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INNOFUSION OR DIFFUSATION? THE NATURE OF TECHNOLOGICAL DEVELOPMENT IN ROBOTICS

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UNIVERSITY OF EDINBURGH

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INNOFUSION OR DIFFUSATION? THE NATURE OF TECHNOLOGICAL DEVELOPMENT IN ROBOTICS

James Fleck*

In this paper, it is argued that the process of **"innofusion"** - that is, the collapsing together of innovation and diffusion - is of fundamental importance in the development of process innovations such as industrial robotics. With innofusion, important, even radical, innovations can evolve in the context of use, during the implementation process. Innofusion is characteristic of a certain type of technology - **configurational technologies** - which are distinct from **system technologies,** in that they lack an overall system level dynamic. Configurational technologies are particularly subject to influence by contingencies, and particularly dependent for their development upon the role played by users. The structure of knowledge associated with technological innovation is examined to identify the role of different agents in the technological innovation process. In these terms, innofusion can be characterised as an experimental learning process which crucially involves a range of agents across an industrial sector, and across several organisations. Consequently, policies aimed at encouraging **industry sector learning effects** may be the most appropriate for facilitating innofusion.

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INTRODUCTION

In this paper I want to outline a specific alternative to the linear invention-innovation-diffusion model which implicitly or explicitly underlies most analyses of technological development, and most measurements of technology-related statistics of economic performance, despite claims to the contrary [14].

In the proposed model, henceforth referred to as INNOFUSION, the processes of innovation and diffusion are collapsed together - hence the title "innofusion or diffusation?" The site of application and use of technology then becomes the prime site for innovation itself, not merely the locus of diffusion of something developed somewhere else, or the locus for "secondary" or "incremental" innovation, and certainly not merely the locus for "post innovation improvements". All of these latter terms, while recognising the existence of innovatory activities during diffusion, nevertheless implicitly assume the linear scheme by deemphasising the importance and potential radicality of innovation through use.

Innofusion is clearly of greater relevance for process rather than product innovations, though it may apply to certain products which require the consumer's participation in arriving at the ultimate product that is actually used: DIY software is perhaps a case in point, and the development of certain innovative computer games programs may represent possible instances of innofusion.

It is not meant to be a general model of innovation, but a specific model, intended to capture only one type or mode of innovation among several. Such a process need not operate to the exclusion of other more conventional innovation plus imitative diffusion processes: the complexity of any social system is more than adequate to sustain a variety of different processes, and innofusion may exist either as an alternative or a complement to other mechanisms of innovation.

MOTIVATION

There are various reasons for wanting to develop this new notion of innofusion. One is the inadequacy of linear schemes of innovation in trying to understand the development of certain new bodies of technology, such as robotics, flexible manufacturing systems, computer integrated manufacture, and, indeed, large information technology systems in general. In such cases, considerable development work and "customisation", usually with the active participation of the ultimate user, is necessary before they can be usefully employed. In these cases, it is quite clear on careful historical analysis (rather than the retrospective rational reconstructions that often pass for history in the field of innovation studies) that the emergence of the relevant body of knowledge **followed and accompanied** the practical (though not necessarily economically or even technically successful) use of the technology, rather than preceding it. Furthermore, the growth of the relevant bodies of knowledge is organically bound up so closely with the diffusion/innovation processes, that it becomes impossible in many cases to identify separate phases of innovation and diffusion.

Another, closely related, reason concerns the epistemological status of the distinction between radical and incremental innovations, between initial innovations and post innovation improvements, and, more generally, between any two instances in a series of innovations that is unfolding during the diffusion process. Clearly these distinctions only have sense in relative terms, and hence the categories are necessarily ex-post. It is not possible to definitively state, ex-ante, that something is, or is not, a radical innovation, though there may be very good structural or analogical grounds for making such a judgement. As many writers have pointed out [3,12,21], uncertainty is intrinsic to the innovation process, and it is only after the process has been worked through that judgements can legitimately be made. Thus the questions arise: what grounds do we have for assuming that changes arising during the diffusion process are always necessarily secondary ? And what grounds do we have for assuming that innovation and diffusion are always necessarily distinct? Hence the present attempt to outline a model which recognises significant innovation at the site of use and describes possible mechanisms through which such a process might take place.

A third reason is that innofusion is one way of effectively eliminating the problem of the conventional innovation studies opposition between technology-push and demand-pull: it essentially provides for the possibility of the development of technologies which are at the outset intrinsically constituted in terms of user needs and requirements - that is, in terms of the characteristics of demand. This is achieved, not through some esoteric, arbitrarily plastic, "black box" of technology which responds to market signals conveying information about demand, but through determinate processes of technological design, trial, and exploration, in which user needs and requirements are discovered and incorporated in the course of the struggle to get the technology to work in useful ways, at the point of application. This is not to say that this is what always happens in general with technological change across the economy, but it does open up the possibility of a probably complementary alternative to the variety generation / environment selection mechanism frequently posited. Indeed, it suggests the validity of a Lamarckian mode of evolution in addition to a Darwinian one, a suggestion that seems eminently reasonable given that human beings do in fact explicitly design and construct technology to meet their needs, and do not necessarily have to wait for the spontaneous generation of suitable mutations by autonomous technological change processes quite independent of the selection environment.

The innofusion model is one which, I believe, may have utility in helping us to understand the nature of certain important examples of current technological development. The model is described and its basic mechanisms detailed in terms of the differential distribution of knowledge among the various agents involved in the innofusion process. This distribution is related to patterns of work organisation and therefore provides a means whereby factors pertaining to the nature of work can be seen to be important inputs in the process of development of new technology, rather than merely being factors affected or "impacted" (as conventional terminology has it) by the adoption/diffusion of technology.

This paper presents the theoretical background for the innofusion model, and outlines how it relates to a particular example of technological development, namely robotics.

