding of the role of the technical in innovation and technology development. Many studies show explicitly or implicitly that the term technology merely black-boxes the true complexity of an enormous population of specific technologies, each with its own practical implications for technological processes and innovation strategies. The paper signals a direction for future research and lays down the foundations for a generic open-ended taxonomy of technologies designed to help raise the role of the technical in the analysis and practice of innovation. The theoretical case makes use of the author's sociotechnical constituencies approach and includes a selective review of concepts and taxonomic definitions of technologies. The taxonomic instrument is applied to two empirical cases of strategic development of technology—formal methods and microprocessors. A concluding section situates the perspective of the paper within the general relationship between the social and the technical and suggests directions for further research. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

This paper aims to advance our systematic understanding of the role of 'the technical' in innovation and technology development. Many studies show explicitly or implicitly that the term 'technology' merely black-boxes the true complexity of an enormous population of 'specific technologies', each with its own practical implications for innovation strategies and technological processes. Indeed, technologies are often qualified by adjectives such as complex, science-based, high-tech, networks, components, systems, emerging, mature and so on, suggesting a reality with immediate implications for the pursuit of successful innovation or development. Moreover, as a simple matter of experience, we realise that there are real differences between a hammer and a microprocessor. The issue is how to systematically integrate this realisation into our understanding and practice of technology development.

The intention of this paper is not to provide definitive answers, but rather to signal a direction for future research by taking the first steps in a possible programme that builds on the individual contributions of many other authors. A definite intention is to lay down the foundations for a taxonomic instrument aimed at helping innovators, technology strategists and students of technology, not just to be aware of the strategic influence of technical characteristics, but, above all, to brainstorm and raise creative questions about the strategic implication of the technical in their processes of innovation and technology development. It proposes that the nature and state of development of given technologies do condition the strategic limits and opportunities for their processes of development. It proposes further that systematic knowledge of this 'technical' dimension may greatly enhance the soundness of strategic approaches and, consequently, the chances of successful innovation or development.

The case is made up of five parts: (a) a selective review of concepts and taxonomic definitions of technologies; (b) the presentation of a theoretical environment enabling the treatment of the strategic implications of 'the technical' in innovation processes, namely, 'sociotechnical constituencies'; (c) the introduction of a conceptual tool designed to help raise the role of 'the technical' in the strategic analysis and practice of innovation—

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‘a generic open-ended taxonomy of technologies’ or, more precisely, ‘technology ‘genotypes’’[1](i.e. characteristics which in combination help to define the nature and state of development of individual technologies); (d) the application of taxonomic categories to two empirical cases of strategic development of technology—formal methods and microprocessors; and (e) a concluding section situating the perspective of the paper within the general relationship between ‘the social’ and ‘the technical’ and pointing to directions for further research.

2. A selected review of the technical

All technologies are created by humans and, in this basic sense, they are all socially shaped. Once this basic fact is realised, however, it is important to move on to acknowledge that many of these social creations evolve characteristics which tend to remain stable for long periods of time, to say the least. These characteristics congeal into a form of technical terrain which has critical implications for specific strategies of innovation and development of technological capabilities.

In fact, the realisation that the nature of technology plays a role in the evolution of technological and economic processes is not new. Its roots may be traced back to the days of Smith’s division of labour, Ricardo’s chapter on Machinery (see Ricardo, 1929), and above all the determining role accorded by Marx to the development of the productive forces (see Marx, 1977). Then onwards, other scholars have identified the conditioning role of technology, especially within the development of society as a whole. These include the classical work of Lewis Mumford on technics and the megamachine (see Mumford, 1934, 1967, 1970); Marcuse and Habermas on technical rationality (see Marcuse, 1941, 1964; Habermas, 1971); Ellul’s technological society (see Ellul, 1963, 1967), which is followed closely by Goulet (1977); Galbraith’s technostructure (see Galbraith, 1967, 1971) and Winner’s autonomous technology (see Winner, 1977, 1985).

Descending from the societal to the level of specific technological processes, Hughes’ ‘technical reverse salients’ resemble Rosenberg’s ‘set of imbalances and compulsive sequences’ in that both point to the determining effect present in the systemic relationship between parts in a system. Reverse salients refer to those areas where the frontal development of a technological system falls behind, costs accumulate, and innovation efforts eventually concentrate (Hughes, 1983). In a similar way, “complex technologies create internal compulsions and pressures which, in turn, initiate exploratory activity in particular directions.” (Rosenberg, 1969, p. 4) Rosenberg stressed that the concept of compulsive sequences was not a crude form of technological determinism, where changes in society are explained in terms of changes in technology; it was rather an assertion that technology is much more of a cumulative and self-generating process than economists had generally recognised.[2] Some sociologists—especially of the social constructivist school—have been quick to issue a blanket condemnation of technological determinism without much regard for systematic analysis. Even here, however, the role of the technical has led to the use of phrases such as ‘technology shapes technology’ (MacKenzie and Wajcman, 1985), or ‘the sociotechnical moulds the sociotechnical’ (Law, 1988). On the whole, however, the-role-of-the-technical is not an area where social constructivists feel comfortable.

Economists—particularly of the tradition of evolutionary economics—have clearly perceived that the nature of technology plays a major part in the development of firms and the economy. As a result a number of taxonomies have been proposed, most of them with a focus on innovation, the firm and the economy, rather than on the technologies themselves. Innovation in particular has been a well visited theme.

2.1. Innovation-focused taxonomies

A basic distinction is between product innovation and process innovation. Utterback and Abernathy (1975) defined product innovation as “a new technology or combination of technologies introduced commercially to meet a user or a market need” (p. 642). In turn, process innovation concerns improvements in the production process defined as “the system of process equipment, work force, task specifications, material inputs, work and information flows, etc. that are employed to produce a product or service” (p. 641).[3] In their classical study, Utterback and Abernathy proposed that the characteristics of the innovation process systematically correspond with the stage of development exhibited by the firm’s production process technology and with its strategy for competition and growth. Product innovation predominates in the early stages of development, but gradually gives way to a greater number of process innovations as the product become more standardised.

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[1] The concept of genotypes is used in its biological sense of genetic or factor constitution of an individual.

[2] Rosenberg (1969) was concerned that inside economics “in looking for the origin of technological changes in the manufacturing sector, the technological level itself had been badly neglected” (p. 3).

[3] In practice, as Laage-Hellman (1987) notes, “it is often very difficult to distinguish between process and product development. Firstly, process and product innovation are frequently combined in the sense that new process technology is used to make new products. Secondly, what is thought of as a process innovation by one firm, e.g. a semiconductor company, may be considered by another, e.g. a machinery supplier, as product innovation” (p. 26).

One of the best known taxonomies is Freeman's 'taxonomy of innovations' (see Freeman, 1985, 1988) which looks at technologies from the point of view of their transformational impact on firms, industry and the economy. It has four categories: incremental innovations, radical innovations; changes of 'technology systems,' and changes in 'techno-economic paradigm'[4] (technological revolutions).

Incremental innovations occur more or less continuously in any industry or service activity, although at different rates in industries depending upon the combination of demand pressures and technological opportunities. Radical innovations are discontinuous events, usually the result of R&D from enterprises, universities and/or government laboratories. In products, they provide potential springboards for the growth of new markets (e.g. nylon). In processes, they provide potential big improvements in cost and quality of existing products. They may have dramatic effects over long periods of time, but their economic impact is small and localised unless a whole cluster is linked giving rise to whole new industries (e.g. synthetic materials and semiconductor industries). Changes of technology systems are far reaching changes in technology affecting several branches of the economy as well as giving rise to entirely new sectors. They combine radical and incremental innovations along with organisational innovations. Changes in techno-economic paradigm are changes in technology systems so far reaching in their effects that they have a major influence in the behaviour of the entire economy. A techno-economic paradigm takes a relatively long time (a decade or more) to crystallise and a much longer period to diffuse through the system. This diffusion involves complex interplay between technological, economic and political factors.[5]

A similar taxonomic approach is contained in Abernathy and Clark's (Abernathy and Clark, 1985) concept of resilience mapping which relates innovation to the overall competitive performance of firms. The diamond of Fig. 1 shows the relation of Abernathy and Clark's concepts to those of Freeman. According to Abernathy and Clark "the competitive significance of an innovation depends on what it does to the value and applicability of established competence—that is, on its transilience…[In addition]…It is the particular combination or pattern of technology and market transilience that is important in determining competitive impact" (pp. 5, 7).

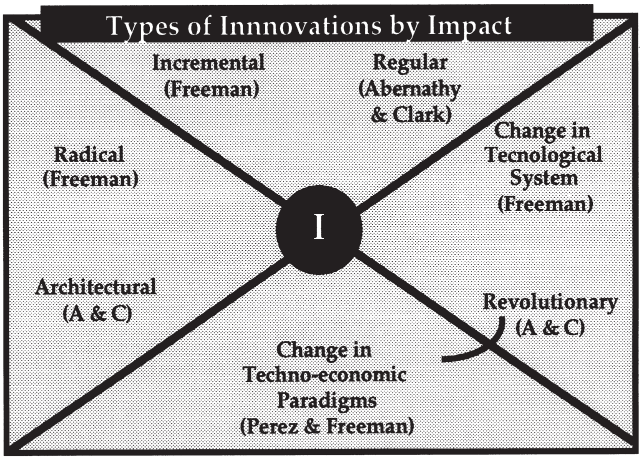

Fig. 1. Diamond of taxonomies of innovations.

The 'transilience map' relates market transilience to technology transilience, giving rise to four quadrants representing different kind of innovations: architectural, niche, regular and revolutionary. Architectural innovation is new technology that departs from established systems of production, opening up new linkages to markets and users. It is associated with the creation of new industries as well as the reformation of old ones. Niche creation is using existing technology to open up new market opportunities. The effect on production and technical systems is to conserve and strengthen established designs. Regular innovation is similar to incremental innovation. It is often invisible but can have dramatic cumulative effect on product cost and performance. A revolutionary innovation is applied to existing markets and customers, disrupting and rendering established technical and production competence obsolete.

In a different approach, Kleinschmidt and Cooper (1991) sought to categorise innovation by their degree of innovativeness. They distinguished three categories. Highly innovative products consisting of new-to-world products and innovative new product lines to the company. Moderately innovative products consisting of new lines to the firm, but where the products were not as innovative (that is, not new to the market); and new items in existing product lines for the firm. Low innovativeness products consisting of all others: modifications to existing products; redesigned products to achieve cost reductions; and repositionings.[6]

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[4] The concept of techno-economic paradigm was first developed by Carlota Perez. See Perez (1985).

[5] Freeman (1974) has also proposed a taxonomy of firm strategies centred around the competitive positioning of firms regarding innovation. Thus, *offensive strategy* is introducing products ahead of the competition; *defensive strategy* is early adoption of technology; *imitative strategy* is follow the leader, not necessarily closely; *dependent strategy* is accepting a subordinate role to stronger firms; *traditional strategy* is to remain with traditional often craft-based products; and an *opportunist* or *niche strategy* is identifying a new market opportunity for basically the same technology.

[6] Later, Cooper and Kleinschmidt (1993) extended their innovativeness categorization to seven types on new products based on a modified version of a typology found in Booz *et al*. (1982). These are:

(1) True innovations—a totally new product to the world that created an entirely new market;
(2) a totally new product to the world, but for which there was an existing market;
(3) a totally new product to our company, but which offered new

Further distinctions have been introduced by Tushman and Anderson (1986) who characterise radical innovation as either competence-enhancing or competence-destroying technological discontinuities. For instance, the transistor was competence-destroying for vacuum tube makers, but competence-enhancing for computer makers. In turn, Henderson and Clark (1990) have re-defined the meaning of architectural innovation. For these authors architectural innovations change the way in which the components of a product are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched.[7] They argue that 'incremental' and 'radical' technologies are just two possible types of innovation. Two further types are modular innovations which change only the core design concepts of a technology, and 'architectural' which change only the relationship between them. They make clear that they are not arguing that architectural innovations leave components themselves untouched. Indeed, this type of innovation would often be triggered by a change in a component that creates new interactions and new linkages with other components in the established product.

From yet another angle, Teece (1988) differentiates autonomous (or 'stand-alone') from systemic innovations. In his view, an autonomous innovation is one that can be introduced without modifying other components or items of equipment. In turn, a systemic innovation requires significant readjustment to other parts of the system. The importance of this distinction is that it stresses the different amount of design coordination which firms are likely to require in the development and commercialisation of the two types of innovations.

2.2. *Firm-focused concepts of technology*

Focusing on technology rather than innovation opens up a number of additional taxonomic contributions. Some authors have sought to classify technologies from the point of view of their strategic importance to the competitiveness of firms. Ford (1988), for instance, identifies three types of technologies. Distinctive technologies—giving the company a distinctive competence in relation to competitors. 'Basic' technologies—on which the company depends and without which it would not be able to operate in its markets. External technologies—which are supplied by other companies. Ford suggests that 'older (mature) technologies' are much more likely to be acquired externally as they are also more likely to be available for sale. He also distinguishes the category of 'support technologies', since often a newly developed product technology can only be effectively exploited through use of supporting production technology or a marketing skill which the company does not possess (p. 93).

Indeed, the theme of the competitive role of technology for the firm is recurrent. Thus, 'distinctive' and 'support' technologies relate to Teece's (Teece, 1986) discussion on complementary assets and the appropriability regime determining a company's ability to control, or fully appropriate, the commercial benefits of successful products. Teece himself identifies the nature of technology as one of the most important dimensions of such a regime.[8] He defines product, process, and tacit and codified knowledge as key dimensions. Thus, a technology based on codified knowledge is likely to have a weak appropriability regime, since it can more easily be copied than one based on tacit knowledge which by definition is difficult to articulate. Patents do not always guarantee perfect appropriability because many can be circumvented at modest cost. On the other hand, when the innovation is embedded in processes, tacit knowledge is greater and trade secrets are likely to provide better protection than patents.

Similar concepts are pursued by Whelan (1988) in the form of three categories. Critical technologies which—like Ford's 'distinctive' and 'basic'—directly affect a company's competitive position—here the aim is to acquire a better position than competitors.[9] Enabling technologies which help a company to operate but do not directly help them to compete—here the company aims to be at least equal to its competitors.[10] Strategic technologies which are still in their early stages of development but could eventually lead to new areas of critical technology and competitive opportunities.[11]

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features versus competitive products in an existing market;
(4) new product line to our company—but competed against fairly similar products in the market;
(5) a new item in an existing product line for our company which was sold into an existing market;
(6) a significant modification of an existing company product; and
(7) a fairly minor modification of an existing company product (p. 99).

