Working Paper

The Changing Economics of Technological Learning

R. Cowan (University of Western Ontario) and
D. Foray (CNRS, IRIS TS and IIASA)

WP-95-39
May 1995

IIASA International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 807 □ Fax: +43 2236 71313 □ E-Mail: info@iiasa.ac.at

The Changing Economics of Technological Learning

R. Cowan (University of Western Ontario) and
D. Foray (CNRS, IRIS TS and IIASA)

WP-95-39
May 1995

IIASA International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 807 □ Fax: +43 2236 71313 □ E-Mail: info@iiasa.ac.at

Foreword

Incremental improvements of existing systems will not be enough to achieve the scale in the reduction of energy and material consumption and their associated environmental impacts that would be required to counterbalance the twin pressures of population growth and economic development. Radical innovations will be needed including new transport, industrial and urban systems.

From this perspective, global environmental sustainability requires a shift to a new "techno-economic paradigm". Such a new paradigm cannot at present be described comprehensively even in qualitative terms (and it can be reduced even less to simple tabulations of environmentally critical technologies). The reason for that is that many essential features of the interactions between technology and environment at present are uncertain. We are unsure about the temporal and spatial scales of environmental change, about the exact causation mechanisms of these changes, how past and current patterns of development and use of technologies influence environmental change, and especially how all these factors interact in the future. Uncertainties and surprises are thus not only genuine elements in technological evolution (and the formation of past techno-economic paradigms), but even more so in the way technology and environment interact.

There are at least two types of uncertainties in the interactions between technology and the environment. The first one is uncertainty about technical change. It deals with the unknowns of performance and functions an emerging technology may ultimately assume, what kind of modes of social usage it will entail, and what the cumulative long-term effects of these modes of usage might be. The second uncertainty deals with environment proper: not only current environmental problems are frequently ill-understood, there is yet more uncertainty concerning possible future environmental problems. To illustrate this, just imagine how difficult it would have been to anticipate changes in stratospheric chemistry (ozone depletion) at the time CFCs were introduced as benign replacements of propellants and refrigerants in the 1920s.

Facing uncertainty, which is the main characteristic of the interactions between technology and environment, it is thus necessary to improve the capacities of broadening our portfolio of technological alternatives; to learn continuously about the evolving characteristics of the interactions between development and environment; and to strengthen what Herbert Simon termed "metatechnologies" (technologies of decision procedures). A new techno-economic paradigm must, therefore, above all, entail new modes of production and distribution of environmentally valuable knowledge, allowing the system to acquire and monitor information continuously and to reassess both environmental and technology policy objectives. Here, new methods of learning and observation technologies, capable of producing data on a global scale (such as the Global Ocean Observation System), as well as the old (but changing) methods of "research by accident" matter. In our view, the most important problem deals, perhaps, no longer with the lack of available knowledge. It deals rather with information handling, filtering, and distribution. This perception is based on the Simonian recognition that the scarce resource is no longer knowledge but attention.

The issues of production and distribution of environmentally valuable knowledge are being addressed in a series of informal discussion meetings of the Technology and Environment (T&E) network established at IIASA within the framework of the Environmentally Compatible Energy Strategies (ECS) Project. The T&E network is organized to produce a series of discussion papers on various aspects of the problem at hand (research by accident, attention management, new economics of technological learning, large scale observation systems, origins of technological "lock-in"), and is aimed at establishing an interdisciplinary base to discuss the interactions between technology (or rather of technological change) and the environment.

The paper by Cowan and Foray is the third of this series. It deals with the emergence of new technologies of learning. In general, new tools and technologies of learning (simulation methods, electronic networks, etc.) ease some of the problems in the economics of learning. They help to reduce costs of information processing and to preserve technological diversity, as it is economically feasible to maintain alternative technology designs much longer. These effects in turn have a positive influence on the adaptive capacity of the techno-economic system. First, it enables to explore an entire spectrum of technological variety and thus to broaden the portfolio of technological alternatives. Second, it enables to produce both effective outputs and knowledge in the process of using a technology. This means that knowledge and information about environmental impacts of a technology can be continuously generated very early on.

THE CHANGING ECONOMICS OF TECHNOLOGICAL LEARNING

R.Cowan (University of Western Ontario)
D.Foray (CNRS, IRIS TS and IIASA)

When a new technology first appears as a possible solution to economic or technical problems, it is typically not well-understood. The degree to which any particular technology is subject to uncertainty about its characteristics and costs varies with the extent to which the technology is new and novel, but for some technologies it can be extreme. When this is the case, developing the technology will involve a considerable amount of learning about its functions, performance, and operational characteristics.

We can characterize the process of learning about a technology as involving two essential dichotomies. The first concerns whether the knowledge is created through deliberate "off-line" experimentation or is generated "on line" as a by-product of economic activities through learning-by-doing and learning-by-using. The second dichotomy concerns the life cycle of the technology. Learning through diversity and learning from standardization are the two sources of learning, which can be thought of as operating at different phases in the development of a particular area of technological (or scientific) practice.

This characterization relates to traditional analyses of technical change through the concerns expressed in that research. The concerns with the under-supply of learning-by-doing, or the separation between production and learning, all depend on the first dichotomy. On the other hand, the concern with the effect of standardization and the loss of variety on technological change depends on the existence of the second.

While these two dichotomies have not generally been explicitly enunciated, until recently they have applied well to the generation of economically valuable knowledge. In this paper we argue that the evolution of learning technologies in recent years has undermined these classifications and is causing the collapse of both dichotomies. Changes in the technologies of learning have increased the variety and the complexity of the situations in which learning can occur. In particular, new opportunities of "learning continually", through the methods of "on-line" experiments, and of maintaining technological diversity, through the methods of "options generation" are the base of the new economics of learning.