QUALIFICATIONS

This essay is a preliminary attempt to articulate and argue for this specific (as opposed to general) model of innovation. There are, therefore, several areas still requiring development. The major shortcoming (especially since the model is essentially empirically motivated) is in the provision of empirical evidence, which is here presented only in broad outline, for one technology. A detailed discussion of the working through of a particular example of innofusion would be appropriate, though it will have to be the subject of a further paper, for reasons of space.

Another aspect that requires further development is an explication of the interface between this model and others, in order to produce a **general** rather than specific model of innovative activity. By specific here I mean that, rather than trying to achieve generalisation by building a model to capture **all** types of innovation, and therefore in principal testable using general macro-economic statistics, this model attempts, at a more microscopic, fine-grained level of detail, to identify and clarify only **one** among several (possibly even many) different types or modes of innovation. Generalisation in this case would then amount to identifying the extent to which this particular mechanism was widespread. This, of course, may make it difficult to test the model at the macro-economic aggregate level using such regression models as have been employed in previous work by economists on the subject of innovation.

A final issue requiring further development and articulation, concerns the links between this model and economic theory in general, for my perspective is that of an empirical observer of technological innovation equipped with conceptual tools from the sociology of science, rather than that of a participant in the economic debate over innovation.

CONSTITUTION OF THE MODEL

There are two major components which make up the innofusion model: (a) the essential involvement in the innovation process of **knowledge**, not as the neoclassical ideal of "information", but as determinate, socially-distributed **bodies** of knowledge; and (b) the empirically based observation that, in many areas (which I shall broadly indicate and venture some way to specify, through the identification of a certain class of **configurational technologies**), the conventional distinction between innovation and diffusion does not hold. In the following, the nature of knowledge will be discussed in some detail, and different types of technology explored with respect to this discussion. Finally, the evidence from one area, robotics, will be outlined.

TECHNOLOGICAL KNOWLEDGE AND INNOVATION

There has long been a tradition of writings on innovation, which, rather than assuming the frictionless, instantaneously transmitted information of economic equilibria analysis, emphasise the crucial importance of knowledge and its uneven distribution for the innovation process [16]. In recent years, work in this tradition has intensified, and become more closely incorporated into economic analyses [10,18,25,26]. Terms bearing on the nature of knowledge and its relations to technological innovation have proliferated; and include the notions of natural trajectories [21]; technological regimes [19]; design configurations [19]; technological guideposts [27]; innovation avenues [27]; and technological paradigms [3].

However, for our present purposes, there are several general deficiencies in the treatment of knowledge by the innovation literature. While the basic **importance** of knowledge is recognised, certain aspects of its nature and structure, as revealed by studies of scientific and technological knowledge, tend to be overlooked. Knowledge becomes viewed as some sort of aggregated resource with a very generalised, rather than well-specified, relation to innovative activity. In particular, certain features relating to the social organisation and distribution of knowledge, which are crucial to innofusion, rarely attract the attention they deserve. There is

also a tendency in innovation study treatments of knowledge, to view technological knowledge as an external given, autonomous from the innovation process. Related to this is a further tendency to view technological knowledge in relatively static terms, at least as far as the relation to innovation is concerned. But, as we shall again see, there is evidence, in the field of robotics, in any case, for a high degree of interaction between activities producing innovation and activities producing knowledge.

Thus the notion of "natural trajectories" (such things as economies of scale, mechanisation, improvement of mechanised operations, exploitation of an understanding of electricity and the improvement of electrical devices, and a similar exploitation of an understanding of chemistry), as elaborated by Nelson and Winter, is said to be underlain by: "a certain knowledge on the part of the technicians, engineers, scientists, involved in the relevant inventive activity." No detailed account is given of how this "certain knowledge" is specifically involved in the inventive activity, while in the very notion of "natural trajectories", there is a clear sense of some sort of pre-existing body of knowledge or practice which is deployed in innovative activity, and directs it along certain pre-determined paths of development.

Similarily, the knowledge-related notions put forward by the Manchester school indicate clear assumptions of a given or pre-existing body of knowledge, which is more or less efficiently deployed in innovatory activity: for instance, according to Metcalfe:

> "A technological regime is a framework of knowledge, describable in terms of a set of basic design parameters, which guides and constrains engineers and innovators in the design of a range of products and their related processes of production. This knowledge

is, in principle, shared by all firms in a given technological area. A Design configuration, by contrast, relates to specific products and processes and it is to be identified and mapped in terms of the performance characteristics, input coefficients and product attributes, which embody a particular constellation of the basic design parameters. While the regime provides the element of continuity and shared experience, the design configuration provides the element of variety and differential performance in products and processes.[19,p.7]

In later writings, however, on the "knowledge base" of a firm, Gibbons and Metcalfe do take note of some of the characteristics that we are looking for:

"While major components [of the knowledge base] are contained within firms, external knowledge held by other institutions, eg. university departments and government laboratories is often important, as is any firm's ability to inwardly transfer knowledge from these external sources. A core of knowledge will often exist in a codified, publicly available form but for the competitive process it is the tacit, proprietary knowledge of individual firms which is of crucial importance. This knowledge exists in the minds of the firm's employees and its application is contingent upon how the organisation pools their individual capacities. In understanding differences between firms in revealed technological performance, it is quite impossible to separate questions of strategy and organisation from questions of technological knowledge proper. The routines and structures of organisations are critical to the process of technological differentiation. Typically, the knowledge base of a

firm builds cumulatively, through experience, formal R. & D., and inward transfer of the knowledge contained in other organisations". [11,p.3]

Here the non-uniform, socially-distributed structure of knowledge is explicitly acknowledged, and, moreover, the dynamic nature of its development hinted at in the last sentence, thus moving us towards a conception of knowledge similar to that articulated by work on the development of scientific and technological knowledge [13,15,17,24,29]. However, Gibbons and Metcalfe do not follow up all the implications of such a conception of knowledge, but restrict themselves to elaborating an evolutionary model of competitive innovation, in which the knowledge base serves mainly as the generator of variety, which is then in turn subjected to competitive selection by the environment. Once again an implicit linearity is introduced, in the clear distinction between generation and selection.

