WHO LEARNS WHAT? A CONCEPTUAL DESCRIPTION OF CAPABILITY AND LEARNING IN TECHNOLOGICAL SYSTEMS

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ABSTRACT

The evolution of technological systems has structural similarities to the evolution of biological systems, in terms both of individual units and of groups or organizations. Bonner's description of biological development is used: the law of growth of the constructive processes, the internal and external constraints on this growth, the resulting changes of form, differentiation, specialization of function, and increased complexity, are all features common to developments in the biological and the technological fields. Examples of the latter are described, from several industries. The pursuit of economies of scale illustrates the parallelism with the biological development.

The evolution of technological capability is seen as a learning process, in which information is acquired, stored and transmitted. Information can be stored in people, paper (or equivalents), or embodied in physical plant. These specifically human capabilities differentiate learning in technological fields from biological evolution by natural selection, and open up more rapid and efficient means of information or technology transfer. However, all theoretical knowledge is of significance only when translated into practice, and learning itself originates in and depends on practice: there are limits to the effective "storability" of know-how, and similarly to its transmission. A distinction is drawn between "primary" (direct) and "secondary" (derivative, indirectly transmitted) learning.

The terms introduced underly the phenomenon known as cumulative experience, manifest in the "learning curve". Learning, however, is a multi-level process, and levels are described as a basis for distinguishing the type of learning

or information transfer characteristic of each level; answering the Bela Gold question, "who learns what?" The intrinsically discrete nature of the learning process--a step-function rather than a curve--is illustrated by Waddington's data on aircraft-submarine attack performance. The capability possessed by an organization is described in terms of a network of capabilities.

The final section discusses policy implications of the conceptual framework developed.

Contents

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1. INTRODUCTION

Decisions are based on expectations, explicitly stated or implied. The level of expenditure devoted by government and industry to research, development and technological innovation implies expectations of tangible effects, but the academic literature has offered meagre support for such expectations, in terms of explanatory causal models. Descriptive case studies (e.g., Langrish et al., 1972) are valuable raw material, but synthesis and generalization have been lacking; and in the absence of prior formulation of some hypotheses or conceptual framework, case study descriptions or data collection may omit facts relevant to the hypotheses. The aggregative quantitative studies of econometric relationships or economists' production functions have been rightly criticized by Gold and colleagues (1977) as quite inadequate for understanding the complex reality of industrial decision-making in the context of specific products, processes, times, companies and other relevant circumstances. Gold reviews the diverse analytical foci from which technological innovations may be assessed, pointing out that this

> "...broad perspective...helps to explain the continuing absence of convergence among published empirical studies. It demonstrates the need to develop a far more complex structure of theoretical expectations along with more penetrating concepts than have guided the formulation of past studies."

This paper seeks to offer some concepts as a basis for convergence on modelling the evolution of technological systems. One source of the ideas here has already been presented (Sahal 1979), based on this author's work at the International Institute of Management, Berlin, and previously. The emphasis on the role of size in this work has naturally converged with the program of research on "Problems of Scale" which has been undertaken at the International Institute for Applied Systems Analysis (Cantley and Glagolev 1978). IIASA's June 1979 workshop, "Size and Productive Efficiency--The Wider Implications" provided a rich opportunity for inter-national and interdisciplinary exchange on the subject, as will be partly evident in the works and authors cited below.

In the concepts presented below, we identify common ground or relationships between a number of separate strands of thought from various disciplines. Fundamental to our thinking are the two dimensions of a technological system: its physical or spatial characteristics, and its dynamic evolution over time. Gold has raised doubts (op.cit.) about the feasibility of "generalizations which are both widely applicable and also directly relevant to critical evaluative or decision-making issues". On the other hand, a good example of such apparently successful generalization has been the widespread application of the "learning curve" concept discussed below. This is a generalization not only well-documented by empirical studies in many industries (Yelle 1979, gives a comprehensive review), but promulgated with commercial success by consulting groups using it as the core of a strategy formulation framework (e.g., see Hedley 1976 and 1977). At the IIASA workshop referred to, "learning" was much in vogue, the term being used with more breadth than precision; in seeking to redress this situation, we borrow in our title the sharp riposte Gold threw at the workshop: "Who learns what?" The applicability of the learning curve and the nature of learning is one focus of this paper. We see it as essential, however, to set it within the context of the general pattern of growth and change of capabilities which constitute the evolution of a technological system. Our usage of these terms is, hopefully, gradually clarified below: we shall deliberately pull together a variety of related or similar terms used for common phenomena, because it is in demonstrating this underlying commonality that we seek to display the potential convergence, from multiple disciplines, on a common conceptual framework.