[7] Following Clark (1988), they distinguish a component as a physically distinct portion of the product that embodies a core design concept, while the overall architecture of the product lays out how the components will work together.

[8] The other critical dimension in the appropriability regime is the efficacy of legal mechanisms of protection, i.e. patents, copyrights and trade secrets (Teece, 1986).

[9] These technologies are commonly developed by the firm's own R&D and the firm owns the intellectual property rights. To develop these technologies, it may be necessary for the firm to undertake some basic scientific research itself, or to access the public science base.

[10] This is more concerned with access to capability. This means that a much wider range of options is available for technology acquisition and development, i.e. collaborative R&D, licensing, use of subcontractors, and joint ventures.

[11] These technologies emerge from the basic research that firms are undertaking, or from pre-competitive research being undertaken with universities, research institutes, or in collaboration with other companies who need not be in the same industrial sector.

An earlier taxonomy on the same lines is found in A.D. Little (1981) which contains three categories. Base technologies which are the rock on which a business rests and are thus very essential. They resemble Whelan's enabling in that they may have enabled a firm to enter a business, but no longer provide a competitive advantage because they are readily available to all competitors. Key technologies which—like Whelan's critical—have the greatest impact on competitive performance and are essential to the firm's development of distinctive and indispensable skills for business success. Pacing technologies which are still in an early developmental stage and have a demonstrated potential for changing the basis of competition. A.D. Little (1981) also included a categorisation of different phases of maturity of technology: embryonic, growth, mature and ageing. These phases are spread along an S-shaped curve rising from first experimental attempts to full achievement of performance potential of the technology.[12] "There is usually a difference in maturity between pacing, key and base technologies. Pacing technologies are—by definition—newer or less mature than key technologies; key technologies are often less mature than base technologies" (A.D. Little, 1981, p. 15). Like Whelan's 'strategic,' pacing/less mature technologies focus on the state of development of technologies, and consequently on their relationship to product life-cycle.

For our purposes, the important element of all categories such as 'distinctive', 'basic', 'enabling', 'critical', 'key,' is that they are defined relative to their contribution to the firm's competitiveness and not in relation to their implications for the development of technological processes themselves. This means that the categorisation does not reside in the character of the technologies themselves but in what they contribute to firms. Different is the case of pacing, emerging, mature technologies because here the categorisation resides in the state of development of technologies rather than exclusively in their positioning inside the firm. This kind of differentiation by the nature and state of development of technologies and its impact on company development, is what leads Kantrow (1983) to say that "technology has an inner logic that simply must be considered in a company's strategic planning" (p. 3). This type of categorisation by 'the nature of the beast' is the principal concern of this paper.

2.3. Technology-focused concepts

A good starting example is Didrichsen's (Didrichsen, 1972) concepts of extensive central technology and branching technology.[13] Didrichsen identifies them to describe firm diversification through internal development, but these concepts are basically technology-centred in that they bring out the related or unrelated nature of technologies or products in firms' development. Thus extensive central technologies are broad competences with the potential for spinning off scores of new products, for instance, organic chemicals in companies such as Du Pont. In contrast, branching technology is not clustered around a central competence. A company exhibiting branching technology may have started with a narrow speciality and typically evolved step by step into progressively unrelated product directions, for instance, mining and abrasives in companies such as 3M.

On the same technology-focused track, Afuah and Utterback (1991) talk of assembled products and non-assembled products. The former would be products such as televisions, the latter products like flat glass, rayon, and electric power generation. Interestingly, they point out that the original Utterback and Abernathy product/process model applies to assembled rather than non-assembled products.[14]

Another interesting technology characterisation is found in Saehney (1992), who develops the concept of infrastructure technologies to refer to human-made geographically extensive and interconnected technological networks which are critical for the working of a modern society. There are only a handful of technologies which can be classified as infrastructural technologies, including railroads, inland waterways, highways, postal system, electricity, telegraph and telephone.[15] These examples indeed define what are infrastructural technologies. According to Saehney, "Perhaps the most characteristic feature of an infrastructure technology is the 'sys-

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[12] A.D. Little (1981) suggests that several "indicators can be used to determine the maturity of a given technology:
Its degree of technical uncertainty, which tends to be the highest for embryonic technologies and lowest for mature and ageing technologies;
The level of interest and activity around that technology, which tends to be maximum at the growth stage:
The breadth of its potential new applications;
The technical nature of the work needed to develop it further:
Its productivity pattern—i.e. its cost/benefit outlook;
Its patent activity focus;
The technical prerequisites for having access to that technology;
Its general availability" (p. 15).

[13] Didrichsen's concepts follow Chandler's work in firm diversification. For instance, Chandler (1962) finds that "From a single specialized technological base, such as cellulose, calcium, or chlorine chemistry, enterprises have quickly developed a wide range of products. Since the development, engineering, and processing of the new items involved much the same technical know-how and equipment as the old, the transfer and application of the company's resources into new lines of products have proved comparatively easy" (p. 375).

[14] According to Afuah and Utterback (1991), some work on product and process change in non-assembled products is found in Utterback and Nolet (1987).

[15] "In the case of infrastructural technologies, examples not only illustrate but also define the concept." (Saehney, 1992, p. 540, note 25).

tem of relationships' that organise its constituent elements into a network…In the case of infrastructure technologies, the interconnections or the 'system of relationships' between elements are more important than the constituent elements themselves. This 'system of relationships' is greatly influenced by social, economic and cultural factors…the network structures of the infrastructure technologies grow in accordance with the sociocultural milieu of the larger society" (p. 540).

More recently, the Interim Report of the High Level Group of Experts on the Information Society (1996) characterised information and communications technologies (ICTs) as 'informational technologies'. Their characteristic feature would be that, as they develop, they lead to "increased memorisation, speed, manipulation and interpretation of data and information. Their development will increasingly make possible 'codification' of large parts of the skills required of people in the workplace" (p. 11). This characterisation is used to discuss the potential employment implications of the 'information society.'

A different angle on ICTs is found in Orlikowski et al. (1995). They argue that many computer-mediated communication technologies are general-purpose media, and hence 'open-ended technologies' potentially facilitating a range of possible interactions and interpretations. The benefit of open-ended technologies is the flexibility they offer. At the same time, full and appropriate utilisation of these technologies requires their adaptation to the context and vice-versa; they must reflect local conditions or communications norms (Orlikowski et al., 1995). Similar types of technologies are categorised as 'equivoques' by Weick (1990), who argues that new technologies bring a combination of increased cognitive demands, increased electronic complexity, and dense interdependence over large areas, thus increasing the incidence of unexpected outcomes that ramify in unexpected ways. For Weick (1990), new technologies exhibit three major qualities: stochastic events, continuous events and abstract events. Stochastic events because they show unclear cause–effect relations, permanence of uncertainty, frequent design by implementation, difficulty to diagnose because of the substantial mental demands they make on operators, difficulty to control because of interactive complexity, and difficulty to measure because people disagree about what constitutes effective performance. Continuous events because they are continuous processes imposing a shift from efficiency to reliability imperative. Abstract events because more and more of the work associated with new technologies has disappeared into machines.

ICTs have also been categorised as 'generic technologies' because of their intrinsic potential for significant impact on the development of the 'information society' (Molina, 1994). In this respect, generic technologies are associated with features such as pervasiveness, cross-sectoral basis, multi-disciplinary basis, and inter-penetration in marketed products. In addition, they seem to challenge the traditional economic view of diminishing returns in that they tend to give cumulative competitive advantages to those who first succeed in their creation, production and diffusion. This case is made by Arthur (1993) as follows: "The average cost of producing high-technology items falls off as more of them are made. There is positive, not negative feedback: once a product gets ahead of its rivals, it gains further cost advantages, and can get even further ahead. High technology is subject to increasing returns" (p. 6).

A recurrent theme is that of complexity. We already saw Rosenberg (1969) describing that "complex technologies create internal compulsions and pressures." Other authors take up the same theme with different overtones (Singh, 1993; Kash and Rycroft, 1993; Tidd, 1995; Kline, 1991). Kline offers a mathematical definition of complexity in the form of $V + P + LC < V \times P \times L$. Here C is complexity; V is the number of independent variables; P the number of independent parameters; and L the number of feedback loops in the system and the surroundings. Using this definition, Kline argues that technological systems, being sociotechnical, are inherently complex and "we have no principles of any significant predictive power about complete sociotechnical systems, although we can make accurate predictions about some parts" (p. 475).

Tyre and Orlikowski (1994) take up the theme of complexity from the point of view of the degree of difficulty different technologies present to people wanting to make changes. Stand alone systems, for instance, are used and adapted by individuals, with the result that any change made by one person does not affect others' use of the technologies. In contrast, complex production systems require group effort for their implementation, use, and adaptation. Individuals either cannot make changes independently to the technology (due to the technical complexity), or are prevented from doing so by work norms and procedures.

For Singh (1993), three characteristics define the nature of complex technologies or product systems. They are systemic in that they consist of numerous components and subsystems; they exhibit multiple interactions across different components, subsystems, and levels; and they are nondecomposable since they cannot be separated into their components without degrading performance. Complex systems depend strongly on the quality of both the components and the interfaces within subsystems. In these cases, according to Tidd (1995), "radical innovation becomes more difficult because different sectors and firms will be responsible for different subsystems and components" (p. 308). From an opposite angle, Kash and Rycroft (1993) argue basically the same point: "economic success with complex technologies results from incremental innovations. For these authors, complex technologies are also characterised by many components and interactions. Consequently, they are not subject to full understanding by an individual and monopoly protection is difficult, because their substance is continuously changing and because there are great economic benefits to be gained from rapid small improvements. Complex technologies and their ingredients are the recipient of many patents. What makes them different from simple technologies is the enforcement difficulty and the frequent lack of economic benefits from enforcement" (p. 30). In contrast, simple technologies are those which can be understood by an individual expert. They normally can be accurately described and communicated on paper and they are susceptible to effective communication among experts across sectors and over distances. Kash and Rycroft argue that incremental innovation of simple technologies is either not possible or economically unattractive. Pharmaceuticals, for instance, prevent a disease (such as polio vaccine) and thus completely satisfy a demand (p. 29). From the viewpoint of innovation, there are two major characteristics associated with the nature of complex technologies:

- expanded opportunities for incremental innovations as the many components provide plenty of opportunity and multiple ways for improvement.
- legal protection is hardly possible since "the opportunities for rearranging interactions among components and subsystems, plus the possibility of introducing new subsystems and components provide the means to engineer around the legally protected products and processes" (p. 30).

This complexity is clearly found in Hughes' large-scale technological systems and Saehney (1992) 'infrastructure technologies'. It is also found in the kind of systems resulting from Kodama's (Kodama, 1991) 'technology fusion'. Fusion essentially blends incremental improvement from several often previously separate technologies to create a new product, a new market and new growth opportunities for participants in the innovation. Home automation is a case of technology fusion analyzed in Tidd (1995). He argues that different modes of technological innovation will demand different inter-organizational linkages. Thus, by definition, "technology fusion requires the bringing together of diverse technologies and therefore will involve links with suppliers and firms able to offer complementary technologies" (p. 317). The whole area of complex technologies has now become the subject of a major research effort with the formation of the Complex Product Systems Innovation Centre (CoPS) in Brighton, UK [see Hobday (1997) for a CoPS' statement on product complexity]. In the coming years interesting results are expected.

Another major theme is that of the relation between the nature of technology and the players required for their successful innovation. For instance, architectural innovations are said to demand a deep knowledge of user needs and access to a wide range of component technologies. A close relationship with customers and a range of suppliers is therefore important (Tidd, 1995).

Fleck (1994) identifies 'configurational technologies' as technological and non-technological components built up to meet local contingencies. As such, the "participation of users at various levels, familiar with local contingencies, is *necessary* to build configurations. User knowledge, job design, and human factors are not just adjuncts, but essential *inputs* to the innovation process, helping to crystallise contingencies into novel artifacts" (Fleck, 1993, p. 15). In short, if configurational technologies are to be at all successful, they "demand substantial user input and effort and such inputs can provide the raw material for significant innovation" (Fleck, 1994, p. 637–638).

Fleck (1988) distinguishes four categories of technologies and relates them to different theories of innovation and technology development. These are discrete technologies, component technologies, generic system technologies and configurational technologies. Discrete technologies function as self-contained packages requiring no interfacing with other elements so that they can be used in a direct and immediate manner by customers or ultimate users. The implication for innovation is that discrete technologies do not require the active participation of users, beyond decisions in the market place. This means that the traditional linear model of innovation (i.e. innovation stage followed sequentially by diffusion stages) may be adequate in this case. This model may also adequately apply to part of systems or component technologies (especially the more mature). "With component technologies, it is often possible to make innovations within relatively stable design specifications…thus improving overall system performance" (p. 19). Fleck's generic system technologies come closer to 'complex' and 'infrastructure' technologies. They "refer to complexes of elements or component technologies which mutually condition and constrain one another, so that the whole complex works together" (p. 18). These technologies exhibit similar characteristics to Rosenberg's "set of imbalances and compulsive sequences" in that innovations in particular components tend to necessitate changes in several other components as well as at the level of the entire system (e.g. aircraft). In this case, the innovation process is much more complex. In particular, "there are extensive iterative interactions between all the various agents involved as mature systems evolve out of mutual adaptation and processes of incremental innovation" (p. 23). Active user involvement in the innovation process will depend on the extent to which systems are stabilised and standardised. The greater the standardisation, the smaller the requirement for user involvement, and the closer they approach to the conditions of discrete technologies. In this context, configurational technologies are essentially systems in early stages of evolution. Thus, they are made up of components working together but the ensemble shows no internal standardisation or stability in the overall system performance requirements. Indeed, the interacting components may be put together in a wide range of ways to match externally set requirements. In this sense, they are open rather than closed systems and each installation is more or less a unique adaptation to the local contingencies of application. It is this openness that differentiates configurations from generic system technologies and, as described above, calls for extensive user participation in their application and innovation. Fleck sees an evolutionary relation between configurations, generic systems and discrete technologies (i.e. an evolutionary taxonomy of technologies). Thus, in time, as requirements become clearer and standardisation emerges, some configurations may give rise to generic systems (Fleck, 1993). Even further away in their stabilisation and standardisation, some generic systems may evolve into discrete technologies and, indeed, may become constituent components of other systems and/or configurations.