Another author in this area, Dosi, has explicitly drawn on related work from the philosophy of science to develop a notion of "technological paradigms", as bodies of knowledge analogous to the scientific paradigms of T.S. Kuhn [15]. Dosi's discussion is specifically directed to studies of innovative activity. He defines technology:

"as a set of pieces of knowledge, both directly 'practical' (related to concrete problems and devices) and 'theoretical' (but practically applicable although not necessarily already applied), know-how, methods, procedures, experience of successes and failures and also, of course, physical devices and equipment. Existing physical devices embody - so to speak - the achievements in the development of a technology in a defined problem-solving activity. At the same time, a 'dis-embodied' part of the technology consists of a

> particular expertise, experience of past attempts and past technological solutions, together with the knowledge and the achievements of the 'state of the art'. Technology, in this view, includes the 'perception' of a limited set of possible technological alternatives and of notional future developments." [3,p.151]

While this again approaches the notion of technological knowledge that we are seeking, Dosi still makes the assumption that, certainly in the short term, this knowledge is autonomous, essentially providing the generation of a variety which is then subsequently subjected to selection pressures provided by the environment:

> "Thus economic and social environment affects technological development in two ways, first selecting the 'direction of mutation' (ie. selecting the technological paradigm) and then selecting among mutations, in a more darwinian manner (ie. the ex post selection among 'Schumpeterian' trials and errors)." [3,p.156]

Again the crucial distinction between generation and selection, between innovation and diffusion is preserved, and with it the linearity of the innovation process, albeit strongly modified by selective feedback. Further, Dosi, in that his use of the notion of paradigm is limited to its philosophical features, makes little reference to, and even less use of, those features immanent in the structure and nature of knowledge on account of the associated social characteristics of paradigms.

Sahal, the final author to be considered here, provides an analysis of particular relevance for our purposes. He presents many

observations about technological knowledge vis-a-vis innovation, although he does not provide a detailed systematic account of innovation in terms of the knowledge processes involved. Many of Sahal's conclusions are strongly conformable with the implications of the proposed innofusion model, despite the far broader scope of his generalisations. This suggests that innofusion itself may have a wider range of relevance than originally envisaged.

Sahal proposes that innovation may be conceived as a process of learning by experience - "the learning by doing hypothesis, that technological innovations originate in accumulated experience of a practical nature"; and comments:

> "A great deal of contemporary theorizing on technological change is based on the assumption that the adoption of an innovation is fundamentally a process of imitation starting from the initiative taken by a few individuals. The alternative viewpoint advanced in this study is that the diffusion of a technique is intimately linked with its development." [28,p.98]

Earlier he observes:

> "In summary, there is preponderance of evidence suggesting that the nature of technical progress constitutes an evolutionary system. This is not to say that radical advances in technology do not occur. Rather, the major innovations are made possible by numerous minor innovations. The cumulative impact of many seemingly minor changes in technology often tends to be quite substantial." [28,p.37]

On examining the mechanism underlying the origin of new techniques, Sahal proposes the negative binomial distribution as an appropriate model of innovative activity. This applies equally to a multitude of unrelated cases of innovation, and suggests that the determinants of new products and processes tend to be very many, while the effect of each is rather small, a result at variance with the popular belief that innovation depends on initiatives taken by a few progressive individuals or firms [28,p.61].

Clearly, this is in line with the feature of innofusion in which innovation and diffusion are concomitant, and which therefore suggests that the linear view requires modification. However, Sahal need not discount the possibility of major innovations emerging per se, even if very infrequently, rather than simply as the culmination of many minor innovations. As discussed earlier, these categories are retrospective, and their attribution therefore depends upon what happens in subsequent development; that is, upon the uncertain unfolding of contingencies.

Sahal's conception of innovation as a learning process is also in agreement with the innofusion model, even though expressed in somewhat different terms and from a rather different perspective. According to Sahal: "we must acknowledge a certain fine structure of interactions between the factors on the supply side and the demand side in order to understand observed patterns of innovative activity." This is precisely where the proposed innofusion model fits in: it attempts to detail some aspects of the fine structure of innovation.

THE STRUCTURE OF KNOWLEDGE

The economic notion of perfect information assumes that knowledge is a freely-available, frictionless entity to which any individual agent has immediate access. In reality, however, scientific and technological knowledge is very unevenly distributed across many different social groups. This state of affairs does not arise by accident, but is a necessary consequence of the very nature of knowledge and its generation. A vast amount of research and scholarship has demonstrated that knowledge exists as **socio-cognitive structures** of varying complexity [9,13,15,22,29]. As well as a knowledge or cognitive content, these structures necessarily involve associated social groups, the **carriers** of the knowledge, who have a lesser or greater degree of commitment, depending on the costs of acquiring and maintaining their investments.

In the case of scientific knowledge, where these costs are obviously very high, one finds strong, richly-interconnected communities of more or less equal peers. T.S. Kuhn, whose work has been extremely influential for studies in this area, used the term "paradigm" to explore and analyse the emergence and development of such scientific communities [15]. His work developed earlier analyses by Polanyi [22] and Ludwik Fleck [9]. Polanyi emphasised the crucial importance of **tacit knowledge**, even for the understanding of formal structures in science. Fleck, whose seminal work on the history of syphilis is receiving renewed attention, used the term "thought collective" (Denkkollektiv), to emphasise the importance of the social character of knowledge structures in science.

In the case of technological and other types of knowledge relevant to innovation, the situation has some similarities with, but also some very important differences from the scientific case. As an adequate approximation for our present purposes, we may conceptualise these socio-cognitive structures as having two dimensions: a vertical dimension which refers to the components of knowledge as they are held by the carriers; and a horizontal dimension which refers to the way in which different bundles of knowledge are distributed among the carriers.