We begin the paper with an analysis of the two dichotomies and relate them to the literature on the economics of technical change, and the concerns expressed therein. We then address the new technologies of learning and argue that changes from the old to the new learning paradigms will reduce the relevance of the two dichotomies. Finally, we suggest that while the collapse of the dichotomies may facilitate positive feedbacks, information distribution as well as the maintenance of diversity, it creates new problems as well.

1 - Learning from deliberate experimentation and analysis versus learning as a by-product of economic activities

The first dichotomy can be seen as a description of "where" learning occurs. Learning can either be deliberate, stemming from activities pursued for the sake of gathering information, or it can be a by-product of activities pursued for other reasons. This distinction is often expressed in the physical location of the learning - either in some form of an R&D establishment, or at the place of production or consumption that uses the technology in question.

I-1 -Learning from deliberate experimentation and analysis

Any attempt to create a new, economically valuable product or process, which inevitably involves generating new knowledge, will take place in the context of some background knowledge[1]. This background knowledge can be characterized as a probability distribution summarizing information regarding the probabilities of success of all of the potential ways of generating the new knowledge. Deliberate learning can be seen as aimed at one of three things: improving the state of background knowledge; improving the tools with which to develop or exploit that background knowledge; and attempting to exploit it.

In the pursuit of these aims, three types of technical knowledge are active: generic technology[2]; infratechnologies[3]; and applied knowledge[4]. While these types of knowledge depend on each other, the dependence is not linear. For instance, in order to produce generic knowledge, which appears to be the most basic of the three, and upon which the others depend, it is frequently necessary to overcome a critical lack of infratechnologies and research instruments. Thus a phase of acquisition of certain technical, and in some sense applied, knowledge, may precede basic, and applied, research[5].

Deliberate experimentation consists in developing prototypes and demonstrators and carrying out simulated and real experiments to collect and record the performance characteristics of technologies under examination. The resulting scientific and engineering

---

[1] Consider, for example, an attempt to create a new alloy having particular properties. There will be background knowledge about things like the make-up of alloys having similar properties, and the reactions of compounds to things like heat and catalysts. The new knowledge needed is how exactly to produce a metal with the desired qualities.

[2] The elaboration of generic knowledge is the first phase in technology research; the objective is to show that the concept for an eventual market application "works" in a laboratory environment and thus reduce the typically large technical risks before moving on to the more applied phases of R&D. See Tassey (1992)

[3] Infratechnologies include practices and techniques, basic data, measurement methods, test methods, and measurement-related concepts which increase the productivity or efficiency of each phase of the R&D, production, and the market development stages of economic activity. (Tassey, 1992)

[4] This knowledge supports the conversion of generic technology into specific prototype products and processes with fairly well-defined performance parameters. It involves production and cost considerations. The research output is a commercial prototype in the sense that proof of a commercial concept has been achieved. (Tassey, 1992)

[5] According to Rosenberg (1992), "the conduct of scientific research generally requires some precedent investment in specific equipment for purposes of enhancing the ability to observe and measure specific categories of natural phenomena".

knowledge forms a basis for systematic technological development. The knowledge produced by experiments and simulation is supposed to ensure the formation of generalizing rules and hypotheses and ultimately to support the construction of predictive models about the performance of a new technology. Thus experimentation plays an important role in deepening scientific understanding of technological operations and processes.

A central feature of this side of the dichotomy is the deliberate and controlled search for knowledge. But the discovery of new knowledge or information can have two sources: systematic, rational enquiry and observation; and what Schelling refers to as accidental discovery (Schelling, 1994). Accidental learning arises from attempts to acquire directly the knowledge needed to produce an economically valuable process or product rather than by systematically exploring the probability distribution that would tell us the most likely place to look for it. Any such attempt may or may not produce the product or process, but it will produce information. Though our perception is of a continuum between the two extremes of exploring the probability distribution and attempting to produce the knowledge-output directly, it is useful to construct a conceptual distinction between these two modes of learning.

We can consider the process of knowledge generation as a compound event (A) which consists of the joint events (Hirshleifer, 1971):

- state (a) is true, which means, for example, that it is possible to create a new alloy (basic research allows agents to assign probabilities [Pr(a), 1-Pr(a)] to the underlying states of the world);

- and, A, this fact is successfully exploited (the alloy is actually created). Thus, [Pr(A)<Pr(a)].

Research by accident is considered here as a deliberate experiment, in which, however, the agent ignores the potential to generate information about Pr(a) during this attempt to make the alloy (there is perhaps little information about the probability Pr(a)). There is, we should point out, a difference between the process of learning from disaster[6] and the process of research by accident because the latter occurs within the framework of deliberate experimentation[7].

By contrast, a discovery based on a rational exploration corresponds to the compound event described above (discovery occurs after having gained information about Pr(a)). In this schema, specific functions are assumed by basic research (assigning probabilities to the states of the world) and by applied research, and development (exploiting successfully the basic information about the states of the world). Thus, the R&D manager must continually trade off between allocation of resources to basic research for improving the state of background knowledge, and thereby increasing the probability of success of applied research and the

---

6 "Learning from disaster" refers to the redirection of attention as a result of experience with unexpected events such as airplane crashes, nuclear power plants accidents, etc. resulting in the discovery of unanticipated phenomena. See P.David, G.Rothwell and R.Maude-Griffin (1991).

7 "Accident" is often, colloquially at least, associated with something bad (as in "car accident"). This not part of the strict definition but the association is strong. We are not using it in that sense but rather in the sense of "something (good or bad) haphazard"

immediate ("in the dark") allocation of resources to a given domain of applied research. He must also trade off between the production of research tools (infratechnologies) and the undertaking of research, bounded by whatever limitations there may be in the availability of those tools.