2. TECHNOLOGICAL INNOVATION AND THE GENERAL THEORY OF DEVELOPMENTAL PROCESSES

The recognition that the development and application of a technology involves a large number of inter-connected activities makes it easy but unhelpful to describe this collection of activities as a "system". It is only when the insights derived at this level of abstraction lead to new practical understanding, and understanding of systems other than those first considered, that the abstraction justifies itself.

Von Bertalanffy's pioheering work on general system theory (1951 and 1968) was largely rooted in his experience of biology, in his perception of underlying similarities of structure and behavior between widely diverse biological entities. Of similarly fundamental importance was the work of the biologist D'Arcy Thompson (1917), now conveniently edited in Bonner's abridged version. Bonner himself built on the work of both these pioneers and on his own extensive researches, to give in "Morphogenesis" (1952) a succinct statement of a general model of the process of development in biological organisms. Although Bonner restricted his general model to the field of biology, we find it remarkably applicable at least as a starting point for modelling technological systems. Since Sahal (1979) has published a clear description of this general theory of developmental processes, we shall summarize it here briefly as our starting point, omitting any of the biological examples with which it has already been thoroughly illustrated in that science by the authors cited. Our purpose is to proceed straight to demonstrating its applicability to technological systems, with examples; then to consider some of the significant respects in which technological and biological systems differ; and ultimately to derive policy implications for the management of technological systems.

Development is separated by Bonner into two broad categories:

> "the 'constructive' processes and the 'limiting' processes. The former are all those which tend to build up, which are progressive, and the latter those which check, guide, and channel the constructive processes. ... Of the constructive processes three seem especially noteworthy: <u>growth</u>, <u>morphogenetic movements</u>, and <u>differentiation</u>. Growth will be used here in the sense of an increase in matter; it involves the intake of energy and the storing some of that energy by synthesis...may be reflected in changes in size or weight... Morphogenetic movement...gives rise to changes in form... Differentiation is an increase in the differences of parts of an organism which occurs between one time during development and another time...
>
> The limiting or checking processes are harder to classify, although in a general way we find that there are external limiting factors and internal ones. The external ones vary greatly from such matters as mechanical stress to food supply limits, matters which often are affected by the size of the organism. The internal limits also vary..."

Bonner continues to elaborate concepts of the development process, and although his terminology and his case material is exclusively biological, one can without any sense of forcing the analogy trace a close parallelism with technological development. He relates his work also to evolution and to phylogeny:

> "We tend in our minds to think of individuals of a species as an object in an instant of time... But the logicians have often pointed out that [the individual] might more correctly refer to some longer segment of time... Any organism is a living object that alters through the course of time by development, and the individual might be defined as the whole of these time-space events. Such a procedure would not only please the philosophers, but also dovetail neatly with de Beer's*

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* de Beer (1940)

notion of evolution. For he quite rightly says, phylogeny is not merely a sequence of varied adults, but a sequence of varied individuals in the broad sense used here."

In translating the biologists' model of development to the technological context, we shall similarly be concerned both with the evolution of, say, an individual production unit or plant; and with the evolution of the class of all such individuals as successive ones are developed over time.

We are conscious that artists, engineers and designers have long drawn on nature and biology for both general patterns and detailed techniques. Our aim is to draw certain structural parallels in precise terms, and to consider also the limits of the parallelism and the key differences, between biological and technological systems. As examples of the relevance of the basic Bonner model of development as growth, morphogenesis and differentiation, we can cite two of Gold's points. He criticized the confusion between "size" and "scale" at the IIASA workshop referred to, pointing out that "size" was increased by mere addition and accumulation (i.e., Bonner's "growth"), but that an increase of scale properly implied a re-design of the form of the plant (i.e., Bonner's "morphogenesis"). On the question of scale, Gold (1974) has previously emphasized that "scale economies are derived from the increasing specialization of functions", and hence suggests that "scale be defined as the level of planned production capacity which has determined the extent to which specialization has been applied in the subdivision of the component tasks and facilities of a unified operation". This description again tallies with the specialization of function which Bonner summarizes by the term, "differentiation".