Knowledge may be characterised as being made up of a number of vertical components as indicated in Table 1 (cf. Dosi, above). All of these components are crucial for the effective deployment or application of knowledge, though in fact there has been a strong bias towards considering only the formal knowledge level as important, and regarding the rest as inessential. Thus, for instance, until relatively recently, much philosophy of science took only scientific theories into serious consideration and remained unconcerned about other elements of scientific practice. Yet experimental skills are clearly also of crucial importance. And with respect to the application of technology in industrial production, such phenomena as learning curves, for instance, are primarily based on the other components. The high value almost universally placed on experience also derives directly from the importance of the other elements, rather than the formal component.

There will clearly be differences in the relative importance of the various components, depending on the area concerned. Thus for scientific fields, the major focus is on developing new theories that explain some natural phenomena. **Instrumentalities**, that is to say knowledge "embodied" in tools and instruments, are also important in scientific fields, but not as a central focus, more as a means to an end. With technological innovation, the emphasis is the other way round: the focus is far more on the instrumental level, while the theories become the means to the end. Moreover, with technological innovation, instrumentalities are a crucially important route for the introduction of innovations from other sources, to be combined together and, literally, incorporated, into further innovations, at a higher "systems" level.

Indeed, this process is also important in the case of scientific development; consider, for example, x-ray crystallography, the electron microscope, or even the humble telescope, when it was first used for astronomical observations. In all these cases the instrumentalities were essential components in dramatic scientific discoveries. Thus we can see that instrumentalities are a significant route for mutual interaction between science and technology, and constitute one of the key mechanisms by which technological innovation enters into, and helps shape, scientific development. And at the same time, the scientific needs call forth novel technological configurations. Perhaps the most dramatic example in this connection is the use of large-scale high energy cyclotrons, which demands extensive engineering innovation, and has contributed directly to major scientific breakthroughs. De Solla Price, from whom the term "instrumentality" in this connection is derived, provides a very pertinent discussion of these matters in a paper explicitly addressing the science/technology relationship [23].

Another important difference between science and technology arises from the extent to which the distinct components of knowledge become the preserve of different specialists; that is, the extent to which a **vertical division of labour** emerges. In many academic areas of scientific activity, there is a very shallow hierarchy approximating to the collegiate ideal of a community of equals, while in most areas of technology (for example, modern automobile production) there is, in sharp contrast, a very extensive division of labour, with many levels of engineers and technicians, specialising at different levels and in different components, mainly around a host of different instrumentalities. Some areas of science, of course, such as high energy physics, approximate to the division of labour conditions found in modern manufacturing.

The vertical division of labour interacts with a **horizontal division**

of labour arising from the horizontal dimension of the socio-cognitive structures introduced earlier. This horizontal dimension is directly concerned with the distribution of knowledge among the communities carrying that knowledge. In scientific areas these communities are relatively undifferentiated. Polanyi characterised the scientific enterprise as a whole as being covered by "overlapping neighbourhoods" of scientists. In each neighbourhood there would be a commonality of skills and knowledge, shared by the members of the neighbourhood (a group of "peers"), but not extending far beyond the neighbourhood, at least not to any reasonable degree of competence.

There would not be a perfect one-to-one correspondance, of course, between the commonalities of knowledge and the communities of peers. And so a measure of overlap results, sufficient to enable the transmission of certain elements of knowledge through extensive networks of communication and contact, despite the necessarily highly localised distribution of specialist competence. Such a localised distribution follows of necessity because of the tacit and contingent (ie. specific to the particular context) elements in the vertical structure of knowledge, which create very formidable barriers to entry and transmission, so that once a practitioner has made an investment in a particular area, he or she becomes de facto committed.

In the case of technological innovation, the situation is quite different. The communities are, in sharp contrast, highly differentiated, not just in terms of the vertical division of labour already mentioned, but also in terms of a horizontal division of labour, because of the wide range of institutions involved in technological activity. These institutions include a variety of user firms and supplier firms, all linked together (primarily by the physical transfer of instrumentalities in fact), in complex webs of supply relationships. In addition, there exist a range of

promotional, advisory, and educational agencies, which are concerned with technological development. A plethora of non-technical support agencies, such as finance and investment bodies, also have a role to play in technological innovation, in a way that they do not in the more esoteric fields of academic scientific endeavour. Finally, to further complicate the picture, there are a range af bodies which have come into existence specifically to protect and promote the interests (often based on the skill and knowledge investments made) of different groups of knowledge carriers - namely professional bodies, trade unions, and employers' federations.

This institutional, disciplinary, and professional structure effectively fragments the population of people involved in technical innovation, to such an extent that it becomes impossible to talk about a technological community in the same way that we might talk about the scientific community. Instead of a coverage of overlapping neighbourhoods, there is a very complex, fragmentary set of quite separate interest groups. And instead of being integrated by an extensive network of informal communication and contacts, relationships between the groups are mediated primarily by formal contracts, by market exchanges, and by the physical transfer of the technology itself. Of course, informal contacts and communications do exist, especially where technological development is rapid, and one finds that the actual movement of personnel (and hence of the vertical components of knowledge they carry with them) is crucial in new firm formation and growth. Moreover, the fragmentation penetrates even into individual firms with explicit, often formalised, and sometimes confrontational relations between different interest groups; not just between workers and managers, but also between distinct professional groupings, as is frequently found, for instance, between engineers and accountants, or between production and marketing.

Clearly, therefore, the nature of the bodies of knowledge, the socio-cognitive structures, will differ according to the nature of the innovation, and the nature of the associated supply and user industrial infrastructures. In some cases, elements of explicit political conflict and negotiation will be endemic, not necessarily as an irrational barrier to progress, but rather as underlying knowledge commitments which structure the technical decisions made in positive as well as negative ways, and hence influence the final design outcome [30].

Even where no explicit conflicts are involved, the patterns of work organisation (ie. the manner in which different organisations arrange the vertical division of labour around the various knowledge components) will have an important influence on the design outcome, and on the opportunities for innovation. For example, if a given innovation makes use of certain technological resources, then any organisation which either does not have people who can command and perceive the importance of those resources, or which does not provide a working environment in which they can be appropriately deployed, will be excluded at the outset from any possibility of ever being able to produce that innovation.