This review has shown that the nature and state of development of technology has been a preoccupation and theme of technology studies for a long time and from a variety of angles. In my view, however, there is still plenty of room for improvement and especially missing is an overall framework aiming to bring together multiple categories into a generic taxonomic instrument for technology management and strategy. In the following, I shall seek to develop the foundations of one possible taxonomic instrument, incorporating some of the categories already discussed, as well as others such as Price's (Price, 1984) instrumentalities, Molina's (Molina, 1993a) architectural technologies and Katz and Shapiro's (Katz and Shapiro, 1986a, b) network externalities (see Appendix A). Prior to this, it is necessary to set the sociotechnical constituencies approach as the theoretical environment for dealing with the strategic implications of the role of the technical.

3. Sociotechnical constituencies and alignment

The basic tenets and evolving conceptual aspects of the sociotechnical constituencies (STCs) research programme are found in various papers (Molina, 1990, 1992, 1993a, 1994, 1995, 1997; Molina and Kinder, 1998). Here its presentation will be limited to those aspects of most relevance to set the discussion of the technical into perspective.

The constituencies programme starts from the realisation that the processes of innovation and technology development always entail the build-up of sociotechnical constituencies. STCs are briefly defined as dynamic ensembles of technical constituents (e.g. machines, instruments) and social constituents (e.g. institutions, interest groups) which interact and shape each other in the course of the creation, production and diffusion of specific technologies. This definition grants an intrinsic role to the technical in the emergence and evolution of specific constituencies. The aim of this paper is to unpack this role by examining in detail the nature and maturity of technology in constituency-building. This sets the guidepost for the discussion. My concern is not with the nature and maturity of technology in the abstract; it is with the systematisation of its role in the build-up of sociotechnical constituencies and hence technology development. This makes it necessary to describe the concept of sociotechnical alignment to help position the role of the technical in the constituencies programme. This will also enable the formulation of a taxonomy with strategic implications for constituency-building or innovation processes.

3.1. Constituency-building as sociotechnical alignment

3.1.1. Sociotechnical alignment

Sociotechnical alignment is the answer to the question: how are sociotechnical constituencies built up? It is what social constituents try to do (however consciously, successfully, partially or imperfectly) when they are promoting the development of a specific technology either intra-organisationally, inter-organisationally, or even as an industrial standard.[16] It may be seen as the process of creation, adoption, accommodation (adaptation) and close or loose interaction (interrelation) of technical and social factors and actors which underlies the emergence and development of an identifiable constituency. As such alignment should neither be seen as a mere jigsaw-like accommodation of static available pieces nor as complete and permanent, once achieved. For this reason, the term 'alignment' is well supplemented by those of 'misalignment' and 're-alignment' which express, on the one hand, situations of tension and dis-harmony and, on the other, changes or re-accommodations in the life of a constituency. Non-alignment may preferably be used for situations in which the parties have not come to each others' attention and is thus less proper to talk of tensions or conflict. Also, alignment between people should not be reduced to consensus. The latter is one possible form of alignment but there might also be 'authoritarian'

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[16] The concept of alignment is used in the literature dealing with the implementation of information technology in the organization. It commonly refers to the process of 'matching' business and information systems strategies but, as we have seen, it has also been used, more generally, to deal with the mutual adaptation process involving 'incoming' technologies and user-organizations (Leonard-Barton, 1987, 1988, 1991). For strategic alignment see, for instance, Venkatraman et al. (1993), Baets (1992), Chan and Huff (1993), Luftman et al. (1993), Broadbent and Weill (1993).

forms in which alignment is enforced by one party over another through sheer use of power.

3.1.2. The diamond of alignment

The concept of ‘diamond of alignment’ has been used to illustrate the multiple dimensions of alignment required for successful constituency-building in intra- and inter-organisational contexts. Molina (1994); Molina, (1995, 1997); Molina and Kinder, (1998)) contain a detailed explanation of this concept for different cases. In this paper, only a summary of the basic aspects is given in the form of Fig. 2 and Table 1.

At the centre of the diamond is the evolving technology of the constituency. At all times, specific products, solutions and applications are not separate from the constituency. Rather they are evolving technical manifestations crystallising its state of development. The constituency is illustrated by the shaded areas (I) and (II), which include both its constituents’ perceptions, goals and resources and its specific technical nature. The areas (1, 2, 3, and 4) represent aspects of critical influence to the success or failure of constituencies’ technologies. The key to technology success lies in the quality and effectiveness of the alignment strategies and tactics implemented to keep all these aspects evolving in a convergent and synergistic direction.

3.2. Taxonomy of technology ‘genotypes’

This paper is fundamentally about Dimension II (Nature and Maturity of the Technology), although it is clear that, in the diamond of alignment of Fig. 2, other dimensions contain technical ingredients too. Dimensions 3 and 4 have been the subject of some taxonomic development. This is shown in Fig. 3 where Freeman’s (Freeman, 1985, 1988) and Abernathy and Clark’s (Abernathy and Clark, 1985) ‘types of innovation by impact’ fit well the diamond’s Nature of the Target Problem. Thus, the target problem posed by an incremental innovation is, in principle, incomparably less complex for constituency-building than that posed by a radical innovation, let alone the problem posed by a change in techno-economic paradigm engulfing all society. In turn, the taxonomy in Dimension 4 has been developed as an intrinsic part of the concept of sociotechnical alignment, again highlighting the fact that, in principle, constituency-building is more challenging with some technologies/constituencies rather than others (e.g. antagonistic as compared to complementary).

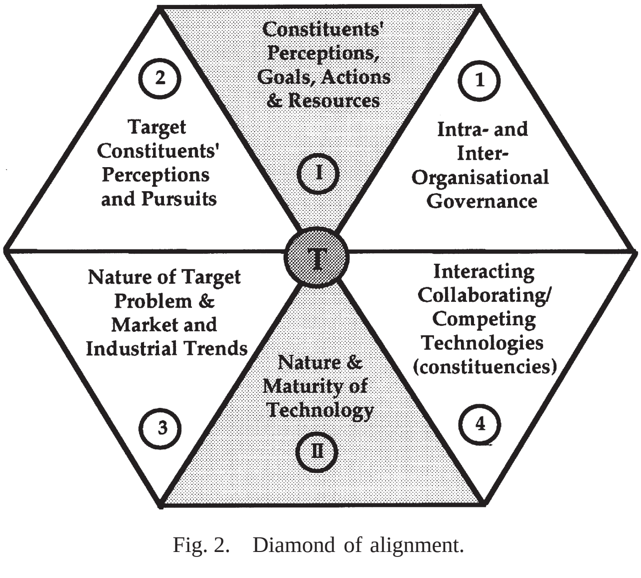

Fig. 2. Diamond of alignment.

Taxonomic work for Dimension II has been basically evolutionary and includes A.D. Little’s (Little, 1981) categorizations related to product cycles, as well as Fleck’s (Fleck, 1988) categorization more akin to industrial cycles such as those in Utterback and Abernathy’s (Utterback and Abernathy, 1975) product/process innovations. Fig. 3 illustrates this through the S-shape curve commonly typifying the evolution of technology from birth to maturity. In addition, as the review has shown, it is precisely in this dimension that a number of categories for different types of specific technologies have been identified and discussed by many authors.

These categories, however, are largely piecemeal and scattered waiting for a first effort to generate an overall more systematic picture. This is what this paper tries next by first proposing the foundations for an open-ended taxonomy of technology ‘genotypes’ and, second, applying this taxonomy to two empirical cases of sociotechnical constituencies. It must be stressed that the intention of this first effort is not to generate a fully accomplished instrument; it is rather to signal a direction for future research. Nevertheless, as said at the beginning, a definite intention of the taxonomy is to help innovators and technology strategists not just to be aware of the strategic influence of technical characteristics but, above all, to brainstorm and raise creative questions about the strategic implication of these features for creation, production and diffusion/implementation processes. The two case studies are intended to demonstrate the usefulness of the taxonomy even at this early stage. The hope is that other studies may add, improve, or modify it altogether if this is appropriate to advance our systematic understanding of the role of the technical in constituency-building.

The open-ended taxonomy is composed of two basic elements: the set of definitions collected in the glossary of Appendix A and the diagram of Fig. 4 organising them from the left circle of technology, passing through ‘state of development’, and reaching the wide range of specific features which may be used for the most detailed characterisation of specific technologies. From left to right the figure moves from the most general to the most specific. Thus the general T (circled) is the starting point; this decomposes into three categories which encompass

Table 1
Overview of aspects of diamond of alignment

(I) Constituents' Perceptions, Goals, Actions and Resources

This dimension relates to the present state of the constituency's resources: the type of organisation, people, material and financial resources, knowledge, expertise, experience and reputation and other elements such as current perceptions, goals, visions and strategies. In short, what the constituency is at a given point in time.

(II) Nature and Maturity of the Technology

This dimension highlights the importance of the nature and maturity of the constituency's technology for strategy. Constituencies' strategies must be aligned with the strategic opportunities and limits implicit in the particular characteristics of technologies. It is a simple fact that the nature of microprocessors is different from that of hammers or drugs, and a 'universal' approach will not do.

Alignment 1: Governance

This dimension highlights the importance of alignment of the constituencies' technologies with the governance and strategic directions of organisational, industrial and market environments. In an intra-organisational context, this means, on the one hand, that the market or objective addressed by the technology is perceived as highly significant to the organisation's performance; on the other hand, it means a simultaneous perception that the potential technical and market solution is promissory and viable so as to merit allocation of resources and market demand.

Alignment 2: Target Constituents' Perceptions and Pursuits

This dimension relates to the people and organisations the constituency is seeking to enrol behind its technology. This includes alignment of perceptions and goals between the technology developers and potential or 'target constituents' in the organisational, industrial and market environments, including users, suppliers, and other relevant organisations such as independent developers.

Alignment 3: Nature of Target Problem

This dimension highlights the importance of alignment between the capabilities of the constituency and the technical requirements of envisioned products/services and markets (e.g. target functionality and cost). This includes alignment between the technology and widely-recognised technical and market trends and standards in the target industrial area (see alignment 4). In short, to avoid 'failure', constituencies must have the technical capacity to deliver appealing products/services within available resources and in competitive time.

Alignment 4: Interacting Technologies/Constituencies

Commonly, technologies emerge in an organisational, industrial and market environment populated by other technologies. This dimension relates to the type of interaction and relations established with these other technologies in the pursuit of success and implies the four situations described below. It also includes alignment between the technology and technical/market trends (see alignment 2).

- *obligatory complementarity* in which the technology requires of others to realise its contribution (e.g. product and production process). In this case, specific solutions will demand expertise-based alignment, giving rise to a process akin to what Fleck (1983) has referred to as 'management of expertise' and Collinson (1993) as 'knowledge-integration';
- *non-obligatory complementarity* in which the product and other technologies may contribute to a common purpose, but their interaction is not a pre-condition for one or the other to work; there might or might not be a process of knowledge integration;
- *antagonistic competitive* in which the product and other technologies are disputing the same role and resources in the market and the acceptance of one may imply total displacement of the other. The essence of this case is a high-degree of conflict;
- *non-antagonistic competitive* in which the product and other technologies are actually or apparently addressing similar functional roles or markets, but they can or are allowed to co-exist and compete. In practice, the boundaries between this and the antagonistic case are seldom given-they are rather a matter of players' perceptions, negotiating stance and, generally, approach to constituency-building.

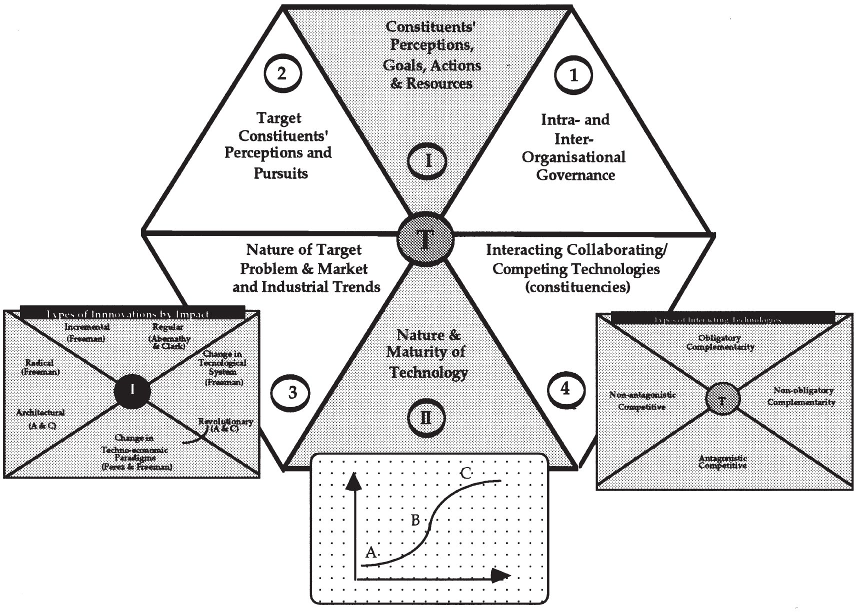

Fig. 3. Technical ingredients in the diamond of alignment.

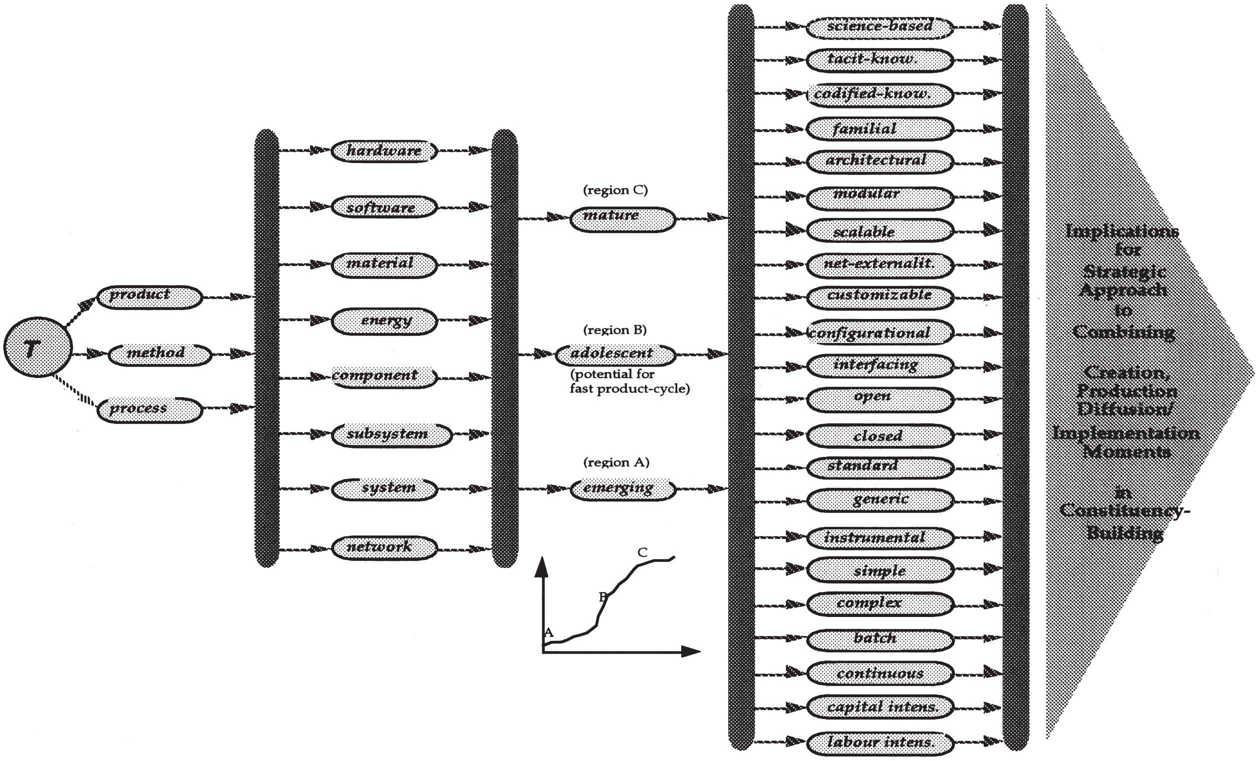

Fig. 4. Open-ended taxonomy of technology genotypes.

all technologies: product, process and methods. These are in turn decomposed into eight possible kinds of products, processes and methods, including a combination of them. The third column introduces the time, evolutionary factor, and this leads to the final column where a range of characteristics are located, most of them collected from the scattered sources. Last but not least, the large head-of-arrow at the right of the final column points to the aim of the instrument, namely, to help elicit and facilitate more systematic thinking on the implications of technologies' features for strategies of innovation and technology development.