I-2 -Experiential learning as by-product of economic activities

The second side of the first dichotomy refers to by-product learning as the second main mechanism for reducing uncertainty about the characteristics of a new technology. On this side of the dichotomy, the motivation for acting is not to acquire new knowledge but rather some other activity: to produce or to consume. As a by-product of economic activities, this mode of learning has two main aspects: (a) learning-by-doing, which is a form of learning that takes place at the manufacturing stage; and (b) learning-by-using, which is linked to the irreplaceable role of users and adopters in the process of knowledge creation. The user has specific, sometimes idiosyncratic knowledge and masters those situations requiring the local implementation of the technological processes and objects. By interacting with the producer, he will engender learning-by-using mechanisms, of which Rosenberg, Lundvall and Von Hippel have demonstrated the significance. Users and adopters are a critical link in the chain of positive feedbacks which is at the root of the dynamic evolution of technology.

Two reasons seem to explain the importance of this sort of learning in the process of technological change.

The first one deals with the fact that new technologies are typically very primitive at the time of their birth. Thus, the main part of knowledge about the potential functions and performances of a new technology is generated during the process of use and diffusion which will facilitate the elimination of "bugs", as well as generate a flow of improvements in technical and service characteristics. Rosenberg explores the magnitude and the effects of learning by using in the particular case of aeronautics: "The confidence of designers in the structural integrity of a new aircraft is an increasing function of elapsed time and use. Prolonged experience with a new design reduces uncertainties concerning performance and potential, and generates increasing confidence concerning the feasibility of design changes that improve the plane's capacity..The stretching of aircraft, so critical to the economics of the industry, has been closely tied to the growing confidence in performance generated by learning by using" (Rosenberg, 1982).

The second reason is clearly demonstrated by T.Schelling (1994). In the general case of an existing technology that causes problem and needs to be replaced with an alternative, engineers are preoccupied with simply accomplishing with the new technology what the old did, and, consequently, can miss opportunities inherent in the new technology. Only a period of long use can reveal all the effective functions with respect to which the new technology has the potential to be superior to the old one.

I-3 -Functional assignment

Having made a distinction between deliberate experimentation (whether controlled or "by accident"), referring to an organized, "off-line" research process, and experiential learning as a by-product of economic activities, occurring "on-line" in the course of the production and diffusion of new methods and products, we can define a sort of functional assignment, a division of labor among the various processes of learning, which is based on the trade-off between productivity and knowledge-production. According to Arrow (1969), deliberate experiments are situations in which the actual output (e.g. nylon) is of negligible importance (in motivating the actors) relative to the information. In the case of experiential learning as byproduct, the opposite holds; the motivation for engaging in the activity is the physical output, but there is an additional gain, which may be relatively small, in information which reduces the cost of further production.

Intermediate cases are possible, the most obvious example being the pilot plant, in which, while the main goal is to generate knowledge about production processes and to learn something about the probability distribution of outcomes for future repetitions of the activity, the output of the plant is known (or at least expected) to be economically valuable.

This figure describes a sort of world where the goals of improving static efficiency in production and consumption and generating new ideas and findings to put them in the economy are strictly separate. Here, the trade-off between production and knowledge acquisition is particularly stark - resources are allocated exclusively to one activity or the other. Within the management of R&D on the one hand, and of the manufacturing process on the other, no such trade-off problem exists. It is important to note that this "division of labor" was not only an abstract representation of the world; it was also a basic principle of the functioning of the real economy of mass production and consumption.

I-4 - Economic implications: feedback failures

The description of learning as having these two sources creates the vision of a system having several parts which are interlinked. Learning in one part of the system affects the benefits to learning activities pursued elsewhere. It is clear that to exploit such a system fully these links must be active. This is the simple fact that underlies concerns in the literature regarding knowledge feedbacks. The difficulties activating these links are worst when the first dichotomy is strong.

Complementarities between activities in the two spheres of learning have the potential to form many "virtuous circles", which can play a role in raising the performance of innovation systems. As David, Mowery and Steinmueller (1992) have demonstrated, one can impute to basic research an informational payoff that increases the efficacy of resources allocated to applied research: basic research produces knowledge like surveying; it generates maps that raise the return to further investment in exploration and exploitation. Applied research, in turn, produces instruments, prototypes and data (infratechnology) - as well as new observational phenomena - that improve the marginal social efficiency of investments in basic research. The production of scientific instrumentation lies at the heart of these feedback complexes between basic research and industrial development, and has contributed to accelerating the pace of productivity improvement in research activity itself, as both David (1993) and Brooks (1994) have pointed out. For instance, robotics or laser technology are potentially effective "bridging agents", which support the connection between different communities of researchers and engineers and may generate virtuous circles of learning.

There is another virtuous circle that can operate between users and producers. As a technology is used, users' experiences indicate potential improvements that can be made to it. If they are made, this will increase the value of the technology to other potential users, and