These questions have been explored to some extent by Burns and Stalker, who put forward two organisational extremes: the **organic** and the **mechanistic**, each with different implications for innovation [2]. Broadly speaking, the organic arrangements approximate to the condition of "overlapping neighbourhoods", and so facilitate informal communication and the emergence of new combinations of components, thus favouring innovation. The mechanistic arrangements, on the other hand, tend to be characterised by relatively impermeable departmental boundaries and fixed task routines, and are well adapted for effective operation in stable or slow changing environments, where efficiency rather than innovation is at a premium.

The horizontal dimension of the socio-cognitive structures will also vary according to the particular innovation. In some cases, it may be possible for a small, closely-integrated research group to come up with the innovation; while in other cases, the cooperation or participation of quite widely separated groups may be necessary. In the case of innofusion, I am suggesting that the **active participation** of user groups as well as suppliers is crucial. This raises the issue of whether it is possible on theoretical grounds to identify certain classes of technology which may be particularly susceptable to development by means of innofusion. In this connection, I would like to argue that we can make useful distinctions between **discrete technologies**, **component technologies**, **system technologies**, and what I shall call **configurational technologies**.

Discrete technologies refer to those products (and to a lesser extent processes), which the ultimate user or consumer can make use of in a direct and immediate manner, as a self contained package, independent of other such packages, requiring no learning or interfacing with other elements, and hence discrete in its implications. Such a characterisation is of course an idealisation, but nevertheless captures the nature of many consumer products, and even some processes, where, for example, new innovations are embodied in the technology to substitute for existing elements without changing the basic functions of the process, so that from the point of the user, there is no significant learning or adaptation: the only perceivable differences are perhaps in price, or in improvements along the existing dimensions of performance. Clearly discrete technologies do not require the active participation of users, beyond their selection decisions in the market place to transmit patterns of preferences and the scale of demand to the suppliers. For such technologies, autonomous teams of

R & D researchers, and an independent supply-side may well come up with appropriate innovations, the success or failure of which is a straightforward matter of competitive selection in the market place. Furthermore, for such technologies, linear models of initial innovation - subsequent diffusion are probably entirely adequate.

System technologies refer to complexes of elements or **component technologies** which mutually condition and constrain one another, so that the whole complex works together, and the implications of innovations in particular components have to be worked through the overall system, in all likelihood necessitating changes in several components, as well as involving changes at the level of the system as a whole. For instance, in aircraft design, attempts to gain the benefits of reduced air friction at high altitudes, necessitate pressurisation of the cabin, and the development of engines able to perform efficiently at a wide range of altitudes.

With **component technologies**, it is often possible to make innovations within relatively stable design specifications set by the functional requirements of the overall system, and thereby to improve overall system performance; the substitution of lighter plastic materials for metal in the construction of car bodies, or improvements in the power/weight ratio characteristics of the engines used, are examples here.

Clearly, various different communities and groups of knowledge carriers, each commanding relevant components of knowledge, have to cooperate closely together for innovation where system technologies are concerned. One would also expect a new body of expertise to emerge at the systems level, concerned with the overall operation of the system rather than the workings of particular components. According to the extent to which systems are stabilised and standardised and therefore require little in the way of

customisation, there will be a correspondingly lesser or greater need for active user involvement. The greater the degree of standardisation, the more conditions will approximate to those for discrete technologies, but with a greater level of complexity in terms of the number of different groups involved on the supply side.

With component technologies, similar considerations obtain, except that the users/consumers in this case themselves consist of system suppliers. Again, with highly standardised, readily specifiable components, the participation of the users will be relatively minimal and probably highly formal (as, for example, in automobile component production).

For system technologies, clearly, simple linear models of the innovation process will not suffice. The more complex notions of trajectories, or technological paradigms, however, may well be useful here. These effectively capture the manner in which an overall system structure emerges, associated with some form of "internal" autonomous system-level dynamic which provides a direction for the subsequent working out or improvement of components.

By **configurational technologies**, I mean to refer to situations similar to system technologies, in that the whole complex works together, and is made up of component technologies. But in contrast, there is no clear system level dynamic: configurations of component technologies may be made up in a very wide (if not arbitrary) range of patterns; the mutually interacting (but not necessarily mutually constraining) components may be deployed in a very wide, possibly arbitrary, range of ways in order to match externally set requirements.

For such technologies, therefore, no linear form of innovation model will do. Development is a thoroughgoing evolutionary process, in which environmental contingencies are explictly built in at each stage of variation. Thus each instance of diffusion, each configuration, may well represent a unique variation, a new innovation in its own right. In short we have a process of innofusion.

The crucial point about configurational technologies, then is the lack of any stability in the overall system performance requirements. There is no necessary internally determined direction for development. Requirements need to be decided by the users, and hence the active involvement of the users is necessarily called for: it will rarely be possible for the users to simply play a formal role by setting specifications. Even with 'proven' configurational technologies, extensive user participation is demanded, due to the characteristic penetration of the configuration into the user's activities (as is found, for instance, with company-wide computer systems, which are good examples of configurational technology). With newer configurational systems, user participation will be demanded to an even greater extent, as relatively few of the configurational possibilities will have been fully understood or even previously identified, and therefore the users will have to be involved in order to ascertain whether the new possibilities that come to light are what they want.

In some cases, there may exist a long-term developmental relation between system and configurational technologies. Stable systems can emerge within configurational technologies, following the development of knowledge about the ranges of possibility open to the configuration, and the eventual identification of subsets of those possibilities which exhibit a degree of internal consistency and the establishment of a clear dynamic (often in the form of stable performance parameters) for further development. This process would

constitute the crystallisation of "technological regimes" out of the innofusion process, and would involve the emergence of a standardised body of knowledge resources out of a more open and uncertain process of technological experimentation and discovery. Thus, for example, as we shall see below, while robotics as a whole is still in an open process of experimental development, with many configurational opportunities still to be explored, several clear examples of robotic systems appear to be emerging, such as robot arc-welding or paint-spraying cells.