In the following section, we cite specific technological illustrations of the development theory outlined above. In section 4, we turn our attention to "learning". This term embraces processes of acquiring, storing and transmitting capability, and in considering these functions, some significant differences between technological and biological systems will be explored.

3. ILLUSTRATIONS OF TECHNOLOGICAL EVOLUTION

In the evolution of a technological unit or the system of which it forms a part, physical size or output capacity is a conveniently measurable and conspicuous aspect of growth. The growth itself, however, is motivated not by the desire for increased size *per se*, but by the pursuit and competitive "natural" selection of fitness for purpose--measurable in terms of various functional parameters relevant to survival in the wider system. One therefore typically observes, for any chosen parameter of functional significance, a monotonic improvement in performance.

Sahal (1978) has documented the increase in fuel efficiency of farm tractors throughout this century, relating it particularly to the cumulative number of tractors produced. During the turbulent competitive history of this industry in the U.S., many technological changes were brought in. At each point, the continuation of a line of development eventually encountered a limiting process, internal or external. By ingenuity and redesign, each limit could eventually be overcome, by some suitable evolution of design; and as with natural selection, there were many more variants than ultimately survived the test of competitive viability. Generally speaking, the limits were overcome at the cost of some increase in complexity.

Lee (1977) describes a similar process in the context of electric power transmission lines:

> "History tells us that as we move to higher voltage levels, new technical problems may surface. Below 345 kv, lightning used to be the controlling factor for insulation design. At 500 kv, switching surge took over that role. At 765 kv, we found a new problem--audible noise--and at 1,100 kv, another--electrostatic induction. We do not know at this

> time what problem will appear at voltages higher than 1,500 kv. On the other hand, history also shows that as these problems were discovered, solutions were found to preserve the economy of scale. For example, addition of a relatively inexpensive resistance and switch in 500 kv circuit breakers preserved the economic attractiveness of 500 kv transmission. Whether this trend will continue, no one can tell. But unless economics shows that higher voltage is more beneficial, I don't believe that anyone will move to higher transmission voltages just for the sake of change."

The limiting processes, as Bonner observes, may be internal or external. Many examples of "internal" constraints are manifestations of the familiar fact that, as size increases, not all functional capabilities will increase in constant proportion. The simplest illustration is that surface areas increase as the square and volumes as the cube of the linear dimensions. Different functions will bear different relationships to these geometrical characteristics.

Fossil-fuelled electricity generating plants have over the 100-year evolution of their technology achieved great increases in both physical and economic efficiency. During the post-war years, the advantages of larger scale plants were perceived and achieved, and the scale of unit ordered in the U.K. increased from 30 and 60 MW up to 1950, to 200 MW by 1953 and 660 MW by 1966 (Abdulkarim and Lucas 1977). Similar development in the U.S.A. and elsewhere achieved units with ratings in excess of 1000 MW. In summarising this development rapidly, we should not oversimplify the engineering problems involved in this scaling up. There were many examples where scaling up the physical size encountered a barrier on some function or component capability: such as the cooling of bearings, the strength of turbine blades, or the alignment of the shaft. A significant constraint was the weight of the rotor: single loads greater than 160 tons could not be handled by the transport system from factory to site. Maximum weight and size limits on transportability continue to determine which units of plant, in any part of the process industries, have to be site-fabricated rather than factory made. Clearly, the transportability limit is an example of Bonner's external constraints on growth, being imposed by the environment.

The solution to this particular constraint has already been referred to: on-site fabrication. However, this has significant technical disadvantages--the quality and ease of assembly work achievable in a factory environment is not readily replicated under field conditions. The growth of scale of generating unit has been shown by Fisher (1978) to be clearly and positively related to an increase in construction period--see Figure 1.