Of particular importance would be the strategic approach to combining creation, production and diffusion/implementation moments in constituency-building. As we shall see later on, any technology can be identified by a combination of characteristics from left to right of the diagram—and where a characteristic is missing it could be added, since this is precisely the meaning of its open-endedness. The first type of questions would be: Is the technology under consideration a product? a component? mature? science-based? architectural? and so on. The second type of question would be: What are the strategic implications of the technology being a product? a component? mature? science-based? architectural? and so on. In particular, what do these characteristics mean for the way the competitive battle can be approached? Is it possible to protect the technology from competitors simply through patenting? What are the chances of migrating the customer base from one product generation to the next? Or, what do these characteristics mean for the way its creation, production and diffusion/implementation can be approached.[17] Should these moments be approached in a linear sequential fashion? or do they require a more circular model involving deep interactions from the beginning? For instance, if a technology is 'emerging' and 'configurational' (e.g. computer-aided production management systems), this would indicate that its creation, production and diffusion/implementation moments

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[17] The development of sociotechnical constituencies can be seen as an interaction of several fundamental moments of activity: creation, production and diffusion/implementation moments. These moments must not be construed as a sequence of stages in a linear, unidirectional process leading from creation (e.g. laboratory) to diffusion/implementation (e.g. the market). They deeply interact in the life and evolution of constituencies in processes which have no fixed recipes and may manifest themselves in many forms. From the point of view of building sociotechnical constituencies, it is important to differentiate between the *initial models* (i.e. the actors' initial perceptions and approaches to the relationship between the creation, production and diffusion/implementation moments) and the *'best practice' models* as shown or taught by the actual experience of constituency-building. In particular, the chances of success and failure of a constituency are likely to be seriously affected by the players' initial explicit or implicit models and their alignment with the nature and development of the technology. This is a major reason for the taxonomic instrument of this paper, namely, to help bring a systematic input of *the technical* into the formulation of these strategies. See Molina (1992).

collapse into a single process that requires deep user involvement—with innovation as an intrinsic part of the process of implementation. Clearly the strategic implication of this case would be that failure to involve users carries a high-risk of failure. On the other hand, there will be technologies which are not configurational and will not require deep user involvement in their creation and production (e.g. drugs).

3.2.1. Something on the specific categories or 'genotypes'

It is worth stressing that the use of the term 'technology genotypes' does not imply that the categories in the taxonomic instrument are 'purely technical' in nature. This is clearly not the case, for instance, of the categories of 'capital-intensive' or 'standard.' But this is not a problem for this paper. I said at the beginning that, as human/social creations, technologies evolve stable characteristics which congeal into a form of technical terrain which has critical implications for specific strategies of innovation and technology development. For instance, if a product has become a dominant standard in the market, this characteristic cannot be ignored, since it will have an obvious impact on strategies for its further development.

Second, the definitions given are not intended to draw up sharp and rigid separations and, indeed, some definitions may contain elements of others. The world of technology does not lend itself to absolute classifications. A great deal depends on the position (role) of the technology in relation to organisations, markets and the different types of players associated with the constituency-building processes. Thus, if we take the definitions of product and method, it is clear that a product can be many other things than a method. On the other hand, a method may certainly be considered a product, if it is the end result of a conscious effort to generate it. At least, this is what the players producing the technology are likely to perceive. However, when a method is solely an ingredient in a conscious effort to generate another product, then the players using the technology are likely to perceive it as a method only. In certain cases, the method may not be readily usable and requires effort to make it really operational. In this instance, the technology would be both a method and a product under development at the same time. For this to happen, however, the nature of the technology is likely to be such that it might be both a product and a method.

Finally, it must also be said that the taxonomic characterisation is related to real processes of constituency-building. It does not take into account the existence of unusual cases such as a camcorder being used as a weapon to batter someone to death. From a camcorder constituency-building point of view such a use is unlikely to stimulate the mass market diffusion of the constituency.

4. Two cases of constituency-building and the role of the technical

The paper has argued that the nature and state of development of technologies (i.e. the technical) conditions the strategic limits and opportunities of their processes of development. In this section, the cases of formal methods and microprocessors show the application of the instrument in greater detail. The cases themselves are a brief revisiting of previous research with exclusive focus on the analysis of the technical (see Molina, 1993a, b, 1997). This produces original discussion (particularly in the case of the microprocessor industry) demonstrating the workings and value of the taxonomy. In the accounts of the cases, the process of sociotechnical alignment will involve one or combinations of dimensions of the diamond of alignment at different instances. This is made explicit through the identification of the pertinent dimensions in italics brackets, e.g. *[D1], [D1&2]* and so on.

Both the microprocessor and formal methods examples have the benefit of hindsight. Constituency-building processes have happened and are still happening and the full understanding and explanation of some critical aspects and patterns of their development are simply not possible without resorting to the nature and state of development of the technologies involved. Since the cases are both information technologies, there will be some recurrence of taxonomic aspects ('genotypes') characterising the technologies. On the other hand, they are clearly different in nature as well as in the context of their constituency-building application so as to merit separate examination (Table 2).

Table 2
Cases illustrating use of open-ended taxonomic instrument

Technology	Constituency-building situation
Formal methods	Effort to establish a new constituency inside a company environment (intra-organisational constituency-building)
Microprocessors	Establishment and maintenance of a dominant position in the world market by a specific product constituency and its originator company (industrial constituency-building)

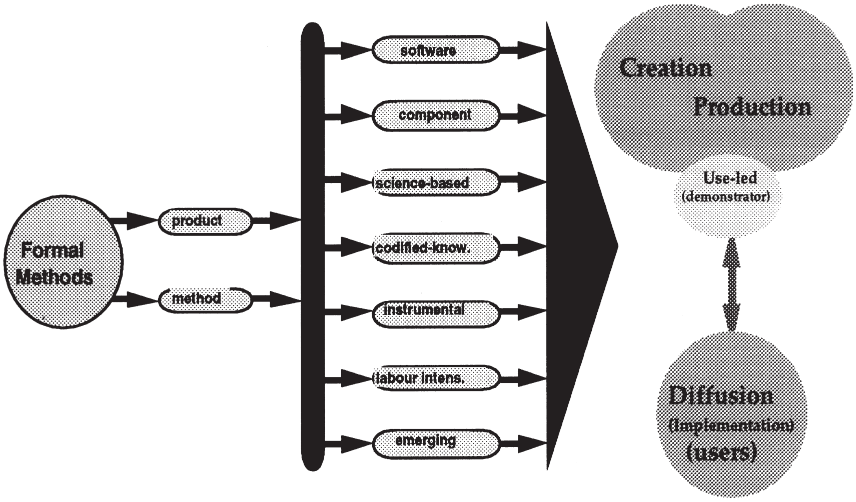

Fig. 5. Taxonomical characterisation of formal methods technologies.

4.1. Formal methods

The case of formal methods concerns the effective acceptance and implementation of a new technology inside the environment of a company. From a constituency-building viewpoint, it amounts to the emergence of a new constituency at an intra-organisational level.

In such an implementation situation, a taxonomic mapping of the technical 'terrain' of formal methods technology is most useful, since it helps reveal key features conditioning the process of sociotechnical alignment and, specifically, the opportunities and limits for integrating the fundamental moments of creation, production, diffusion/implementation in constituency-building.

The obvious starting point is a definition of formal methods. The organisation Formal Methods Europe defines them as "mathematical approaches to software and system development which support the rigorous specification, design and verification of computer systems. The use of notations and languages with a defined mathematical meaning enable specifications, that is statements of what the proposed system should do, to be expressed with precision and no ambiguity" (Formal Methods Europe Information Resources Newsletter, 1996). The role of mathematics is central to the distinctiveness of the technology.[18] Formal methods is a good example of a technology that is both a product and a method at the same time. Fig. 5 shows the detailed characterisation of this technology, seeking to interrelate its nature and maturity to the interaction of the three fundamental moments of creation, production and diffusion/implementation. The general instrument of Fig. 4 was used to 'interrogate' the technology and structure the sub-set specific to formal methods.

At the time of the research, a total of nine categories characterised the technology: product, method, software, component, emerging, science-based, codified-knowledge, instrumentalities (enabling), and labour-intensive. Thus, formal methods were a product for those creating them. They were a method to be used in the design process, and hence they were a component of this process. They were a specific case of software, since their creation and production involves the manipulation of abstract symbols only. They were labour intensive because the tools for this symbol manipulation were simple hardware such as a pencil and at the most a workstation. Formal methods were instrumentalities insofar as their use enabled the design of another technology to be debugged and, ideally, 'bug-free'. They were science-based since their creation or creative implementation involved direct highly mathematical knowledge and skills. In this sense, their creation had a clear element of tacit-knowledge, but the product itself was of a codified-knowledge nature. Finally, formal methods were an emerging technology with relatively few mature tools to facilitate its diffusion (implementation).

The full story of the emergence of the formal methods constituency within the microprocessor company Inmos is found in Molina (1993b); Molina, (1997)). Here my purpose is limited to illustrate how each of these features of the technical did played an important part in the sociotechnical alignment process of the technology within Inmos. In particular, the following strategic considerations were important from the point of view of the integration of creation, production and diffusion/implementation moments.

As a mathematically-based software technology, in

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[18] "It is really the application of basic mathematics…[t]hat will distinguish it from more informal methods…It could be a set of transformation rules or a set of logical axioms, something like that" (Personal communication with formal-methods developer D. Shepherd). See also Tierney (1992).

formal methods the creation and production moments collapse into a single process, which tends to be labour intensive (at least initially), with most of the costs accounted for by highly mathematically specialised labour. There are no separate expensive manufacturing plants transforming tangible physical materials. This had a favourable impact on the cost of implementing formal methods, and hence on the constituency-building process, especially as arguments about their cost effectiveness relative to other methods were an area of major contention. It was much easier to justify their contribution against a background of relatively low cost.[19] Looking at the diamond of alignment of Fig. 2, this represented favourable alignment involving dimensions *[DI-II and 2&4]*.

As an instrumentalities (component) technology to the design process, the diffusion (implementation) of formal methods depended on their adoption by designers—in this case microprocessor design engineers. Ultimately, it was a case of aligning the technology with the designers' practice and vice-versa. In the design process, this could happen by introducing it right upstream into the design of microprocessors themselves, or, more downstream into the testing and checking of already designed products. The highly mathematical base of formal methods was crucial here since a lack of mathematical expertise by design engineers tended to make it difficult for them to understand, let alone shape in detail, the creation of the technology. Obviously engineers could have learned the mathematics. But this is not the point. The point is that as a science-based technology, formal methods presented a very specialised language which is not in common use among engineers *[mis-alignment between dimensions II and 2]*, thus making the diffusion of the technology a more difficult process. The practical result was that this could not be a user-produced technology,[20] although feedback on desired functionality would be a possible interaction between creation/production and diffusion (implementation) moments. This situation is illustrated in Fig. 5, where the creation and production moments merge, but the diffusion (implementation) moment is shown in a relationship of more 'distant' bidirectional interaction.

Why did formal method developers not offer engineers an easy-to-use tool which hid the complexity of its science-based aspect (a sort of shaping of the technology by users' limited knowledge)? Formal methods developers would have certainly liked to do this but, as an emerging technology, formal methods were rather a long way from possessing a variety of easily usable products (tools) which would satisfy the potential range of designers' requirements. The strategic implication for the constituency-building process was that the initial implementation of formal methods into the Inmos' design process proceeded through a use-led approach rather than a user-led approach which would have proved much more difficult to achieve. In practice, this meant the involvement of the creators of formal methods themselves in implementing and demonstrating the technology, with preference in those areas in which the technology provided an added capability rather than disputed the role of other established methods such as simulation *[alignment between dimensions I and 2&4]*. In Fig. 5, this use-led approach is illustrated by the small circle bridging the creation/production moments with the diffusion (implementation) moment of the technological process. In addition, the least-controversial implementation was found (at least initially) in the area of testing and checking microprocessor designs, rather than in the upstream area of the design itself *[alignment between dimensions II and 3]*.

For the long-term, however, formal methods developers realised that the widespread diffusion of the technology could only happen if it was freed from the constraints of their own limited resources and demonstrator implementation. For this reason, their constituency-building process took the technology beyond its initial form of methods to encompass computer-aided-design (CAD) products which other players in the design process could also use without worrying about the mathematics. This was approached through the creation of new technical constituents intended to facilitate the alignment of formal methods to users' existing expertise *[dimensions II and 2]*. Specifically, formal methods constituents were striving to generate a sort of hybrid tool, incorporating engineers' representations, particularly in those areas of direct relevance to engineers' practice. This piece of interfacing technology (Appendix A) was a new element in the constituency-building process, and it was purely an outcome of the need to establish bridges between formal methods and an engineering community 'speaking' a different technical language. Ultimately, the process of evolution was pointing towards automatization in the form of CAD tools which would be bought and sold in the market, just like any other CAD product. By then the technology would have evolved beyond its emerging character towards a state of development which is more characteristic of mature technologies. At this point, the technical terrain for constituency-building would have also changed quite markedly from the fragile early days. In particular, there might be less need for closer user involvement in the creation of the tech-

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[19] For instance, it was estimated that the cost of the first implementation of formal methods at Inmos was approximately 1 man/year. At the same time the saving from their use might have been around £1 million (Molina, 1993b).