Thus, we can see that the vertical and horizontal dimensions of the relevant socio-cognitive structures, which are related in turn to the internal patterns of work organisation, and to the external patterns of industrial structure, are **directly** related to the process of innovation. More importantly, we can see that different types of technological innovation will be associated with different patterns of socio-cognitive structure. In particular, innofusion will be associated primarily with configurational technologies, and to a lesser extent with system technologies.

In the next section, we shall examine the development of robotics as an instance of a configurational technology in which development has depended on innofusion.

INNOFUSION AND ROBOTICS

It is not adequate to view development in robotics as simply a process of imitative diffusion following an initial innovation. J.F. Engelberger was the entrepreneur who took the invention made by George Devol and first made it commercially available in the early 1960s. (The first use was for the unloading of die-casting machines). Engelberger also deliberately **chose** the term "robot", from the sience fiction of Isaac Asimov, in order to attract publicity because of great problems in persuading people to buy or use these devices. Resistance to use has certainly characterised experience to date in general: indeed, no profits were achieved by Engelberger's company until the very late 1970s, and even then only for a short period, (which raises problems for those economists who identify profitability as the major motor of diffusion).

The original vision, never yet realised, behind Engelberger's entrepreneurial intervention was the notion of a **universal** replacement for arbitrary human labour (the "steel collar" worker), which would be economic since it could be made in large quantities, precisely because it **was** universal. Hence the name "Unimation" (universal automation) for Engelberger's company, and "unimate" for his devices. (For a general overview of some of the issues in robotics development, see references 7 and 8.)

But in the event, there has been a general efflorescence of different models and different types of robots, each more or less well adapted and designed for their particular application niches. Models are so disparate that it is hard to see them as being instances of the same thing, thus leading to interminable debates over the definition of what in fact is a robot.

Moreover, later innovations, far from being minor improvements, or incremental modifications, have certainly been more radical in nature and influential for subsequent developments than the initial Unimate model. This model, the unimate 2000, was made out of standard machine tool parts and looked more like a tank turret than any conventional idea of a robot. Nor have later robot designs have been at all similar in appearance. Furthermore, many of these later developments have derived from development very close to, if not

actually in, the context of use.

Among such influential, innovative developments have been: the Trallfa paint-spraying robot, revolute in configuration (ie. like an upside-down human arm), very spidery and relatively non-rigid in structure, which emerged from a wheelbarrow painting application in Norway; the PUMA (programmable universal manipulator arm) robot, which resulted from specifications derived out of a process of detailed analysis of assembly operations in General Motors; and the SCARA (selective compliance assembly robot arm) configuration, a deceptively simple adaptation of the revolute configuration obtained by turning the latter on its side. This recent (1981) development has had a dramatic influence on assembly applications because it produced (a) a working envelope more closely matched to the characteristics of existing workspaces, and (b) compliance characteristics (horizontally compliant, vertically rigid) which again were more appropriate for assembly tasks, such as vertical parts mating. Finally, there have also been radical developments on the software and control front, so that these aspects are now a far cry from the magnetic memory based record-playback system of the original unimate.

Another general feature of development has been the emergence of a recognition that robots are just one part of larger robotic systems (or configurations in our present terms): both the ancillary equipment and the manipulator require to be designed explicitly for the application. Thus spot welding transformers, guns and robots are now designed in conjunction with one another. The robots for this application are extremely rigid and often squat in appearance (eg. Kuka robots), completely different from paint-spraying robots for instance, which tend to be very spidery and rather wobbly.

Indeed, this tendency for robots to be designed specifically for the particular application has gone so far, that a range of "bolt-on" robots are emerging for various machine tool unloading applications: these robots are built to such precise working specifications tied into particular machine tool models, that they are bolted on to the relevant machine and become an integral element of the overall system - there is simply no scope for any "universal" use of such devices.

This systems approach has also become an underlying principle for the organisation of robotics supply companies. One finds that successful robot suppliers are either application niche specialists (like Trallfa for paint-spraying, or British Federal for underbody welding robots), or application oriented and organised generalists (like GM-Fanuc, who organise their activities around a range of application divisions). Again, this indicates a radical departure from the original concept of a stand-alone universal replacement for human labour, to a new conception of specialised, albeit programmable, systems. And again, it indicates the importance of the context of use - so crucial in fact, that the immediate context of use has become merged together with the basic robotics technology into broader application systems categories.

Thus it is clear that, on several counts, the original innovative notion of a universal handling machine has been left far behind. What we have today, is a vast differentiated population of machines which are quite different in appearance and capability from the original device, and from each other. The only element in common is some notion of "choreographic" capability, that is, a capability for carrying out a range of programmed motions in three-dimensional space. The scope of this basic idea is still in process of being actively explored, and there is no sign of the efflorescence of new robot types and models becoming exhausted. Indeed, it is possible to predict that, if one takes a new application area, perhaps in an industry where robotics have not previously been used, then new

innovations, possibly radical (depending, in accordance with previous comments, on the contingent opportunities in that particualar domain), are highly likely to emerge.

For instance, in a recent participant study of the implementation of industrial robots [4,5], it was found that no robot was available on the market to exactly match the specific requirements of the particular firm concerned. On the basis of a set of workplace analyses, outline specifications were produced for **two** new robot models. Once again, we see the importance of the context of use in generating new designs, and thus new innovations.

This latter example introduces evidence at another level of analysis, at the level of the **process of implementation.** Precisely because they are configurational technologies, robots cannot be bought off-the-shelf, plugged in, and immediately set to work (as can discrete technologies such as consumer durables). A lengthy process of implementation, of organisational learning, is necessary before successful operation is achieved. This implementation process is common to all new process technologies, and is becoming recognised as a central issue in the management of technology. Implementation does not always lead to success: indeed, evidence suggests that the more sophisticated the technology (or in our present terms the more configurationally complex the technology), the greater the likelihood of failure, with failure rates ranging from 40% for robots, up to 90% for computer integrated manufacture, and perhaps 80% for manufacturing resource planning systems [1]. It is during this process of implementation, a process of "learning by struggling to get it to work in a practical application", that innovative opportunities are recognised, and innovative developments are generated, sometimes to be transferred to other companies, or even the market, via the agency of the people involved in the implementation process.