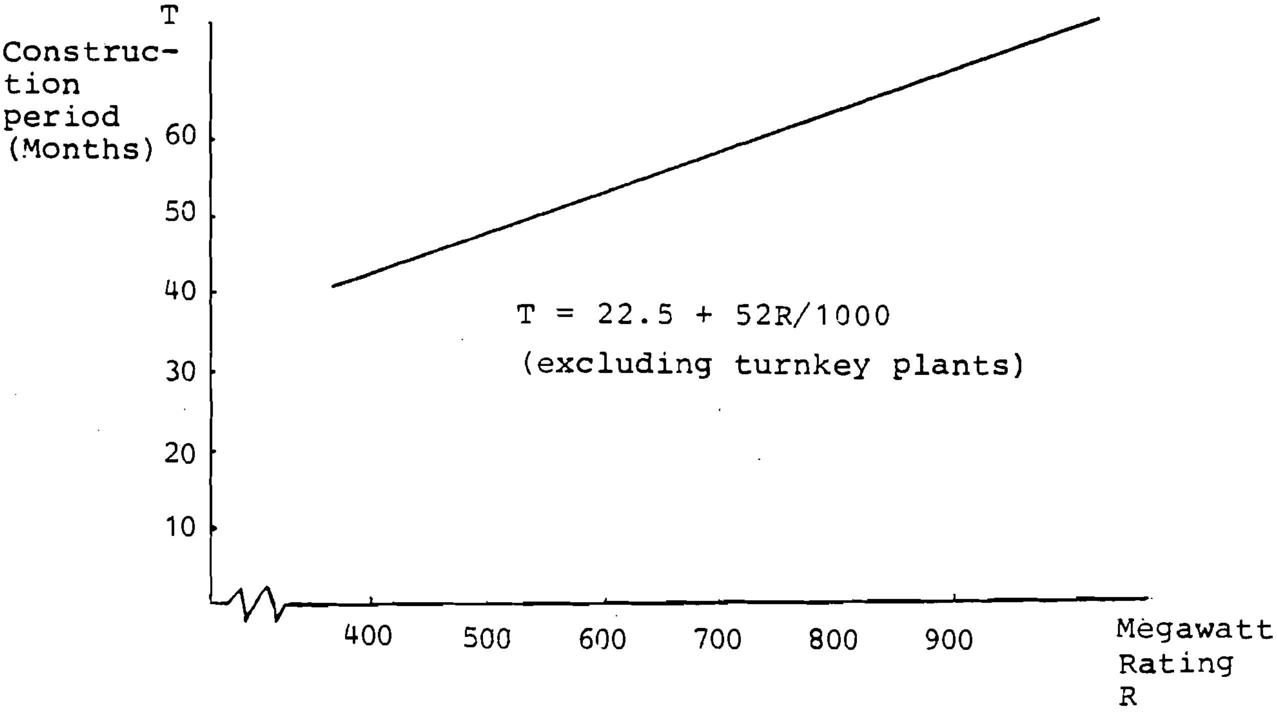

Figure 1. Scale of fossil-fired generating unit and construction time.

Source: Fisher 1978.

Similarly for chemicals, Woodhouse et al (1974) give the following figures for olefin plants (quoted in Cantley 1979):

Size of plant (tons of ethylene/year)	Construction Period (months)
300,000	30
450,000	36
900,000	42

These examples illustrate how the basic pattern of growth, originally pursuing efficiency by increase of size, progressively encounters a succession of internal and external constraints. Overcoming these constraints is achieved by changing the form as well as the size, i.e., morphogenetic movement. This is typically towards greater complexity, specialization of function, and differentiation. However, the increased complexity, the pushing of components and constituent materials closer to the limits of their capabilities, will inevitably lead to some loss of reliability, as is all too clear from the figures quoted by Anson:

Table 1. Availability and forced outage rate by size groups, 10 year average, fossil fired power plant.

Unit size	Average availability		Average forced outage rate	
MW	1964-73	1965-74	1964-73	1965-74
60-89	91.7		2.0	
90-129	88.3		3.5	
130-199	89.0		3.3	
200-389	85.9		4.9	
390-599	79.6	78.9	8.9	9.5
600 and larger	72.9	73.3	16.5	15.8

Source: Edison Electric Institute. Report on Equipment Availability for the ten-year periods 1964-1973 and 1965-1974.

In the chemical industry, disenchantment with the very large scale plants has not yet been so clearly documented. However, the long construction times lead to uncertainties in forecasting and planning these large discrete additions to capacity, thus exacerbating the problems of cyclical overcapacity. Friedman(1977) also argues the need for chemical engineers to rethink some of their designs on scaling up: as he points out, beyond a certain diameter, it becomes more appropriate to view a pipe as "a large pressure vessel of peculiar geometry. This question implies the use of a different design discipline". Dealing with the problem of site fabrication and extended construction times, Malpas (1978) has advocated factoty-built modular construction of standardized units.