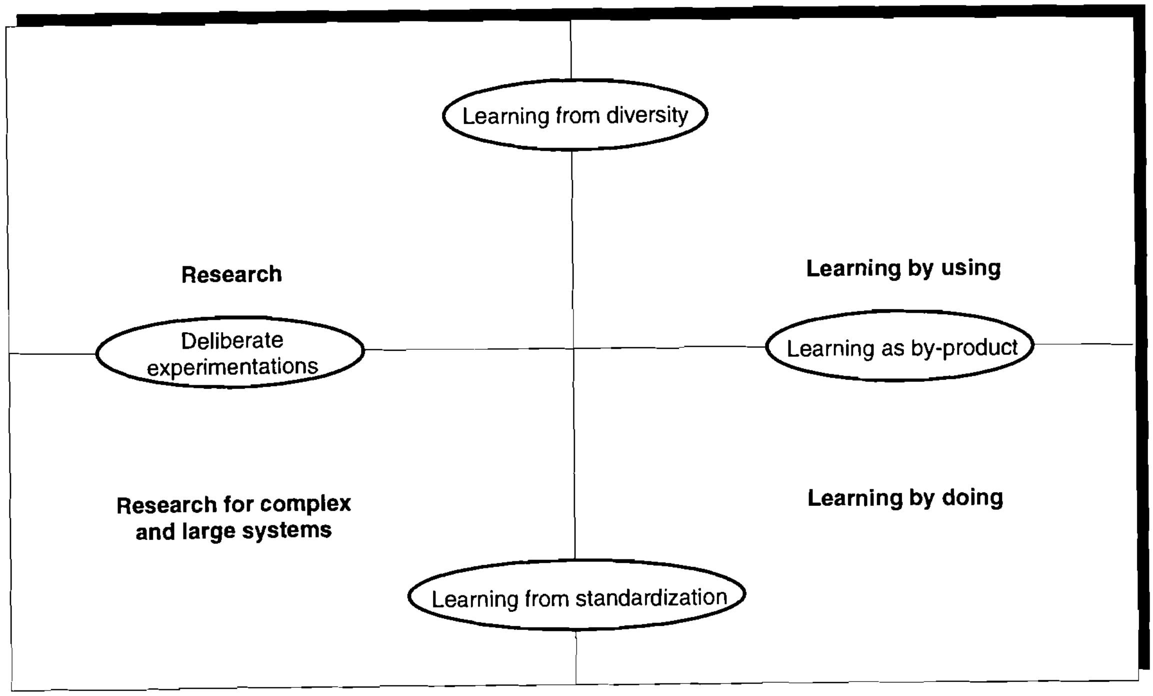

Figure 1: Functional assignment in the economics of technological learning.

will thereby increase incentives to adopt it. Increases in adoption, of course, imply increases in use and further learning by using. This is, potentially at least, a second virtuous circle whereby learning increases use, and use increases learning.

The potential benefits of these feedback loops will only be realized, though, if there is a smooth flow in the intensive distribution of knowledge between the entities involved in the different forms of research, and between users and producers. With reference to the first communication, in an extremely dichotomous situation, we can observe a failure of this feedback stemming from the nature of the knowledge produced in the two locations. It is relatively tacit knowledge that is generated on-line, and this sort of knowledge is difficult to incorporate into the process of deliberate search[8]. Deliberate search tends to place more emphasis on codified, (and therefore easily transmittable) knowledge[9].

---

[8] Tacit knowledge cannot be dissociated from the work practices of research and production units. These forms of knowledge are acquired experientially, and transferred by demonstration, rather than being reduced immediately or even eventually to conscious and codified methods and procedures. Tacit knowledge therefore cannot be expressed outside the production context in which it is generated. See, P.A.David, 1993; and P.A.David and D.Foray, 1994

[9] Codification of knowledge is a step in the process of reduction and conversion which renders the transmission, verification, storage and reproduction of information especially easy. Codified information typically has been organized and expressed in a format that is compact and standardized to facilitate and reduce the cost of such operations. The presentation of knowledge in codified form will depend on the cost and benefits of doing so of course. The standardization of language and expressions under different forms strongly reduces the costs of codification. This in an area in which the revolution in information technology, including such advances as the substitution of graphic representation for natural language, the development of expert systems, etc. has made itself very strongly felt. See P.A.David, 1993; and P.A.David and D.Foray, 1994.

The failure can occur even under a more subtle mechanism of assigning resources to different learning activities. The nature of pecuniary and non-pecuniary rewards will determine the extent to which and the way in which knowledge is codified (Dasgupta and David, 1994). As a rough generalization, in deliberate search resources are allocated to the costly process of codification, since the rewards accrue from publication and dissemination, which is only possible if knowledge is codified. On the other hand, few resources are devoted to codifying the tacit knowledge acquired during production and consumption activities, since the rewards from dissemination (at least of knowledge learned by producers) is often negative.

Thus, especially from the point of view of those doing deliberate search, the activities of production and consumption are not thought of as generating knowledge that can be easily used elsewhere. There can be a sort of a vicious circle. The part of the knowledge stock that is produced "outside" (not in places dedicated to knowledge production) remains invisible or tacit. Its invisibility implies that when resources are being allocated among learning activities, this location is overlooked. Thus it is "underfunded" and produces less than the optimal amount. This can generate a further decrease in the amount of learning that takes place "outside", and the cycle continues until "outside" locations are perceived as contributing nothing to technological advances. A system of by-product learning that is not explicitly financed means that market processes do not as a rule lead to socially optimal rates of learning: (a) private producers may be financially constrained to minimize short-run production costs, which makes them myopic in their evaluation of the learning component of production; (b) externalities and spillovers mean that (even with foresight and perfect capital markets) private strategic behavior does not yield socially optimal learning rates (Arrow, 1962).

A strict functional assignment implies a strong separation of functions, personnel, and location of learning. This, in its most extreme form, constitutes a feedback failure and an inability (or more generally a difficulty) in generating the virtuous circles described above.

II - Learning from diversity versus learning from standardization

The second of the two dichotomies characterizing technological learning concerns the life-cycle of the product or technology, and the different types of learning that tend to occur during different phases. When there is a large amount of uncertainty about the technical functions and economic merits of a new technology, its first introduction typically ushers in a period during which many variants are formulated, tried out and even tested with potential consumers or users. After this period of experimentation, one, or perhaps a small number of variants will emerge as "standard practice" or "dominant design". The selection can be passive, through the competitive market mechanism, for example; or active, as in the case when a dominant economic or political actor decides that a particular variant should become the standard. When the development of a technology conforms to this pattern, two types of learning are distinguishable.