As already suggested, the implementation process may be accurately characterised as an organisational learning process: it involves **all** the people within the organisation, each with their own specific areas of knowledge and concern. I have discussed the importance of expertise and knowhow for the implementation of robotics elsewhere, and in particular commented on the crucial contribution of contingent knowledge:

> "Another element, particularly important in the application of robotics, is contingent knowledge - detailed and specific knowledge about the particular situation in which it is proposed to introduce a robot, and about the technology itself. Contingent knowledge covers a host of items that can make, break, or delay an application including: a close familiarity with the production processes involved and the idiosyncrasies of the existing machinery; an acquaintance with the set of industrial contacts necessary to get a project completed; an appreciation of the abilities and attitudes ofthe personnel involved; and an understanding of the working environment and industrial relations climate. Contingent knowledge, because of its nature is extremely voluminous and rarely concentrated in one person. Rather it is generally widely distributed through an organisation, often at the lower levels of the hierarchy. As a result its importance is often overlooked or undervalued."[6,p.67]

The crucial importance of the implementation process has also been evidenced, in the case of robotics, by another feature of the development of the industry. This is the fact that many successful robot suppliers are those that have been able to closely link the supply activities with the implementation/use activities, thus

enabling direct feedback from use to design and development. In some cases the users themselves have entered into robotics development and supply: this has happened with ASEA in Sweden (where the very high per capita robot levels are due in large part to the machines used internally by ASEA); with Fiat (Comau) in Italy; with Fanuc in Japan; with Renault in France; with Volkswagen in Germany; and with General Motors and ,latterly, IBM, in the US. This in essence represents an institutionalisation of the innofusion mechanism: The "learning by struggling" process becomes incorporated of necessity into the supply infrastructure.

Thus, both in terms of the overall pattern of development, and in terms of the microstructure of the implementation process, we see that the innovation plus imitative diffusion linear model is inadequate. Figure 1 provides a schematic overview of the robot diffusion, adoption, and development process. The feedback loops are crucial for the development of the most effective systems. Therefore, those companies which can find ways of eliminating, or at least reducing the impermeability of the organisational barriers, are at a great advantage. The context of use is crucial in robot development, and in many cases leads **immediately** to innovations, **not** indirectly through the market mechanism or through a trial and error selective process. In other words we have a process of Innofusion.

Clearly, with respect to robots, the notion of technological paradigms, as put forward by Dosi, appears to have some utility in the sense that there is an initial view-point, a perception of new possibilities, based on the commonality of the choreographic capability. And certainly, these possibilities are then explored by subsequent developments. However, rather than this representing a "natural trajectory", with a pre-existing direction of development, and exploiting a pre-existing body of technological and knowledge resources, it would appear that future development has been almost completely contingent upon the areas of use chosen for attack, whether as a result of competitive pressures (as has happened in the car industry); as a result of decisions made at the level of the firm, in the hope of future competitive advantages; or as a result of government policy initiatives (as has happened in the case of military and space robotics in the US).

Moreover, a body of knowledge in robotics is gradually being built up through organic interaction with the patterns of slowly increasing use of robotic devices. The newly emerging subject of robotics includes the codification of the "rules of thumb" and experiental heuristics discovered in the course of use, and the techniques and practices for constructing successfully functioning robotic systems, as well as conventional academic research.

Furthermore, the academic research in the area is essentially addressing issues in a problem domain which has already been created by the practical use of robotics. In this connection one can identify various links between industry and academic research, including the movements of personnel and transfers of equipment (instrumentalities), all of which transfer knowledge and, importantly, permit the **migration of problems**. This latter refers to situations where outstanding problems thrown up by experience in use become recognised as standard, and are then handed on to academic groups as suitable topics for research. It is a mechanism of rather general import, and perhaps is necessary before "solutions" can be handed back from research to industry. It also conforms to the fact that academic research on robotics scarcely existed before practical activities in the use of robots delineated the scope for research.

The crucial involvement of the context of use and of the active participation of the users in the process of development of robotics has, therefore, to be recognised. If the notion of technological paradigms is to be applied in this case, then the relevant community to be considered must include the users, including the whole range of personnel occupying various roles in the vertical division of labour within the user firms. Thus, in a very real sense, in innofusion, one can identify the user communities as carrying out those activities analogous to experimentation in the sciences.

It also has to be recognised that, in this processes of development, later developments have sometimes been more radical than the initial innovation; they have not always been instances of mere incremental innovation following an initial radical innovation, nor instances of mere post innovation improvement. Rather, they have been an integral part of a new, emerging body of knowledge, a new socio-cognitive structure, which includes the users as active participants, not as purely passive recipients of things developed elsewhere. In short, then, robotics has been strongly dependent on innofusion.

CONCLUSION

Innofusion should, therefore, be recognised as a specific mechanism for innovation, particularly relevant in the development of configurational technologies. Since many process technologies appear to have clear configurational characteristics [20], innofusion may in fact be more widely applicable, than in only the case of robotics discussed above. Certainly, Sahal has presented evidence that the importance of "learning by doing" is far greater than is recognised by conventional linear views of the innovation process [28].
Furthermore, there is increasing evidence that "learning by struggling", ie. innofusion, is of crucial importance with a range of new technologies, such as flexible manufacturing systems, and computer integrated manufacturing [1]. Consequently, with the rise

of information technologies, which are intrinsically configurational, and which, by their very nature, require user participation in their design and development, innofusion may well grow in importance in the future.

The phenomenon of innofusion has a number of direct policy implications, at several levels.

First, users involved with configurational technologies, should recognise their own potential as creative agents: they already "own" much of the information necessary for getting such technologies to work - namely organisation and application specific information and knowhow bearing directly on the context of use. Moreover they should more explicitly recognise the real value of the knowledge distributed around and embodied collectively in their own organisations. At present, many new users lack confidence in their own abilities, and look to consultants and suppliers to provide all the information and knowhow necessary for new configurational systems. As a result, they are all too often sadly disappointed.