In his paper at IIASA, Fisher (1979) similarly concludes by arguing for a retreat from the maximum scale units, and concentration instead on thedevelopment and production of a standardized design which would benefit from the dynamic economies of scale of the learning curve.

Natural selection no doubt found reasons for a time to favor the dinosaur, as the fittest to survive in certain conditions; but in the longer term, the more modestly sized creatures have proved more persistent and adaptable under the changing environmental pressures. Moreover, the fact that a greater number is supportable of species of smaller biomass itself enhances the opportunity to evolve better-adapted designs, a point which did not escape Darwin in "The Origin of the Species":

> "...A great amount of variability, under which term individual differences are always included, will evidently be favorable. A large number of individuals, by giving a better chance within any given period for the appearance of profitable variations, will compensate for a lesser amount of variability in each individual, and is, I believe, a highly important element of success. Though Nature grants long periods of time for the work of natural selection, she does not grant an indefinite period; for as all

> organic beings are striving to seize on each place in the economy of nature, if any one species does not become modified and improved in a corresponding degree with its competitors, it will be exterminated. Unless favorable variations be inherited by some, at least, of the offspring, nothing can be affected by natural selection. The tendency to reversion may often check or prevent the work; but as this tendency has not prevented man from forming, by selection, numerous domestic races, why should it prevail against natural selection?"

This is close in concept to the "learning curve" in technological systems, whereby the group (company, factory) with greatest cumulated production experience can achieve the greatest production efficiency, presumably because they have had the largest number of opportunities to refine and improve both their product and their production process. Thus the changing scale of successive versions of a technological unit should be seen not as a collection of static alternatives, but as points on a continuum of the development process. The "dynamic scale" effect is further discussed below, but at this point two caveats will be noted. Firstly, the successive improvements associated with cumulatively increasing experience will not happen inevitably; the experience creates the potential for improvement, but its realization depends upon the presence of sufficient pressure, competitive or otherwise (a point stressed in conversation by John Grant of ICI Ltd.) Again, the achievement of success creates a complacency which reduces the readiness to innovate, because of the conditioning effect of the established technology. When major challenges emerge from some unexpected direction, the initial response is typically redoubled effort within the familiar technology. Utterback (1978) and with Abernathy (1978) have documented this phenomenon in a number of industries.

4. LEARNING AND DOING: THE ACQUISITION, STORAGE AND TRANSMISSION OF CAPABILITY

4.1 Introduction

The biological mechanisms for the storage and transmission of capability in the form of complex chemical molecules are remarkable structures, exceeding in their subtlety the most sophisticated information-storage artifacts. But these mechanisms are embedded in individuals and species, subject to the constraints and time-lags of natural selection in their ability to transmit and enhance the "wisdom" of the species. The evolution of the capability for memory and language enormously amplifies the potential for information storage and transmission, and it is in these respects that the human species has most significantly overcome the constraints of biology. Moreover, we have learned to disembody capability from individual brains and bodies, and to transmit and store information independently of them. One might qualify this by recalling Planck's observation, that the rate of acceptance of radical new ideas in physics was simply related to the mortality of established experts--our learning methods have not wholly escaped biological or sociological constraints.

In considering learning and the transfer or increase of capability, we confront a complex phenomenon, in which some simple terms and definitions may aid discussion. The following sections introduce the concepts of "primary" and "secondary" learning; and the multiple "levels" on which learning can take place.

4.2 "Primary" and "Secondary" Learning: People, Paper and Plant

Learning in the sense of "know-how", of capability to do something, may exist in people, be recorded on paper (or other media), or embodied in physical plant; or in combinations of these three. We shall use the term "primary" learning for that which depends predominantly or exclusively on direct experience accumulated in the human brain, via information transmitted through any or all of the physical senses, but particularly visual, tactile, the sense of weight, balance, movement and similar physical sensation. Learning to ride a bicycle, to swim, or to tighten a nut are three instructive examples. It is almost impossible to convey in words information which would significantly accelerate the basic process of learning to ride a bicycle. In learning to swim, the role of communicable information is rather higher--the arm and leg movements for effective propulsion can be described in ways which will accelerate learning. The provision of "plant" such as cork floats may accelerate the acquisition of the necessary confidence, and performance can be further amplified by flippers. Tightening a nut is again analytically fairly describable, though in industrialized societies taken largely for granted--including the general assumption of right-hand threads; the torque is a matter of "feel" which is more difficult to put in words, and where it is critical, is partly coded and partly automated by the provision of a torque wrench.