II-1 - Diversity

The first type of learning is extensive learning or "learning from diversity"; which involves experimentation with a variety of options, and through the results of the experimentation, leads to the elimination of certain avenues of development. In this phase, the objective is to gain broad knowledge of many possible avenues by which the problem at hand can be attacked. The point is that any problem has many potential solutions, and it is necessary to learn something about many of them before it is possible to make a sensible choice regarding which is likely to be the most effective. Thus at this stage, the goals of a decision-maker tend to be very broad and involve exploring many variants of the technology. The question being addressed, to speak as if there is a central authority steering the process (this is not always the case, of course), is which of the many possible paths to follow.

II-2 - Standardization

The second type of learning can be called intensive learning or "learning from standardization", in which attention is concentrated on one technological variant, making it easier to identify empirical irregularities, anomalies and problem areas deserving further investigation, correction and elaboration (Cowan, 1991, David and Rothwell, 1993). Here, a choice has been made, either actively or passively, and one solution has been selected. The learning here involves discovery, no longer of broad implications regarding exploration of different solutions, but rather of the details about how to make this particular solution most effective. Here a path has been chosen, and the effect of learning is to make the most of this path, through careful exploitation of all of its potential.

II-3 - From diversity to standardization

The optimal timing of a changeover from a diversity of technical solutions to standardization on one technology depends on the amount of experimentation that has been done with different variants of the technology. Introducing a standard too early could prematurely end the period of experimentation and lead to the diffusion of an inferior technology whereas late introduction may result in excess of novelty, and the formation of wrong expectations about the chances of competing technologies - there will be users who adopt technologies which will not be selected as the future standard.

A shift similar to the one described here can be seen in the history of nuclear reactor technology. In 1955, at the first international conference on nuclear power in Geneva, about 100 types of reactors were discussed. Three years later, the number was down to about 12. When the U.S. Navy decided to produce a nuclear powered submarine, after initial experiments in the AEC with six technological variants, two varieties were considered, and after a single experience with each, only one was intensively explored and developed over the following decade (Cowan, 1990).

II-4 - Economic implications

As described above, technical change and evolution can be viewed as a process of exploring a wide range of technical options. Over time, the cumulative nature of the learning processes about the merits of competing technologies leads on the one hand to a reduction of diversity and to a subsequent loss of development power of the system, while it leads on the other hand to an increase of the efficiency of the technology selected as the standard. Thus, standardization has costs and benefits. It allows the industry to decrease production costs (increasing returns to scale), and to facilitate the diffusion of innovation (due to the existence of technical standards). Standardization, however, entails a loss of diversity. Technological variants having unique properties may be lost and never properly explored. The long run effect is that the scope for future developments will be narrowed. Technological advances that depend on the prior development of these unique, and now lost, properties are put in jeopardy (Cowan, 1991). This suggests a need for policies to maintain diversity, but with the foresight that at some point in time diversity can decrease benefits by preventing economies of scale, a reduction in costs through intensive learning about a technical option, and the potential for network externalities.

Given that a policy of encouraging diversity within a technological family will eventually have to be abandoned, one problem is how to select which technical options to support. A solution which alleviates some of the problems for future developments is to determine the technological distance between several technologies and to support those that are relatively more distant than others on the assumption that the loss of diversity among technologies that are very similar is acceptable. This calls for some measures of collective dissimilarity, as argued and demonstrated by Weitzman (1993). Foray and Grübler (1990) suggest that, though technological distance cannot be measured on a numerical scale, it should be possible to develop simple, though workable, estimates of distance.

III - Types of learning: a tentative schema

Figure 2 represents a tentative schema within which we may locate different modes of generating knowledge. The vertical axis deals with the evolution from diversity to standardization, while the horizontal axis concerns the progression from experimentation to by-product (off-line to on-line) learning. There are two principal modes, combining diversity and experimentation (which corresponds to the basic definition of research, as producing a great deal of information) on the one hand, and standardization and by-product learning (which corresponds to the basic definition of learning-by-doing, as producing mainly actual outputs), on the other hand. It is possible to imagine two other modes, however, involving a mix of information and actual output: combining by-product learning and diversity means that some learning-by-using processes can lead to product differentiation for example (Von Hippel, 1988); combining standardization and experimentation reveals a specific process of knowledge generation in the case of large complex system, where each new plant, or system or program - although produced in a recurring manner - in fact has many features of an experiment (each artefact differs in identifiable, predictable, and sometimes planned ways; and each one generates information that is associated with these differences).

The traditional economics of technological learning - concerned with under-investment in on-line learning, feedbacks failures between research and development, and the loss of variety - is developed on the basis of this double-dichotomy. It is our contention that today considerable changes in learning technologies are affecting the way learning takes place, and so are removing some of the old concerns, and replacing them with new ones.

IV -Recent changes in the technology of learning

Recent changes in the technology of learning have led to the collapse, or partial collapse, of the two dichotomies discussed above. There are three main factors that contribute to this collapse: the convergence of learning and production technologies; our increased ability to codify knowledge; and the progress in information technology that is extending the power of electronic networks as research tools.