Second, suppliers, both of the equipment, and of consultancy advice, also have to recognise the realities of the innofusion process: they only "own" part of the information necessary to make a success of the new technology. Thus success will tend to favour those suppliers who follow strategies of providing intensive support and service during and after implementation, so that they, too, can maximise their learning. In a very immediate sense for them "industry is their laboratory": development certainly does not cease with supply to the users, and information provided by users' groups etc., will consequently prove invaluable.

Finally, successful innofusion will be facilitated by governmental

policies which aim at enhancing general **industrial sector learning** effects. Appropriate policies, therefore, would include those that maximise contact between all the agents involved in the innofusion process: Contact between existing and potential users may be encouraged by demonstration networks, such as are, in fact, already run by the DTI. Contact between suppliers and users may be improved by encouraging personnel mobility in both directions between suppliers/consultants and users, at all levels of the organisational hierarchy, not just the senior and top levels (the Alvey "Sponsored Journeyman" scheme is perhaps an apt example here). Other policies are also possible to improve sectoral learning; for example such schemes as JAROL (the Japan Robot Leasing initiative), which encourage users to experiment with and therefore learn from new technology components, without committing them irrevocably to their first (and probably wrong) choice.

But above all, for the successful development of configurational technologies and effective innofusion, we must throw away our prejudices, both theoretical and practical, that radical or revolutionary innovations cannot emerge from the implementation process itself. Concord is undoubtedly a radical innovation, but its economic importance is slight, and may, indeed, actually be negative. Japan employs some 140,000 of the worlds' total of 200,000 robots, in a bewildering diversity of robotic subspecies, each efficiently designed for specific application niches, and with new configurations continually evolving. Together with other innovations, robots have delivered the undoubtedly revolutionary result that Japan is today the leading manufacturing nation in the world, and now the richest.

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TABLE 1 : COMPONENTS OF SOCIO-COGNITIVE STRUCTURES

meta-knowledge	:	general cultural and philosophical assumptions.
formal knowledge	:	theories, formula etc., usually available in written form: eg. textbooks; handbooks.
informal knowledge	:	rules of thumb, tricks of the trade etc., available in verbal and sometimes written forms: eg. guidebooks; manuals.
tacit knowledge	:	rooted in practice and experience: transmitted by apprenticeship and training.
contingent knowledge	:	distributed, apparently trivial information, specific to the particular environment and its contents: on the spot learning.
instrumentalities	:	knowledge "embodied" in tools and instruments; requires other components - informal, tacit and contingent - for effective mobilisation.

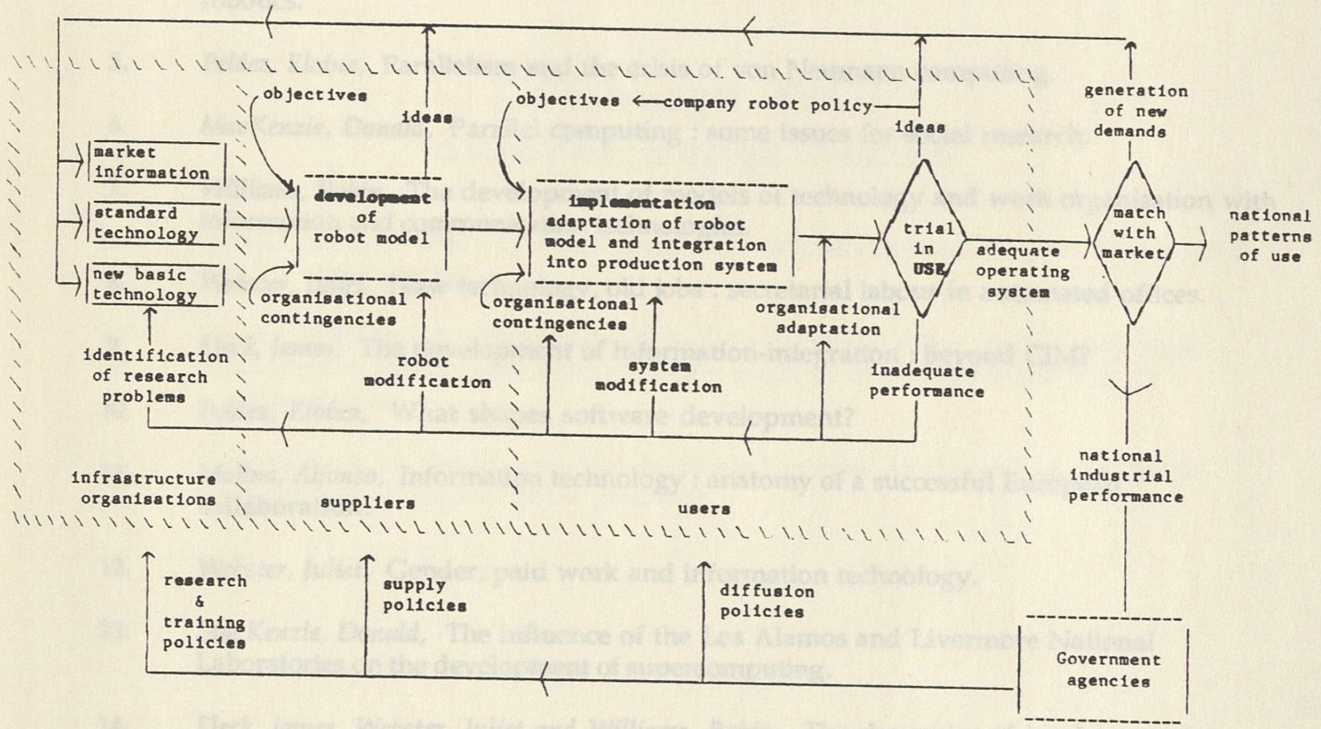

FIGURE 1 MODEL OF ROBOTICS DEVELOPMENT

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