In these simple examples, we have already encountered the three basic forms of storing or transmitting capability. We describe as "primary" the learning processes of human beings acquiring the "feel" of a task by doing it. This sounds like an "individual" pattern of learning. However, people are not only self-teaching entities, but can also transmit their understanding to other people by example and by language, where the latter is common. Given that these activities are also historically the most traditional and ancient methods of transmission, we include them also as "primary" transmission of capability.

The storage of capability in a form independent of the continued presence of its initiator--in writing, diagrams, or computerized information, for example--demands a code. Hence also encoding ability on the part of the originator, and decoding ability on the part of subsequent users. Within groups of people of common background, education and culture, much of the code may be assumed as common property. The greater the differences in these respects between the originators and users, the more explicitly the various codes and terms may have to be elaborated, and the greater will be the delay or effort required to recreate in the recipients the capability possessed by the originators. There is no reason in principle why the degree of difficulty and delay should not be quantitatively describable for any given skill, given sufficient empirical study. At the receiving end of coded information, the creation of capability depends not only on the decoding itself, but on the conversion of the information thus conveyed back into primary learning.

The points which we are laboring may appear obvious, the terminology over-elaborate, for the familiar acts of learning. They are less obvious, however, when we consider such issues as technology transfer between industrialized and primitive societies, or the design of policies and systems for technical education, or mid-career retraining for individuals. Fores and Sorge (1978) go so far as virtually to dispute the feasibility of any effective transfer of technological capability other than that based on direct experience, or "primary" learning in our terms:

> "...a more fitting model is that of *homo faber*, the maker of artifacts, who arrives at his products through a long haul of probing effort which is not guided by formal knowledge, but intuitive past experience... Man does *not* primarily learn what is formally imparted to him in written or oral discourse, but what he is actually made to practise. It is not results, laws or findings which stick in people's minds and increase their competence, but the methods they actually put into practice, the objects they lay their hands on, and the skills they acquire. Formal knowledge has value only insofar as it is closely linked with these processes."

Having described primary learning and transmission (people), and coded transmission (paper), we turn thirdly to <u>embodied</u> know-how in the form of physical plant or tools. The clear trend in manufacturing methods in industrialized socieites has been towards the increased sophistication of equipment in terms of theamount of information-handling capability incorporated in physical form. Automation not only displaces physical labor by human beings, but also the need for mental knowledge; jobs can be de-skilled, as when the torque wrench replaces the "feel" of the experienced fitter. This facilitates the learning process; how for the "de-skilling"has adverse behavioral effects on the quality of work is beyond the scope of this paper, though potentially quite relevant, as a possible "internal" limitation on the feasible development in this direction. Certainly the readiness rapidly to absorb previously alien artifacts and systems has been a characteristic conducive to economic success, as in post-war Japan's not merely learning from American technology but going on to inprove upon it. Spencer (1970) gives the following description:

> "As in any other nation, developments in Japan are a complex of many factors, but what stands out even on casual examination is its postwar technology policy. In simplest terms, this is a discriminating policy of borrowing technology or technological systems whenever these appear more effective than the old Japanese system. This policy is changing today as Japan's leaders become more aware of the need for indigenous research and development. But until recently, the Japanese policy was simply to borrow the technology intelligently and efficiently. For one illustration, the American military presence in Japan during the postwar period provided a distinct demonstration effect and opportunity to borrow through its management-oriented, research-based technology which had defeated Japan. As Japan had done on previous occasions, a large scale take-over of the foreign system occurred. Beginning as humble and slavish imitators, the Japanese took the latest technology and made it an instrument of home production and exports. Gradually they absorbed and

> made it their own by improvements and additions until often the Japanese product was the best in the world. Furthermore, though the Japanese demonstrated remarkable flexibility in bringing in the new systems, they were able to preserve the ongoing Japanese way of life in essential ways which were not threatened by the influx of innovation."

Secondary learning is that which derives from primary, and is distinguished from it partly by being conducted separately in physical terms, but more importantly by its emphasis on

(a) the development of understanding

(b) the emphasis on simplification, coding and generalization.