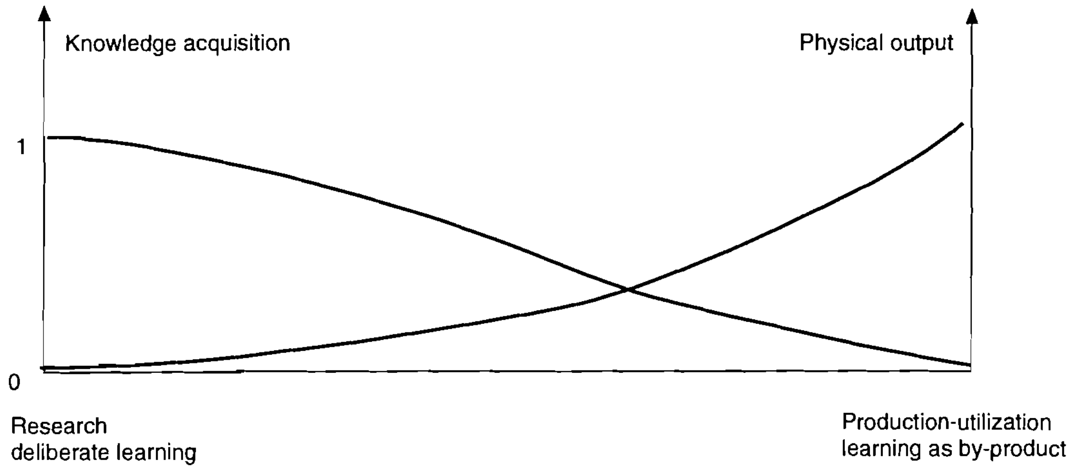

Figure 2: Modes of generation of knowledge.

IV-1 - Convergence of learning and production technologies

In the last two decades the use of computers and computer technology has grown dramatically. This growth has occurred both in production technology and in R&D technologies. Computers are used to control and monitor experiments; they are also used in precisely the same way to control and monitor production processes (numerically controlled machine tools provide the most direct analogue). The digital telephone switch is simply a computer designed to process and transmit particular types of information, but using relatively standard techniques. There has, thus, been a growing convergence between technologies of learning and knowledge generation, and technologies of production. Initially, and most obviously, as computers spread throughout the production process, and are used widely in research, we observe convergence in the technologies used to process information. This, of course, implies the need for convergence in the way information is recorded and stored. In turn, this creates a situation in which the same types of information (since only certain types of information can be efficiently stored in machine readable format) are being used, generated, processed and recorded in the two places. This suggests that the transfer of information between production and consumption on the one hand and R&D activities on the other should be easier. As an illustration, consider the software industry where strong effects of learning by using occur, thanks to the flow of information stemming from the customers: many computers companies routinely provide extensive software support that involves software modification when bugs are discovered by customers (Rosenberg, 1982).

IV-2 - Codification, Algorithmic Successes, etc.

The discussion in the previous sections draws attention to the increased codification of knowledge. In the move from crafts industries to automated fordist manufacturing, what was once tacit knowledge came to be embedded in machines. The digital revolution has continued and intensified this move towards codification. In this regard, we observe a selfreinforcing cycle.

Advances in information science and linguistics have increased our ability to codify and formalize knowledge and information. We have learned to describe more, and more complex, things digitally. This has improved our ability to test models and hypotheses through simulations (using virtual prototypes) rather than through practices, and to do so on the basis of an arbitrarily large range of assumed conditions. To understand these improvements, it is important to realize that many problem-solving tasks involve a degree of complexity far in excess of current computational capacity. It is a common feature of optimization problems that the number of possible solutions and solution paths increases as an exponential function of the number of independent variables - so that the extrema rapidly become too numerous to handle. Therefore, the ability to solve these problems depends on the availability of algorithms which provide reasonable approximations to the analytical optimum. The development of these algorithms is one of the greatest achievements of modern mathematics; a characteristic they share is that while the analytical complexity of the problems being solved increases exponentially in the number of variables, the computational requirements of the algorithm increase by some linear function of the problem's size (Ergas, 1994). These new research tools permit more quickly focussed and hence more productive search, thereby cutting the delay involved in going from the initial specification to the agreed-upon prototype. Moreover by reducing the time and cost required for new product and process design, these tools encourage producers to experiment across a broad front - to develop and try many variants of a new design rather than only one or a few.

The ability to perform many simulations is of no value, however, unless the simulations are good models of reality. Thus the development of good predictive models of the world is crucial to making the previous two advances of value. But of course, these advances themselves make the development of good models easier and more feasible. Codified models can be simulated to see whether they give unreasonable results under reasonable parameter values. If they do, the source of the results can be found, and then changed before doing physical experiments.

Thus, advances in our ability to describe and codify knowledge, combined with advances in algorithms have increased our ability to generate good models of physical processes. Improvements in those models make advances in codification and algorithms more useful, as they can be implemented in a wider variety of places. A virtuous circle has formed which can be deployed in decreasing the costs of developing new products and processes[10].

Clearly, this explosion of the use of simulation methods does not eliminate the necessity of real experiments. In fact, the performances calculated by simulation can vary greatly according to the selected hypotheses and parameters. Therefore, an important task is the validation of those parameters via the correlation between simulation and real experimentation. The new research possibilities provided by the extension of simulation, however, can dramatically decrease the costs of basic research and increase the relative efficiency of systematic and controlled experiments relative to research by accident.

---

[10] According to Arora and Gambardella (1993), a typical example of the new possibilities provided by simulation is in the analysis of car safety. Instead of physically crashing cars, the computer simulation is used to measure the deformation of the structure at different strengths of collision (virtual prototypes). The analysis may even directly suggest directions of improvement in design and structure.

IV-3 - Electronic networks

The perception of an emerging new paradigm for technological learning is reinforced by considering ongoing developments in information and telecommunications technologies that are extending the power of electronic networks as research tools (David and Foray, 1994). The network connects information sources that are a mixture of publicly available (with and without access charge) information and private information shared by collaborators, including digitized reference volumes, books, scientific journals, libraries of working papers, images, video clips, sounds and voice recordings, raw data streams from scientific instruments and processed information for graphical displays, as well as electronic mail, and much else besides. These information sources, connected electronically as they are through the Internet (or the World Wide Web) represent components of an emerging, universally accessible digital library. What appears to lie ahead is the fusion of those research tools with enormously augmented capabilities for information acquisition and distribution beyond the spatial limits of the laboratory or research facility, and consequently a great acceleration of the potential rate of growth of the stocks of accessible of knowledge. It would seem to follow that cooperative research organizations will be best positioned to benefit from the information technology-intensive conduct of science and technology result.