[20] It is interesting to point out that it would not be a user-created technology from our intra-institutional perspective. On the other hand, if we look at the technology from an inter-institutional perspective, Inmos would be both the user and (in part) the creator. Thus, the technology could well be considered a user-created technology.

nology, since this would have largely happened. New users would then be likely to acquire, make use of, and provide feedback on the technology in a more traditional market-mediated relationship. This evolution would be in agreement with the message of Fleck's evolutionary taxonomy of technologies, underlining the fact that the character of the technology is not a static factor, it changes not only as the technology advances and matures but, also, as the technology expands from one category (e.g. method) to encompass another (e.g. product).

Before this happened, however, formal methods developers were living with the conditioning role of the emerging character of the technology. This had limited what the constituents, with their available resources, had been able to offer (regardless of their desires). One might say that a sort of 'negative technological determinism' had operated, that is, a 'determinism' not as much in the sense of shaping the specific content of what is on offer, but rather in the sense of determining what cannot possibly be offered at the stage of emerging development of the technology. This point substantiates Molina's (Molina, 1993a) statement that "technology is conditioned by the opportunities and constraints imposed by the physical world and its own state of the art at any given time. In other words, technology can only be shaped within the realm of the shapeable" (p. 484).

Finally, it must be noted that in the case of the intra-organisational implementation of formal methods, the specific character of the realm of application implied in its instrumental nature was also shown to be a significant factor in the constituency-building process. The fact that this realm was the design process for a high-volume industrial product of increasing complexity did offer formal methods constituents an opportunity to position their technology in a non-antagonistic, more complementary, relation to other technologies already contributing to this process *[alignment involving dimensions I-II and 3 and 4]*. Products such as microprocessors cannot be verified totally, and their failure can lead not only to catastrophic accidents involving death but, also, to economic disasters involving huge losses, or both. Seen in this light, microprocessors are undoubtedly safety-critical and manufacturing companies strive towards an ideal goal of 'zero defect'. This goal, however, is unlikely ever to be delivered, let alone by a single technology, and this fact tended to play in favour of the emerging formal methods constituency since, ultimately, it encourages goal-alignment among different methods (constituencies) in the design process. In principle, this facilitated the acceptance of the technology into the company environment, although the success of the endeavour was always dependent on the effectiveness of the process of sociotechnical alignment as a whole.

4.2. Microprocessors

The microprocessor industry is known for at least two major features: (i) an image of critical strategic importance for the economy and security of countries; (ii) the market dominance of the industry by the US company Intel which accounts for over three-quarters of the most advanced products for the huge personal computer market. A quick glance at the microprocessor market shows that, at its broadest, it has evolved into two major segments: general purpose computers and embedded control. In computers, specific demands may vary from one individual user to another but, on the whole, the pattern is for users to want their computers to run a large number of applications such as word processor, spreadsheet, etc. *[D2]*. In contrast, in the case of microprocessors embedded inside systems such as laser printers and cars (i.e. embedded controllers), end-users generally do not have to worry about applications software *[D2]*. System designers determine much of the functionality and not separate software developers, as in the case of personal computers. Intel in particular has come to dominate the huge computer market segment with its 80 × 86 product family *[D3]*. The case visited here concerns this specific 80 × 86 product constituency and the role played by the nature of the technology in the establishment and maintenance of a dominant standard position in the market by Intel.

4.2.1. The nature of microprocessor technology

A common definition of microprocessor is: a computer central processing unit (CPU) on a microchip. This definition already suggest a reality different from software in that 'microchip' implies a material presence (i.e. hardware) of miniature dimensionality.

A second aspect of microprocessors is that they are programmable technologies; they are able to perform all sorts of logic, mathematical and real-time control tasks as specified by their hardware/software programmes. Since the range of products and processes amenable to computerisation is virtually infinite, this feature combined with miniature dimensionality makes the microprocessor a pervasive technology responsible for much of the versatility of every type of computerised equipment from toys to flexible manufacturing systems.[21] This kind of pervasiveness is what Freeman (1985) associates with radical innovation and changes of techno-economic paradigms.

A closely-related aspect is that microprocessors are a component technology and not products for final consumption as bread or even computers are. Microprocessors realise their purpose by being integrated into

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[21] An important element in the pervasiveness is the abundance of silicon—the material most microprocessors are made of today.

other systems, processes and end-products. This means that their direct users are the designers and engineers of companies producing systems such as computers, cars, or laser printers. Microprocessors only reach the end-user as part of these systems and the capabilities and functionality they offer *[D2&4]*. This produces a chain situation of importance for constituency-building. On the one hand, microprocessor companies are subject to the demand and requirements of system companies. They are the immediate target *[D2]*. On the other, system designers tend to choose those microprocessors which enable them to satisfy end-user preferences and requirements. This leaves open the possibility of a microprocessor company targeting the end-consumer in a form of indirect constituency-building, such as Intel has done, with a view to stimulating or reinforcing demand for the products which use the component *[D2]*. In this diffusion strategy, if successful, the demand of the end-consumer to system companies would translate into a system companies' demand for the component. So far, Intel is the only microprocessor company that has used this approach in a high-profile and expensive television campaign. A final possibility is for microprocessor companies to make the end-user the real target for direct market sales. This could happen if companies make their target the huge accumulated base of systems already in use and offer higher-performance microprocessors which could replace original microchips by 'plugging' directly into their physical place *[D3]*. The difficulty is that the microprocessor will have to work perfectly with all the other parts of a system designed to work with a lower-performance chip *[D4]*. It will also require the user to accept tampering with the original system *[D2]*.

These aspects of the technical in microprocessors already begin to reveal 'the nature of the beast', and their implications for practical constituency-building strategies. However, the picture is still limited and there are other key taxonomic characteristics of the technology with telling implications for company strategy and, indeed, the overall dynamics of the industry.

For instance, an examination of microprocessor evolution reveals that, since their inception 25 years ago, they have been subject to an increasing microelectronics miniaturization which is still underpinning the integration of ever-increasing functionality into the microchips. Indeed, the CPU itself is becoming an ever smaller proportion of the microchip as complete logic systems are being 'swallowed' by the increasing number of transistors available on chip.[22] Admittedly, increasing miniaturization and performance integration are rather features of microprocessors' long-term evolution underpinned by advances in microelectronics and the competitive product-cycle dynamics of the industry *[D4&3]*. After 25 years (and more to come) of sustained pattern, however, it is reasonable to 'adopt' them as major elements (miniaturising technologies) of the technical. For constituency-building, the strategic implications are highly visible. In particular, unlike software, in microprocessors the production moment is clearly distinguishable from the creation moment with serious implications for resource requirements and barriers to entry. Today, given the state-of-the-art of production processes, those who wish to play in leading-edge microprocessor production must commonly invest at least US$1 billion—and the trend has been towards capital intensiveness since the beginning of the technology as a result of miniaturisation *[D3&4]*. At the same time, microprocessors are not a configurational technology and the possible structural separation of creation from production has enabled players to enter the industry on the basis of direct control of creation and diffusion only. For production, they have simply used the facilities of others in the industry, including those of microelectronics players whose main purpose is to provide a production facility or foundry *[D1&4]*. The advantage of this strategy is a dramatic reduction in resource requirements. The disadvantage is the lack of direct control of a major moment of constituency-building, with the risk that players may not have a secure, on-demand, access to the latest production technology.

Microprocessors are also familial technologies in that their basic architecture can give rise to multiple generations as well as to multiple related products inside every generation. These may be used to target different markets as well as to reinvigorate the market presence for the entire family once a generation begins to show signs of market decline or loss of control *[D3]*. Indeed, it is a feature of familial technologies that emerging, adolescent and mature products (see Appendix A) normally coexist as part of the evolution of the entire family. The importance of new microprocessor constituency-building, for instance, is that different markets show different requirements, barriers to entry, and opportunities for diffusion. Thus in the computer market, as indicated earlier, the number of software applications tends to be quite

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[22] To understand the significance of this development one has to only to consider that the first Intel microprocessor (i.e. the 4004 developed in 1971) contained only 2250 transistors packed in an area roughly a sixth of an inch long and an eighth of an inch wide. Two decades later, the scale of microprocessor integration had increased almost 1500 fold to more than 3 million transistors in a single microchip. Now microchips are heading for 100 million transistors, meaning a 45 000 fold increase in integration compared to the original chip. Not surprisingly, microprocessors have in the process continued to absorb into microchips what was before the province of the computer industry. From the point of view of systems, this transformation into components seems to provide a good illustration of Fleck's evolutionary taxonomy of technologies, which anticipates technologies evolving from loose configurations into more structured systems and later, as they become more and more codified, into components of other systems or configurations.

decisive *[D3&D4]*. In contrast, in embedded controllers, system-designers have a much greater freedom to choose a new microprocessor without the fear that they will fail because of lack of applications *[D2&D3]*. The next two characteristics will underline why this is so important for new microprocessors.

Microprocessors are a component technology with indirect network externalities, that is, the hardware is not enough for diffusion. Their benefit to system users (and hence attractiveness to system designers) entails the provision of a complementary good: software (Katz and Shapiro, 1986a, b; Farrel and Saloner, 1985)[23] *[D4]*. In the computer market, in particular, the number of hardware units sold tends to increase with the amount and variety of computer software. This means that constituency-building for new microprocessors normally has to deal with a well-recognised ‘Catch-22’ situation, namely, users will not commit to a microprocessor-based system until enough software is written, but software developers will not write the software until enough users have adopted the microprocessor-based system (Electronics, 1989) *[D2&4]*. This tends to underpin a lock-in standard diffusion effect in favour of those who have accumulated the greatest number of software applications *[D3&4]*. We shall see that this is a major contributing factor to the domination of the microprocessor market by the 80 × 86 product constituency. Indeed, today, perhaps the trickiest hurdle any new microprocessor must sort out if it is to diffuse widely in this market is to break the fortress of thousands of applications which fences the market position of the Intel family. Admittedly, this competitive advantage depends largely on the perception of consumers that large numbers of applications are important, even if most people will only ever use a limited number *[D2]*. The point, however, is that the feature of network externalities does provide a strong foundation for this perception to develop as compared with other technologies.

Microprocessors are architectural technologies, that is, technologies which in the course of their existence may evolve through several product-generations in a way which combines substantial change with continuity or compatibility. The most distinctive feature of architectural technologies is an accumulation and portability of software, which go hand in hand with major transformations in hardware. For constituency-building, the implication is that decline need not follow the maturity of the first generation product. With architectural technologies, new emerging generations actually seek to build upon the technical (particularly software) and social constituents of the previous one, thus re-generating the momentum of the entire constituency. From this standpoint, it is worth noting that the concept of emerging technology in *strictu sensu* may really apply to the first generation only; second and later ‘emerging’ generations inside an architecture will face much less of a ‘greenfield’ due to the constituency already in place by the first generation. At the same time, the possibility of major changes from one generation to another provides an opportunity for equally significant changes in the constituency-building strategies pursued by the originators of the technology. In particular, we shall see that there is ample opportunity to change radically the balance between collaboration and competition, expressed through arrangements such as licensing and second sourcing *[D1&D2]*.

Last but not least, microprocessors are codified-knowledge technologies, implying that they can be more easily reverse-engineered or copied by competitors. In Teece’s concepts this would translate into a weakness in the appropriability regime determining a company’s ability to control, or fully appropriate, the commercial benefits of a successful product (Teece, 1986) *[D1]*. This is reinforced by the fact that microprocessors also exhibit characteristics of complex technologies (i.e. multiple components and nondecomposable systemic interactions), meaning that they offer many possibilities for imitators on engineer around the legally protected products and processes (Singh, 1993; Kash and Rycroft, 1993). In terms of constituency-building, the implication is that those companies seeking to monopolise the benefits of successful microprocessors are forced to keep ahead either by superseding their own products or by resorting to a strong use of legal instruments (e.g. patents and copyrights) to try to fend off cloners *[D1]*.

There might be other aspects but those identified here provide a substantial mapping of the strategic ‘terrain’ implied in the nature of microprocessors. Below, we shall see how these taxonomic aspects have played an important part in the constituency-building strategies implemented by various players since the beginning of the industry. Of course, the entire picture involves technical, legislative, socio-economic, personality factors, etc. The point of this paper is, however, that some of the most distinctive patterns in the historical development of the industry cannot be fully explained without reference to the technical.

4.2.2. Intel dominance, the imitators, and the role of the technical

Figs. 6 and 7 depict what is perhaps the best-known pattern in the historical development of the micropro-

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[23] “…indirect externalities [are] associated with the provision of a durable good (hardware) and a complementary good or service (software)…the externality arises when the amount and variety of software available increase with the number of hardware units sold. For instance, computers and programs must be used together to produce computer services, and the greater the sales of hardware, the more the surplus the consumer is likely to enjoy in the software market due to increased entry” (Katz and Shapiro, 1986a, p. 146). In Teece’s words, software is a specialized complementary asset to the hardware (Teece, 1986).

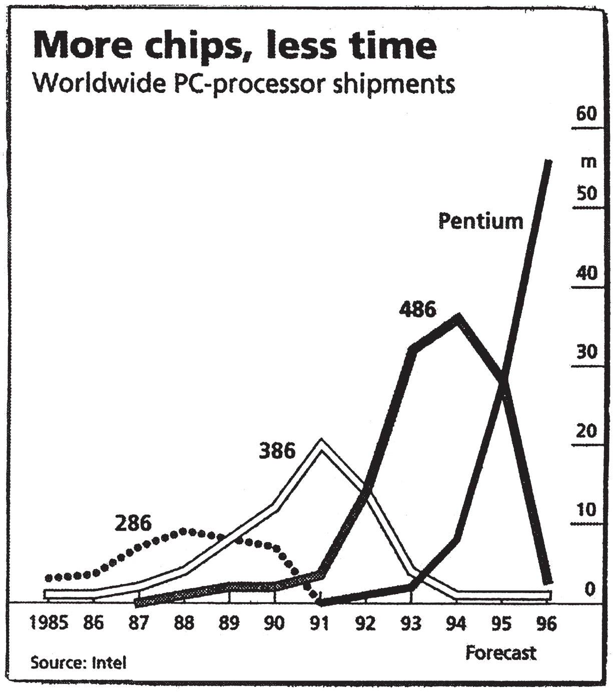

Fig. 6. Market evolution of successive generations of Intel 80 × 86 microprocessors. Source: The Economics (1994), p. 105.