These are, however, means rather than ends. The objective of understanding, coding and generalizing is to aid the primary learning process both by condensing it and by amplifying the range of capability acquired. The amplification has two dimensions. Firstly, the lessons learned through practice are shown, through experimentation and investigation directed towards the increase of understanding, to have wider applicability than the original context in which they were developed. Secondly, the encoding and systematizing of the developed understanding is designed to facilitate its teaching, transmission and storage. If effective, this enables the lessons originally learned in one location to be rapidly and widely disseminated; thus amplifying the application of the primary learning.

Thus the secondary learning has a vital role to play in the acceleration and diffusion of technological learning; but it starts from and returns to the processes of primary learning. As Mao Tse Tung (1937) precisely expresses it:

> "If you want to acquire knowledge you must take part in the practice of changing reality.
>
> If we have a correct theory, but merely talk about it, lay it aside, and fail to put it into practice, then that theory, however good, has no importance.

Knowledge begins with practice, reaches the theoretical level through practice, and then returns to practice."

4.3 Learning and Doing

In discussing the growth of physical scale as one method of enhancing performance capability, we were led to recognize also the dynamic aspect of capability: cumulative experience may be as important a factor as large-scale plant. Relating capability to cumulative experience, rather than to embodied know-how in the form of capital equipment, recognizes the role of "learning by doing". A familiar form of this is the "learning curve", or "experience curve", discussed below.

The central concept of the experience curve is akin to the statement of Mao Tse Tung, quoted above, about knowledge and practice. The concept of capability and practice being inseparable has many implications for technological and industrial strategy. For example, a long-standing argument (used, for example, in the United States by List and Carey in the mid-nineteenth-century--see Calleo and Rowlands 1973) is that industrial capability of a nation must be preserved, in order to avoid unacceptable dependence on foreign supply. List in fact argues that the capability to act is as important as the fruits of acting--productive power is "infinitely more important than wealth itself". Many countries, for example, might wish to take advantage of cheap imports when available--whether of oil, or coal, or food, or manufactured products--but at the same time insure themselves against future potential supply disruption by maintaining a domestic coal industry, agriculture, and manufacturing capability. Similarly at company level, strategic flexibility would indicate as desirable the maintenance of capability in a broader spread of skills or technologies than are fully required by the current activities. But the logic of the learning curve is that, at least relatively, the highest capability is sustainable only by those actively engaged. Capabilities put into cold storage freeze to death.

4.4 Learning and Levels

Some of the confusion which surrounds the discussion of learning curve may be removed by a more explicit consideration not only of the nature of the learning process, but of the different levels on which it can occur. Following Cantley and Glagolev's discussion of the levels on which "problems of scale" may be considered, we distinguish:

1. The unit level: a single piece of equipment, or single-train process plant, or product-line,
2. The plant level: a single plant or factory, which may contain several level 1 entities,
3. The organization or company level: typically the multi-plant firm,
4. The industry level: comprising all the firms within the industry (possibly within one country or market),
5. The societal level: the wider society within which the manufacturing and marketing of the goods takes place.

Figure 2 summarizes these levels in a manner which indicates a typical member of each level lying within the next higher level--e.g., one blast furnace within one steelworks of a steel company which is one of several in that industry, the industry being one sector of the larger economy and society. While reality would complicate the picture, with diversified firms and multi-national industries, the figure serves as framework for a number of arrows representing information transfer, or "learning". They are of three kinds.

1. The circular arrows represent learning occurring cumulatively over time within a particular entity on its own level.
2. The vertical arrows represent transfer of information or knowhow between levels.
3. The horizontal arrows represent transfer between an entity and other entities on the same level--whether or not within the same higher level.