These tendencies to technological convergence, knowledge codification and electronic networking induce the emergence of a new paradigm of knowledge acquisition which, in turn, greatly influence the economics of learning.

V - The new economics of learning

The changes in the technologies of learning described here imply changes in the economics of learning and industrial research. In general, the new tools of learning ease some of the problems in the economics of learning, through reducing costs of storing and transmitting knowledge. The schema (figure 2) presented above is particularly useful to assess the importance of these changes.

V-1 -A more complex "socially distributed" knowledge production system

Following the argument about codification and formalization of knowledge, one can ask to what extent can contracting-out and external competencies replace the capabilities of the corporate R&D laboratories. It is our contention that the changes in learning technologies lead to the increasing importance of external capabilities (outside from the firm) in the innovation process by extending the "mobility" and the institutional diversity of knowledge. These changes conduce to a proliferation of new places having the explicit goal of producing knowledge and undertaking deliberate research activities. They conduce, thus, to a more complex socially distributed knowledge production system. This evolution can be seen as following two paths: on the one hand, the increasing value of on-line learning (by doing and by using); and on the other hand, the emergence of new forms of learning, which share features of both deliberate experimentations and by-product learning.

* The increasing value of on-line learning

As the technologies of research and production are converging, the value of on-line learning increases. First, if "running experiments" has become less costly, then the value of information in general increases. Information acquires value through being explored, refined, and integrated into the knowledge stock. If the cost of doing so decreases (due to an ability to replace some physical experimentation with simulation for example) then information, and activities that generate it, become more valuable. This implies, of course, that information generated on-line is of more value. Second, on-line learning is easier to codify in a way that is useful to knowledge generation that takes place off-line. Ease of integration of the two types of information arises for several reasons. As production controls become digitized they become easier to monitor. If output is similarly, monitored digitally (perhaps through automation of quality control procedures) it becomes relatively simple to generate considerable quantities of performance data. These data are in a form easily used in the off-line learning processes.

The convergence of research and production technologies implies an improvement in the feedback mechanisms between the two locations. As the information produced is more similar in form, it is easier to transmit from one location to the other, and it is more useful when it arrives.

We would expect, then, that since the value of on-line learning increases, and becomes more visible, there will be more of it. We should expect to see more learning in places where, formerly, learning appeared to be of little value in generating further knowledge. Further, if the cost of integrating the knowledge generated on-line into the off-line knowledge generation process decreases, they should become more and more integrated, and the first dichotomy should begin to collapse. With the collapse of the dichotomy, of course, concerns about feedback failures become less pressing.

*** "Off-line" by-product learning or "on-line" deliberate experimentation**

New forms of learning are emerging which are neither pure "off-line" experimentations nor pure "on-line" by-product learning. A major evolution in research and technological learning requires, however, a change in our representation. New forms of learning and experimentation are emerging with an ambiguous position. A characteristic they share is that they do not fit in with the functional assignment defined by Arrow. In certain circumstances (e.g. research in a large/complex technical system) an experiment whose only output is new knowledge may be too expensive to justify itself. This means that some kinds of experiments are feasible only with systems that are simultaneously producing salable products or services[11]. The operation of putting samples of new materials into a nuclear reactor, which is in operation, is a good case in point. Materials are exposed to various temperatures and conditions and then taken to be tested in the laboratory.

Maximizing the knowledge externality benefit, thus, requires the addition of instrumentation in order to take advantage of observational opportunities on the production line, or the slowing down of the production stream for the purpose of eliciting new knowledge that could not be obtained otherwise : either "off-line" by-product learning or "on-line" deliberate experiments or collateral experiments, those new forms of learning cannot be easily

---

[11] This raises major questions about the economic viability of the French nuclear power plant "Super Phenix", which has been converted into a pure research instrument.

classified with respect to Arrow's dichotomy, since they produce both effective outputs and knowledge while tolerating a certain degree of deterioration of productivity. As the Japanese manufacturing experiences suggest, however, a great deal of added value in terms of knowledge may be obtained at very low cost with little sacrifice of product output by adding a certain amount of instrumentation and extra observing and reporting personnel to an otherwise routine production operation. In sum, these hybrid forms of learning allow one to generate knowledge about the performance characteristics of the technology continuously, not only at the research stage but also during the total life cycle of the technology. Of course, the efficiency of those learning processes will be affected by the speed and integrity with which the information and data recorded are transmitted within the technological community involved and by the time lag between the perception (in real time) of a problem and the implementation of the relevant solution.

V-2 -Option generation and recombination, and the exploitation of some virtues of both diversity and standardization

In the vertical dimension of the schema, the new R&D methods allows one to maintain the learning virtues of both diversity and standardization; i.e. to explore continually a large spectrum of technological variants without sacrificing the benefits derived from economies of scale, intensive learning about a technical option and network externalities. The new simulation methods improve the ability to generate a large range of alternatives (virtual diversity) to be explored and increase the efficiency of the process by which alternative design approaches are developed, tested and selected (Ergas, 1994b). This implies the ability to do a more thorough exploration of diverse options before learning moves to the standardization phase. One finds in the literature on technical choice the suggestion that there is a tendency for standardization to occur too early in the life of a technology (Cowan, 1991). The ability to do simulated experiments mitigates this tendency as it lowers the cost of learning through diversity. If some experiments can be simulated, and the information generated can be used to better focus resources devoted to physical experiments, we effectively lower the costs of experimenting, and effectively increase the total number of experiments that can be performed per unit calendar time. This has the effect of permitting a wider and more thorough exploration of available diversity, and of delaying the switch (in event time, which is what is important here) from diversity to standardization.