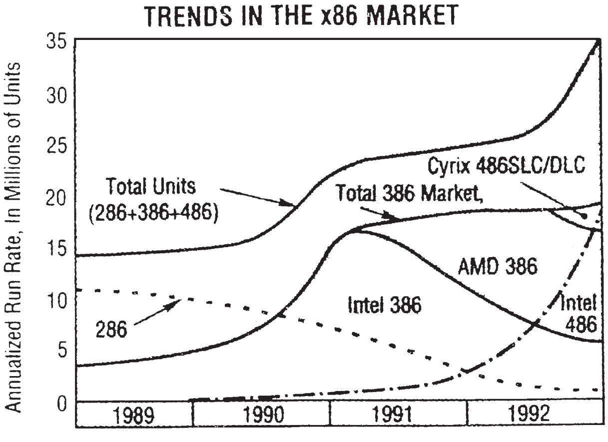

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Fig. 7. Competitive battles within the 80 × 86 product constituency. Source: Electronics (1993b), p. 7.

cessor industry *[D1,3&4]*. The most distinctive aspects are:

- Successive 80 × 86 generations (Fig. 6) and a shortening of the product cycle between them;
- Sustained dominance of Intel within the 80 × 86 sociotechnical constituency (Fig. 7), in a context of sustained dominance of this constituency in the industry;
- Intense intra-constituency competition between the originator company, Intel, and a range of imitators fought in the market as well as in the courts (Fig. 7). This contributes a great deal to the shortening product-cycle.

The familial character of microprocessor technology is immediately obvious in the market evolution of the different generations of Intel 80 × 86 microprocessors shipped for personal computer (Fig. 6). In addition, this figure shows each successive generation taking over (virtually ‘attacking’) the market from the previous one which declines while the overall market grows consistently. In this sense, the ‘maturity’ of one generation is very much the result of companies’ product cycle strategy which is in turn conditioned by the competitive pattern of the industry and the familial nature of the technology *[DI&II]*. Thus, the time between each successive generation (product cycle) has tended to become shorter between the 80286 and the Pentium generations. Strategically, other aspects of the technical—component, network externality, architecturality, codified-knowledge and complexity—are required to explain this dynamic feature as well as the full pattern illustrated in Fig. 7. This figure shows the 80286 generation in dotted line ‘maturing’ and beginning to fall in 1988–1989 while the Intel 80386 generation (solid line) rises to ‘adolescence’ in 1989–1990 and peaks in 1991 when the Intel 80486 generation (line-dot curve) begins to ‘emerge.’ The important feature here, however, is that while Intel 386 begins to fall, the total 386 market continues at roughly its ‘mature’ peak level for 1991/92 since it has been taken by the AMD 386 from Advanced Micro Devices (AMD). This suggests a delayed decline of the product as a result of other companies stepping in and taking over the market. This is possible because the AMD 386 successfully imitates the Intel 386 functionality and is able to run all the software applications available for the constituency *[D1&4]*. Fig. 7 also shows the emergence of another imitator to the Intel 80486 generation, namely, the 486SLC/DLC from Cyrix. Finally, the top curve in the figure shows how the overall 80 × 86 family and constituency (286 + 386 + 486) has continually grown over time. Let us see how other aspects of the technical have played their part in the 80 × 86 story.

The component nature of the technology is reflected in the invention of the microprocessor which was developed by Intel Corporation in 1971 to an order placed by a Japanese calculator manufacturer who required a custom-built processing chip which could perform arithmetic and other functions and yet be cheap enough to allow the selling price of the calculator to be sufficiently low to create a mass market (Bessant et al., 1981, p. 3). In the search for such a component, Intel’s Marcian Hoff eventually arrived at the microprocessor and sparked off the emergence of today’s multi-billion dollar industry (Electronics, 1980).

In the early days, various product-constituencies joined Intel opening up a competitive battle for the leadership of the emerging microprocessor market *[D4]*. Typically of emerging technologies, there were many undeveloped areas including tools for designers to make use of the microprocessor (for a while Intel was making more money selling tools that selling the components) and major systems markets such as the personal computer would come later on the basis of so-called ‘killer’ applications such as spreadsheet and word processing *[D4]*. Also, the new components had yet to show development paths with a secure future based on strong support from stable chip manufacturers, ideally at least two of them to demonstrate ‘second sourcing’ (i.e. chip availability independent of the fortunes of a single company) *[D1]*.

All this was to change in the first half of the 1980s as a result of the convergence of several factors:

- The development of the Intel 80286 microchip and its licensing to other microchip manufacturers, specifically AMD with a view to stimulating second-source production and the adoption by systems companies *[D1&2]*;
- IBM’s adoption of the 80286 microprocessor for its new line of personal computers *[D1,3&4]*;
- The standard off-the-shelf component policy adopted by IBM which led many other companies to clone the IBM architecture based on the 80286 (expanding the market and bringing down prices) *[D1&3]*;
- The development of the so-called ‘killer’ software applications which would underpin the growth of a mass market for personal computers (and hence microprocessors) *[D4]*.

This situation gave the 80286 microprocessor the break over other contending microprocessors in the personal computer market, particularly over the Motorola 68020 which was one of the strongest contenders at the time *[D4]*. In fact, Apple adopted the 68020 microprocessor, but its market pull was limited by the proprietary policy followed by the company (in contrast to IBM) *[D1&3]*. The boost to the constituency-building process of the 80286 in the personal computer market was decisive. Indeed, as IBM and the PC clones expanded the market, the 80286-based PC became the predominant target for most software developers *[D2,3&4]*. This led to a much larger accumulated base of software applications than for anybody else which, in turn, reinforced the market dominance of the 80 × 86 constituency given the effect of network externalities. The IBM PC became the market standard and with it the 80286 microprocessor *[D3&4]*.

Of course, the constituency-building success of the tandem 80286 microprocessor IBM PC was never secure enough to translate into complete market dominance for the companies originating the technologies. The risk of the off-the-shelf component policy is that the likely boost to technology diffusion brings with it intra-constituency competition which may result in the originator company quickly losing the ability to reap monopoly profits *[D1&4]*. This is exactly what happened to both Intel and IBM as both lost market share to the second sourcers. In microprocessors, this set the scene for a competitive battle in which Intel and the imitators made clear use of the strategic opportunities implied in the nature of the technology.

First, Intel took advantage of the familial and architectural aspects of the technology to try to change their relation with AMD once the 80 × 86 constituency was established *[D1]*. Thus, come the next generation 80386, Intel decided to completely reverse their licensing policy, in an attempt to alter the inter-organisational governance to exclude imitators from the gains of future generations, while still carrying and building on the constituency (software, users, etc.) established with their help during the previous 80286 generation. Intel’s strategy was to lock in buyers to their own supply, monopolising the market for their new chips and reaping premium profits for as long as possible. As expected, imitators of the 80 × 86 architecture did not take Intel’s onslaught kindly *[D4]*. They also wanted to enjoy the competitive advantage offered by the software network externality. Thus, instead of bowing out and developing a new microprocessor, they responded by taking advantage of the opportunities to clone implied in the weak appropriability regime rooted in the complex and codified-knowledge nature of the technology. In any case, AMD claimed that they had the right to use the 80386 because of their licensing of the 80286 *[D1]*.

Intel counteracted with court actions seeking to lay legal grounds for the control of their chips *[D1&4]*. By so doing the company transformed its relation with AMD from one which was initially non-antagonistic competitive into one which was definitely antagonistic competitive. Prominent court cases ensued which distinctively characterised the evolution of the 80 × 86 constituency for a long period of time. A crucial case was the Intel vs NEC microcode case in which Intel accused NEC of having copied the 8088/8086 microcode and having used it in the NEC V20/V30 microprocessors. In this case, the very definition and status of microcode was at stake, in particular whether it was subject to copyright or not. The court eventually decided that microcode was a computer program subject to copyright, thus making it illegal for other companies to copy microcode. However, the ruling also accepted that it was legal to emulate microcode, that is, reproduce its functionality while avoiding its particular expression (Electronics, 1990). In this respect, the court found that NEC had not actually copied Intel’s 8088/8086 microcode. Thus, both companies actually won. NEC was able to continue to imitate and Intel was left with a legal weapon to try to tighten control of the 80 × 86 product-constituency.

Subsequently, Intel tried to make good use of the copyright law to put 80 × 86 imitators under strong pressure *[D1&4]*. Indeed, it became Intel’s normal practice to assume that 80 × 86 clones—even those claiming emulation—should be infringing some of the company's 80 × 86 patents somewhere.[24] True, in the case of AMD's 386 clone, this was deliberate since AMD rejected Intel's argument that they should not resell 80 × 86 microcode beyond the 286 microprocessor. As indicated, AMD's position was that the 286 agreement gave them the right to use the microcode in other generations too. Intel sued AMD and after a lengthy battle in which Intel's behaviour was found wanting, a state court gave AMD the right to use the 386 microcode as compensation for Intel's alleged bad faith in the agreement. Unfortunately for AMD, this was not the same as giving them a permanent right to use Intel's microcode. Thus, in June 1992, the federal court settled the issue by agreeing with Intel (Electronics, 1992). By now Intel had moved to the new generation 80486 microprocessor and AMD found themselves barred from using the Intel's microcode for this new chip. AMD was back in the court and by 1994 it seemed to be gaining the upper hand again. The company realised, however, that Intel was accelerating the product cycle (see Fig. 6) and if they were to survive at all they had to break away from just following Intel. They had to emulate the Intel 80 × 86 chips but go better in their performance if they were to have a chance (see Halfhill, 1994). The result was the development of their own independent microcode and the first 'independent' AMD 486 compatibles reached the market in quantities towards the end of 1993, almost four years after Intel's launch of the first 80486. In the meantime, two other companies Chip and Technologies and Cyrix, joined the 80 × 86 competition with 386 clones which they also claimed to be emulation rather than copies of the 386. Intel rejected the claim and sued both companies for patent infringement *[D1&4]*. In the case of Cyrix, however, the situation became more complicated with the involvement of Texas Instruments (TI), the No. 3 US chipmaker, which had a patent cross-licence agreement with Intel. Cyrix's strategy was to make use of TI's fabrication facilities for its chips, but it also licensed its design for TI to manufacture and sell under their own name. Both TI and Cyrix eventually introduced 486 clones. The battle then continued into the Intel Pentium generation launched in 1993, with AMD, Cyrix and NexGen following suit with chips (AMD K5, NexGen Nx586 and Cyrix M1) in 1995. Intel has now moved into the P6 and 786 and the imitators are responding in kind.

All these conflicts underlined Intel's difficulties in enforcing monopolistic control over its technology when imitators could take advantage of its codified-knowledge and complex nature *[D1&4]*. Indeed, Intel learned that court actions would only buy the company time.[25] Ultimately, the key to market dominance lay in moving fast along the different compatible generations made possible by the familial, architectural nature of microprocessors technology.[26] All the more so as cloners had been closing the time-lag between their products and Intel's. Intel learned that the only way ahead was to reap as much premium profits and for as long as possible for every new chip and then invest a large proportion of these profits to move swiftly to the new generation and so on. This is equivalent to attempting to monopolise the market of a single product generation during its 'adolescent,' high growth stage and then move to the next generation, leaving the now 'maturing,' less profitable, product to the catching-up competition. This is extremely costly as witnessed by the estimated US$5 billion invested in the development of the Pentium. Of course, part of this huge expense is due to 'architecturality' and the need to provide compatibility for the enormous base of accumulated application software *[D4]*. On the other hand, the 'network externality' protection of this software base is still paying off, ensuring the huge profits that make possible a level of investment unmatched by any other company in the microprocessor industry.

The issue is for how long can Intel sustain a strategy based on out-spending everybody else in the industry. When Craig Barrett, Intel's chief operating officer, was asked this question, his answer was: "So long as our revenues are growing and our margins are good, it can go on indefinitely"[27]. Nevertheless, this 'indefinitely' may not be as far away in the future as Intel would desire. Like all technologies, the 80 × 86 family is unlikely to go on indefinitely at such high costs/performance. Indeed, in 1995, Intel announced an alliance with Hewlett-Packard to start work on a completely new architecture. Of course, work on the 80 × 86 continues and, not surprisingly, Intel is also claiming that the new architecture will be compatible with the accumulated software base, thus safeguarding the investment of millions of members of the 80 × 86 constitu-

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[24] "Mr. Tom Dunlap, Intel general counsel, has said in the past that he does not believe that it is possible for any company legally to clone Intel's chips" (Financial Times, 1993b).

[25] "The experience with the 386 and 486 may indicate how the Pentium battle will unfold. As Intel introduced the 486, it used fierce patent suits to forestall attempts to clone the 386. As the 486 began to ship in volume, the court clashes came to conclusion after months of manoeuvring…In advance of Pentium, Intel began its legal bombardment…If history is any gauge, the guns will go off when Pentium begins to ship. Intel will protect the 486 until Pentium ramps to volume and the company will relinquish the 486 and make its next fortune on Pentium" (Electronics, 1993a).

[26] "We will compete with the clone makers by staying at the leading edge of microprocessor performance. It is the cannibal strategy. We have to gobble up our older children—our current microprocessors—before the competition does. We intend to move as fast as we can, ripping up the road behind us" Craig Barrett, Intel's chief operating officer, quoted in Financial Times (1993a).

[27] Quoted in ibid.

ency *[D4]*. It remains to be seen what effect the change of architecture will have on Intel's current dominant position. What seems clear, however, is that, very much like in the past successful years, Intel will exploit to the full the strategic opportunities implicit in the nature of microprocessor technology.

Fig. 8 tries to capture some of the elements just described in the development of the 80 × 86 family. It illustrates the taxonomic characterisation of microprocessor technology, with the successive, growing circles of creation, production and diffusion sketching the broad pattern of evolution of the 80 × 86 architecture.

It is clearly not a case of one single market product, but of the market evolution of the entire architecture and hence, the relation between successive generations in the family. This is the reason why all states of development (i.e. emerging, adolescent and mature) are included through the S-curve (A-B-C) to signify broadly the point when the Pentium was 'emerging,' the 80486 was still in 'adolescence,' and the 80386 had reached 'maturity.' Overall, Fig. 8 shows how creation in the 80286 architecture leads to market diffusion, passing through production, and then, to creation of the 80386 and to an enlarged market that builds on the previous generation and so on to the 486 and Pentium generations. All successive circles are larger to reflect, on the one hand, the increasing costs of development a production associated with increasing complexity and performance, and the larger diffusion associated to the expanding market. It must be noted that for other microprocessors the creation, production and diffusion pattern is likely to be different in time, resources and diffusion scales, including the number of generations. But this is the pattern of the 80 × 86 family which has dominated the market, and not to a small degree, on the basis of a constituency-building dynamic which has exploited to the full the opportunities provided by the nature of the technology itself.

5. Conclusion

This paper has argued that all technologies are created by humans and, in this basic sense, they are socially shaped. It went on to argue that the nature and state of development of technologies (i.e. the technical) have a major part to play in the explanation as well as formulation of strategies for innovation and technology development. The technical simply conditions the strategic limits and opportunities for the effective build-up of sociotechnical constituencies. The selected review of literature showed that this is a long-standing concern of the technology field and that the time was ripe for a first effort to try to build on the many scattered contributions and generate an overall more systematic picture. This was done by first proposing the foundations for an open-ended taxonomy of technology 'genotypes' in the form of a glossary and a diagram; and, second, applying this

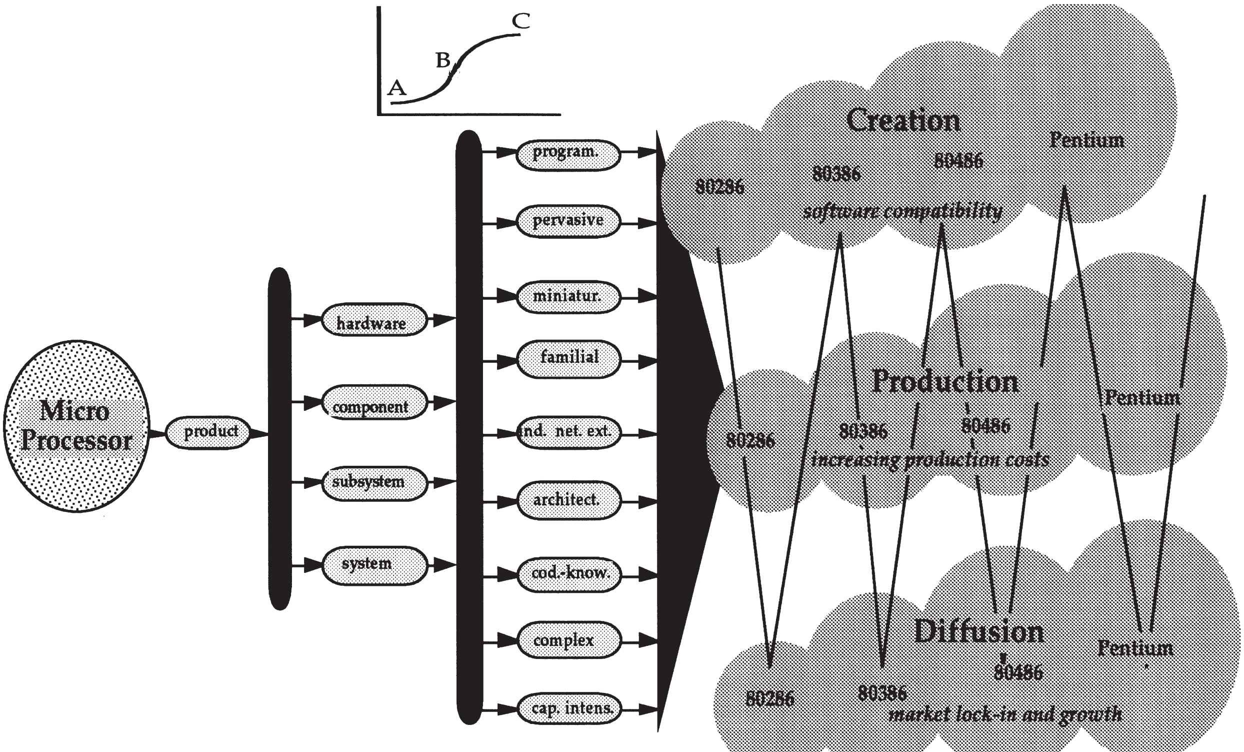

Fig. 8. Taxonomical characterisation of microprocessor technology.

taxonomy to two empirical cases of sociotechnical constituencies. The examples of formal methods and microprocessors illustrated how the technical enables a richer explanation of characteristics features and patterns of technology development both inside a company and at the level of industry. In both cases, it was shown that the dimension *Nature and Maturity of the Technology (II)* in the diamond of sociotechnical alignment constantly interact with one, or, combinations of other dimensions.

In the following, this conclusion discusses the theoretical place of the paper within the general relationship between the social and the technical, as well as pointing directions for further research.

5.1. The general relation between the technical and the social

A major theoretical issue is to what extent and how the technical and the social interact and inter-penetrate each other in the shaping of technology. Fig. 9(a–d) suggest four possible models:

- technical determinism—the technical has its own dynamics and shapes content and direction of innovation and technological development, as well as the social dynamics (if recognised);
- social determinism—the social has its own dynamics and shapes content and direction of innovation and technological development, as well as the technical dynamics (if recognised);
- social and technical shaping—the social and the technical have separate realms and dynamics and influence each other as well as the content and direction of innovation and technological development. In this case, the social and the technical both shape but through autonomous dynamics;
- sociotechnical constituencies—the social and the technical have no real boundaries and constitute the single realm of sociotechnical alignment shaping the content and direction of technological development (Hughes talks of a ‘seamless web’). In this case, the technical is the evolving terrain of innovation and technology development and, as such, it conditions rather than shapes through a completely autonomous dynamics.

As the review of literature showed, most authors

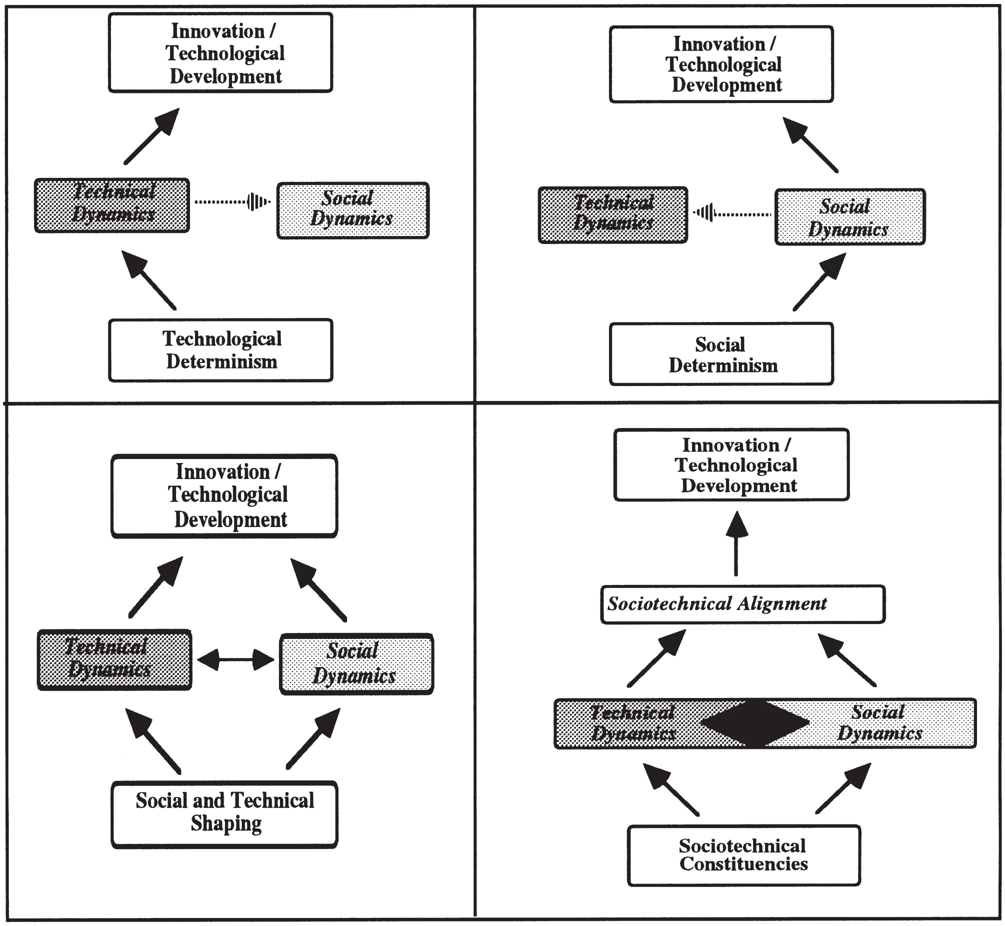

Fig. 9. Models for the relation between the social and the technical.

recognise that the technical and the social interact, although certain statements may appear deterministic in one direction or the other. Crude determinism of either technical or social nature was thus not an issue for this paper. The issue was much more the bias towards the social created by the existence of a large body of literature dealing with social, economic, political, cultural explanations of innovation and technology development as compared with the treatment of the role of the technical. Indeed, the paper identified a clear lack of systematic conceptual environment enabling the treatment of the strategic implications of the technical in innovation processes.

This gap provided the motivation for this paper: to take the first steps of a possible programme of work seeking to systematize the role of the technical, thus helping to reverse the present bias. Of course, the results of the intended systematization would have differed markedly depending on whether the model adopted was the ‘social and technical shaping (9c)’ or the ‘sociotechnical constituencies (9d)’. The first model would have implied discovering both the autonomous dynamics and patterns of relationships within technologies and between technologies, as well as the forms in which these interact with and shape the social and vice-versa.

This was not the problem of this paper. The sociotechnical constituencies approach, as its name makes it clear, does not separate the technical from the social in the process of alignment essential to innovation and technology development.

True, the review of literature not only showed that technologies have socially related characteristics such as key, strategic, or, labour-intensive. It also seemed to suggest some ‘intrinsic dynamics’ as in, for instance, Rosenberg’s (Rosenberg, 1969) compulsive sequences and Hughes’ (Hughes, 1983) reverse salients; or A.D. Little’s (Little, 1981) embryonic, growth, mature and ageing technologies; or Fleck’s evolutionary relation between configurations, generic systems and discrete technologies. On closer analysis, two factors are crucial to this apparent intrinsic technical dynamics: time-dependence and the intrinsic relation system-component. Thus, both Rosenberg and Hughes are dealing with this system-component relation and, although it is clear that components condition each other in the generation of the system’s performance, this is not the same as saying that the total shape of either a component or the system is purely the result of this relationship. Indeed, both authors have pointed out that the shape of components is also the object of economics.

A.D. Little’s and Fleck’s relationships are time-related and capture the fact that technologies evolve in time and seem to follow general trajectories along their life (see also Dosi, 1982). This evolutionary approach, however, does not propose the existence of a general endogenous technical dynamics of innovation. Thus, not all technologies will follow Fleck’s trajectory from configurations to components. For instance, there will always be stand-alone technologies such as drugs. In this respect, Fleck’s conceptualisation seems more appropriate for information technologies where standardisation, miniaturisation and networking are predominant characteristics. Furthermore, evolution from birth to maturity is never pre-determined. There are scores of technologies which never reach maturity as their constituency-building processes lose momentum and dissipate. Indeed, a great deal of Fleck’s point with configurations is that, initially, there might be several configurations competing in an emerging industrial field. In time, as requirements become clearer and standardisation emerges, some configurations may give rise to generic systems and, further on, these systems may themselves become constituent components of other configurations (Fleck, 1993). The specific result, however, is not implied in any endogenous technical dynamics. After all, the essence of standardisation is the interaction (collaboration and/or competition) of sociotechnical constituencies, and this is also implicit in the work of economists identifying the emergence of ‘dominant designs’ through market competition.

For all these reasons, the approach taken by this paper was the sociotechnical constituencies (9d). This defined its theoretical place in the general relationship between the social and the technical. The sociotechnical constituencies approach, as it name makes it clear, does not separate the technical from the social in the process of alignment essential to innovation and technology development. And this is particularly the case as innovation and technology development are understood to entail much more than accumulation of technological knowledge *per se*.[28] By definition, these processes entail creation, production and diffusion/implementation of knowledge, products and processes in the fabric of society. In this context, as said above, the technical is the evolving ‘terrain’ and, as such, it conditions rather than shapes innovation and technology development through a completely autonomous technical dynamics.

5.2. *Further research*

The intention of this paper has been to signal a direction for future research by taking the first steps in a possible programme of research seeking to systematize the role of the technical in technology development. It brought together many contributions and, as it were, ‘opened the curtains’ of dimension II of the diamond of alignment (Nature and Maturity of the Technology). Fig.

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[28] Looking at technological knowledge alone might lead to something reminiscent of the old debate on the exogenous or endogenous development of science epitomized by the work of Bernal and Merton several decades ago. See Bernal (1967) and Merton (1957).

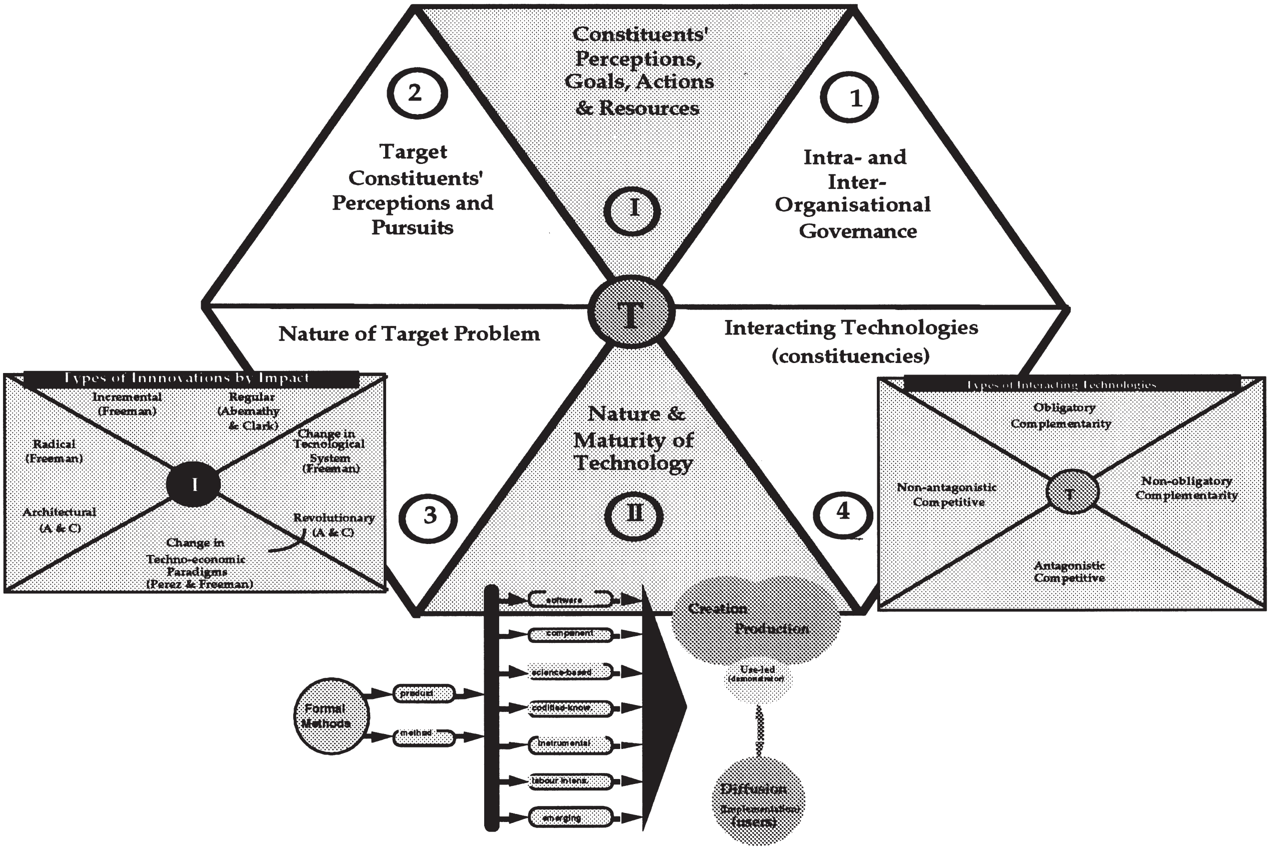

Fig. 10. New technical ingredients in the diamond of alignment.