Here again, the new possibilities of simulation undermine the sharpness of this classification as well as the vision of a continuous and irreversible loss of diversity. On the basis of the virtual diversity which is created and explored by simulation, one can select which technical options to support, in order to deliberately narrow down to a small number of competing standards and carry these along in parallel on a provisional basis while continually carrying on learning-by-doing with both standards. Such parallel standards properly instrumented and monitored, can preserve some of the learning virtues of both diversity and standardization.

As our ability to describe the world and codify those descriptions increases, so does our ability to preserve diversity. This depends of course, on the quality of the models in which the description is located, but if these are good, we can keep variety alive in the form of simulation. The irrevocable loss of variety referred to above need no longer be so severe. It is less expensive to keep a simulation of a process running than it is to keep the process itself running. The more complex the technology the more this is pertinent. Secondly, if the simulation is well-written and documented, it is typically easier to re-start a simulation of a process, or simulated experiments, than it is to re-start the process itself. In the most extreme case, which, we grant, is never likely to be realized, variety need never be diminished, as preserving a simulation, the costs of which is small, will, because the knowledge is codified, effectively preserve the variety implicit therein.

Further, suppose we think of the technological frontier as the frontier between production technology and experimentation (i.e. technology that is tried and true in the production process, but the most recent vintage that meets that criterion). This means that the frontier lies at the frontier between diversity and standardization - if diversity is where learning is taking place, then it is learning about stuff beyond the frontier; if standardization is where learning is taking place, then it is learning about stuff on or inside the frontier. (It is probably this sense of the frontier that the periphery cares about). The collapse of the diversity/standardization dichotomy makes the notion of the frontier much harder to preserve. So "now there is no frontier"; technological advance becomes a much more fuzzy concept - it is harder to think of it as simply pushing out the frontier. If the idea of a frontier collapses, (or to put it another way, if there is experimentation going on "on the frontier") then there can be diversity among many producers who are all technologically advanced, since they are all experimenting. Thus the diversity comes, not from having people around using old and unusual technologies, but from having lots of people using cutting-edge technologies but experimenting with it in different ways.

VI - Conclusion

Thus, new opportunities of "learning continually" (through the methods of "on-line" experimentations) and of maintaining technological diversity (through the methods of "options generation") are the basis of the new economics of learning.

However, while the collapse of the dichotomies provides new opportunities to manage science and technology, it creates new problems as well: the most important policy orientation from the perspective of the emergence of the new learning paradigm deals with personnel training to support access to, and utilization of digital libraries. One might view the investment made in the formal education of the members of society, as required not simply to transmit what is presently thought to be useful knowledge, but to equip economic agents to retrieve and utilize parts of knowledge stock that they may not perceive to be of present relevance but which have been stored for future retrieval in circumstances when it may become relevant. In other words, the accessibility of the extant codified knowledge stock may be indicated by the portion of population that has been trained to access and interpret it.

References

Arora, A. and Gambardella, A. (1993) *The changing technology of technological change*, miméo, 1993

Arrow, K. (1962), "Classificatory notes on the production and transmission of technological knowledge", *American Economic Review*

Arrow, K. (1969) "The economic implications of learning by doing", *Review of Economic Studies*, vol.29

Brooks, H. (1994), "The relationship between science and technology", *Research Policy*, Special issue in honor of N.Rosenberg

Cowan, R. (1990), "Nuclear power: a study in technological lock in", *Journal of Economic History*

Cowan, R. (1991), "Technological variety and competition: issues of diffusion and intervention", in OECD, *Technology and Productivity*, Paris

Cowan, R. and Foray, D. (1995), "Quandaries in the economics of dual technology and spillovers from military R&D", *Research Policy*, forthcoming

Dasgupta, P. and David, P.A. (1994), "Towards a new economics of science", *Research Policy*, Special issue in honor of N.Rosenberg

David, P.A. (1993), "Knowledge, property and the system dynamic of technological change", *World Bank Annual Conference on Development Economics*, Washington D.C.

David, P.A. and Rothwell, G. (1993) *Performance based measures of nuclear reactor standardization*, MERIT publication, 93-005

David, P.A. and Foray, D. (1994), *Accessing and expanding the science and technology knowledge-base*, DSTI/STP, 94-4, OECD

David, P.A., Mowery, D.C., and Steinmueller, W.E. (1992), "Analysing the economic payoffs from basic research", *Economics of Innovation and New Technology*, 2(4)

David, P.A., Rothwell, G. and Maude-Griffin, R. (1991), *Learning from disaster?: changes in the distribution of operating spell durations in U.S. nuclear power plants after Three Mile Island*, CEPR publication n°248, Stanford University

Ergas, H (1994a), *The new face of technological change and some of its consequences*, mimeo

Ergas, H. (1994b), *The new approach to science and technology policy and some of its implications*, Rand/CTI

Foray, D. and Freeman, C. (1992), *Technology and the Wealth of Nations*, Pinter

Foray, D. and Grübler, A. (1990), "Morphological analysis, diffusion and lock-out of technologies: Ferrous casting in France and the FRG", *Research Policy*, vol.19, n°6

Grübler, A. (1992), *Technology and global change, past and present*, IIASA, WP-92-2

Hirshleifer, J. (1971), "The private and social value of information", *American Economic Review*

Rosenberg, N. (1982), "Learning by using", in Rosenberg (ed.), *Inside the black box*, Cambridge University Press

Rosenberg, N. (1992), "Scientific research and university instrumentation", *Research Policy*

Schelling, T. (1994), *Research by Accident*, IIASA WP-95-40, Laxenburg

Tassey, G. (1992) *Technology infrastructure and competitive position*, Chapter 3, Kluwer Academic Publ.

Von Hippel, E. (1988), *The sources of innovation*, Oxford University Press

Weitzman, M. (1993), "What to preserve? An application of diversity theory to crane conservation", *The Quarterly Journal of Economics*, February