10 illustrates the new state of technical ingredients in the overall diamond, with the taxonomy of genotypes now replacing the narrower time-dependent curve in Fig. 3 (for space reasons the formal methods taxonomy is used).

The resulting taxonomic instrument is foundational rather than fully developed, although—even at this stage—a definite intention was to generate an instrument to help students of technology, innovators and technology strategists not just to be aware of the strategic influence of technical characteristics but, above all, to brainstorm and raise creative questions about the strategic implication of these features for creation, production and diffusion/implementation processes. The two case studies demonstrated the usefulness of the taxonomy.

Further research is now necessary to advance the theme on theoretical and empirical grounds. At least three aspects can be distinguished:

1. Developing further the proposed taxonomic instrument by refining, adding, or modifying the present framework and categories. Indeed, the whole instrument may be reshaped altogether if this is appropriate to advance our systematic understanding of the role of the technical in constituency-building.
2. Debating further the general relation between the technical and the social, with particular reference to the ‘social and technical—(9c)’ and ‘sociotechnical—(9d)’ models identified in the previous section.
3. Researching relations and ways of linking systematically all dimensions containing technical aspects in the diamond of alignment. Looking at Fig. 10, it is by and large possible to see it as composed of an upper half (1-I-2) containing predominantly social aspects and a lower half (3-II-4) containing predominantly technical aspects. How can relations and influences between the three dimension of the lower half be theoretically conceptualised? How can relations and influences between the ‘technical’ lower half and ‘social’ upper half be theoretically conceptualised?
4. Developing more empirical cases to substantiate and test further the proposed taxonomic instrument and, more generally, all aspects of theoretical research on the relations between the social and the technical.

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role of the technical in innovation and technology development.

Appendix

Technology Genotypes Categories for the Taxonomising of Technologies

Adaptor—Products which enable other technologies to be used for a purpose, or in conditions, other than that, or those, for which it was originally designed (Chambers, 1987). For instance, electric adaptors enabling different sizes or types of plugs to be connected to one another. Adaptors can be unidirectional or bidirectional (or multidirectional). They are unidirectional when they allow one technology to access the market of another but not the opposite. They are bidirectional when they allow technologies access to each other markets.

Adolescent—A thriving technology in which investment of effort and resources produces high increases in performance. The technology is at the peak of its productivity, i.e. rate of performance gains to technical effort (productivity). Given this characteristic, adolescent technologies are deeply associated with fast product-cycle markets, although this is also depends on the specific competitive structure of these markets.[29]

Architectural—Technologies which in the course of their existence may evolve through several product-generations in ways which combine substantial change with continuity or compatibility. Their most distinctive feature is an accumulation and portability of software, which go hand in hand with major advances in hardware.[30]

Batch—Processes in which operations are carried out with discrete quantities of material or a limited number of items. Different from continuous or mass production. An example is batch processing in computing in which a single program processes many individual jobs (McGraw-Hill, 1978).

Capital-intensive—Technologies in which the share of labour costs in the total cost of the technology is relatively small. The largest proportion of costs is accounted for by the cost of hardware and software.

Closed—Technologies with closed boundaries, no interconnectivity, and capable of fulfilling their purpose in isolation.

Codified-knowledge—Products, processes and methods which are largely formalised and articulated. They can be more easily reverse-engineered or copied by competitors, for codified knowledge is easier to transmit and receive.[31]

Complex—These are technologies characterised by multiple components and systemic interactions and are nondecomposable in that they cannot be separated into their components without degrading performance. They are not subject to full understanding by an individual and monopoly protection is difficult, because the countless possibilities to rearrange interactions and introduce new subsystems and components provide the means to engineer around the legally protected products and processes (Singh, 1993; Kash and Rycroft, 1993).

Component—A constituent part or aspect of a more complex technology (Collins, 1988).

Configurational—Technologies whose implementation demands that users requirements be built into the innovation. In such technologies, each installation is a more or less unique adaptation to the local contingencies of application. Extensive user inputs at all levels are required, to such a degree that in-house development within the user organization is the rule rather than the exception. An example is computer aided production management (CAPM) software, which cannot be implemented without capturing certain idiosyncrasies of the users' production process (Fleck, 1994).[32]

Continuous—Processes involving a sequence of subprocesses performed by a series of machines receiving the materials through a closed channel or flow. Chemical and paper production are good examples (McGraw-Hill, 1978).

Converter or translational—Technologies that translate or convert from one language, or communi-

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[29] "We know from the mathematics of adolescent S-curves that once the first crack appear in the market dam, the flood cannot be far behind…In the 1 K random-access memory, which was the first built, the productivity differences between the emergent and adolescent stages were of the order of 19 to 1" (Foster, 1987, pp. 110, 108–109).

[30] For constituency-building, the implication is that decline needs not follow the first generation product. With architectural technologies, new generations actually seek to build upon the technical and social constituents of the previous one, thus re-generating the momentum of the constituency. At the same time, the capacity for major change from one generation to another provides an opportunity for equally significant changes in the constituency-building strategies pursued by the originators of the technology. In particular, there is ample opportunity to change radically the balance between collaboration and competition, expressed through arrangements such as licensing and second sourcing (Molina, 1993a).

[31] This means a 'weak' appropriability regime (technology is very difficult to protect) affecting a company's ability to control, or fully appropriate, the commercial benefits of a successful technology (Teece, 1986).

[32] "The participation of users at various levels, familiar with local contingencies, is *necessary* to build configurations. User knowledge, job design, and human factors are not just adjuncts, but essential *inputs* to the innovation process, helping to crystallize contingencies into novel artifacts" (Fleck, 1993, p. 15).

cations protocol, into another. Protocol is a set of rules governing information flow in a communications system. Compilers and protocol converters are a good example.

Customizable—Products with an open array structure (i.e. connectable units not yet connected) which can be customised to an exact specification of the customer. In these products the internal connectivity between basic units is 'suspended' until the customer provides the specifications. Logic gate arrays are a good example.

Dynamically-configurable—Technologies which will automatically configure themselves to the requirements of another technology or, indeed, different users' demands. An example is the idea of open-boot software which automatically find out what hardware is on the machine and configures itself to its characteristics.

Emerging—A new technology in which gains in a given performance parameter demand a relatively important investment of effort, time and resources. The rate of performance gains to technical effort to develop the product (costs) is low but increasing.[33]

Familial—Technologies having a generic core underpinning the generation of different products which may potentially satisfy different segments of users. They can give rise to multiple generations as well as multiple related products inside every generation.

Generic—Technologies which provide the foundations for the development of a range of practical applications (e.g. products).

Generational—Technologies which evolve through several generations frequently growing in performance features and complexity.

Hardware—Products with a tangible, material reality of their own, including gases. This includes the physical, tangible, and permanent component of a computer or data-processing system (McGraw-Hill, 1978).

Instrumentalities or enabling—Technologies (methods (techniques), tools, instruments, processes) which help make new science and technologies. More generally methods for doing something to nature or to the data in hand. Instrumentalities or enabling technologies can create new opportunities for application and fill a need that might or might not have been previously diagnosed (Price, 1984).

Integrator—Technologies which enable the integration of a heterogeneous range of other technologies into a coherent functional whole or system.

Interfacing—Technologies enabling the interconnection of two or more other technologies. Two types are converter or translational technologies and adaptor technologies.

Labour-intensive—Technologies in which the largest proportion of costs is accounted for by the cost of labour. The share of labour costs in the total cost of the technology is relatively high.

Maturing—A technology in which gains in a given performance parameter are demanding an increasing investment of effort. The marginal rate of performance gains to technical effort (productivity) is low and decreasing.[34]

Method—A way of proceeding or doing something, esp. a systematic or regular one (Collins, 1988). The mode or rule or accomplishing an end (McGraw-Hill, 1978).[35]

Miniaturising—Technologies characterised by an evolution which shows a dramatic increase in the density of its own components (e.g. transistors/mm^2). This enables simultaneous increases in performance per given physical area, which often result in a dramatic fall in cost/performance. Reduction in physical size per given performance is only a special case of miniaturization.

Modular—Technologies made of self-contained units (i.e. modules) which serve as building blocks for systemic structures. Modules have agreed standard interfaces so that they can be easily joined to, or arranged with, other units to provide an overall functional flexibility (McGraw-Hill, 1978).

Network-externalities—Technologies in which the benefit users derive from their use often is an increasing function of the number of other users acquiring compatible items. Network technologies, such as the telecommunications network have direct externalities in that the greater the number of subscribers on a given communications network, the greater the services provided by that network. Non-network technologies (i.e. without physical network) have indirect network externalities in that their benefit to the users entail the provision of a complementary good. For instance, computer hardware requires software and the number of units sold tends to

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[33] In Foster's words, productivity (slope of the curve) is low but increasing, where productivity is the "technical advance divided by effort expended" (Foster, 1987, p. 283). "At the start of the curve we need to put in significant effort before we can expect to see results. Once the learning is done, we begin to make significant progress for very little expenditure of effort. That usually does not last too long—perhaps a few years. At some point we begin to approach the limits of the technology and we start to run out of steam. [This challenges the assumption] that the more effort put in, the more progress that results. In fact, this is only the case in the first half of the S-curve. In the other half it is wrong" (Ibid, pp. 101–102).

[34] Unlike the case for emerging technologies, at this stage the market is highly segmented and differentiated (Fleck, 1988).

[35] A related definition is technique: method of performance, manipulation, esp., everything concerned with the mechanical part of an artistic performance (Chambers, 1987).

increase with the amount and variety of software (Farrel and Saloner, 1985; Katz and Shapiro (1986a, b)).

Network—An interconnected group of devices or systems which is geographically distributed. In Burch and Grudnitski's (Burch and Grudnitski, 1989) words, networks are the links that bind people and machines together, making it possible for them to share work, facilities, information, and ideas…the basic components of networks are nodes and links. Nodes are the points that can accept data input into the network or output information, or both. Subnodes act as relay devices that manage information between input and output nodes…Links are channels or paths for the flow of information between input/output and relay nodes.

Open—Technologies with open-ended boundaries, normally, offering easy interconnectivity to products from many different vendors. When these other vendors' products include similar (competing) technologies multidirectionally interconnected then there is inter-operability. Open-system computers are a good example.

Pervasive—Technologies with the potential for widespread impact on the technical base of industrial and service sectors. Energy is one such technology.

Process—A series of actions which produce a change or development (Collins, 1988). A system or a series of continuous or regularly occurring actions taking place in a pre-determined or planned manner (McGraw-Hill, 1978).

Product—Something produced by effort, or some mechanical or industrial process (Collins, 1988).

Programmable—Technologies whose functionality can be programmed by a set of instructions which makes it perform an intended activity or task. Numerically-controlled machine tools are an example.

Scalable—A case of modular technologies in which certain performance parameters scale up as more modules are structured together into the system.

Science-based—Technologies whose foundations are derived from scientific knowledge (e.g. physics, chemistry, biology).[36]

Simple—These are technologies which can be understood by an individual expert. They normally can be accurately described and communicated on paper and they are susceptible to effective communication among experts across sectors and over distances (Kash and Rycroft, 1993).

Software—Products of intellectual, symbolic and audio-visual character which may be expressed and transmitted by a variety of media. In the computing field, software is the totality of programs usable on a particular kind of computer, together with the documentation associated with a computer program, such as manuals, diagrams, and operating instructions (McGraw-Hill, 1978).

Stand-alone—A technology capable of performing independently of any other, but, optionally, capable of interconnection with others. Networkable personal computers are a conspicuous example. Also referred to as discrete technologies since they function as self-contained packages quite independent of other packages, requiring no learning or interfacing with other elements, and hence are discrete in their implications. The ultimate user or consumer can make use of them in a direct and immediate manner (Fleck, 1988).

Standards—Technologies which are widely accepted or established within technical communities, as well as within industry and the market. Consensual standards are those technologies which become established by agreement within the relevant technical and industrial community. De facto standards are those technologies which become established or imposed by sheer market strength. Standards are not really a characteristic of technologies but the result of processes of constituency-building. Those technologies which achieve the status of well-recognised standard, however, are in a very propitious constituency-building situation.

Subsystem—A system which is part or component of a larger system or network. A major part of a system which itself has the characteristics of a system, usually consisting of several components (McGraw-Hill, 1978).

System—Any assembly of electronic, mechanical, etc. components with interdependent functions, usually forming a self-contained unit (Collins, 1988). A combination of several pieces of equipment integrated to perform a specific function (McGraw-Hill, 1978).

Tacit-knowledge—Product, processes and methods which are difficult to formalize and articulate, and whose transfer is hard unless those who possess the know how in question can demonstrate it to others.[37]

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[36] According to Freeman (1974), the expression "'*science-related*' technology is usually preferable to the expression '*science-based*' technology with its implication of an over-simplified one-way movement of ideas" (p. 29). On the other hand, the expression 'science-based' technology emphasizes more clearly the fact that scientific knowledge is indeed fundamental to the existence of the technology. Of course, there are many technologies which are not related to science at all.

[37] These technologies are relatively easier to protect from the competition, that is, they have a 'tight' appropriability regime (Teece, 1986).

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