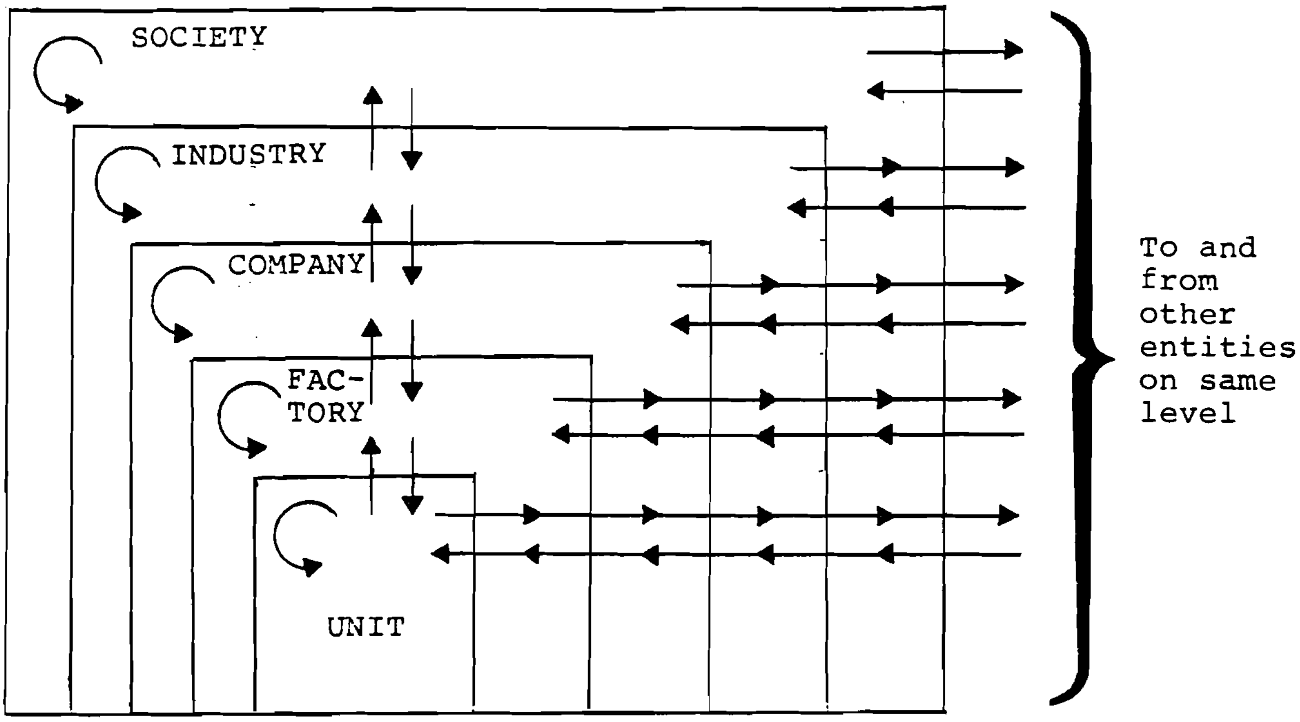

Figure 2. Levels and Directions of Learning, or Information Transfer.

In spite of the over-simplicity of the diagram, the forty-three arrows of Figure 2 represent the many different interpretations and answers which might be offered in response to

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*Since this paper was drafted, we have discovered and been struck by the remarkable similarity of Figure 2 to that which the American sociologist, Amitai Etzioni, developed and described as "Dimensions of a Macro-Sociology of Knowledge". As he expresses it: "Societal units produce knowledge and use it collectively. Knowledge does not exist only in the minds of individuals; like other societal assets, knowledge is stored in collective facilities (from libraries to computer tapes), is made available for collective action (as when an organization retains experts), and is shifted from the service of one societal goal to the service of another e.g. by transfering a large contingent of laboratory employees from the service of the United States Army to that of the national Aeronautics and Space Agency. Though knowledge is an unusual asset in that it is a set of symbols rather than objects, we suggest that it is nevertheless fruitful to view it as an asset and to study the production, processing, and consumption of knowledge as societal activities". In: Etzioni, A. (1968) The Active Society: A Theory of Societal and Political Processes. Collier-Macmillan Ltd., London and The Free Press, New York.

the question, "Who learns what?" Although not exhaustive, the following examples of types of learning are at least indicating represented on the diagram.

At level 1, the circular arrow represents the learning typically documented in empirical studies of the learning curve: a single group or team, working on the same product (more or less), and improving with practice and/or with innovations, particularly in method; these could include increases of scale.

The vertical arrow between levels 1 and 2 represents the acquisition, resulting from the level 1 activity, of experience relevant to their functions by the supervisory, managerial, technical support and other services at factory level. Such staff could be transferred to other factories in the company, could leave the company, take their know-how to other industries, or emigrate; all these possibilities are included in the horizontal arrow(s) at level 2.

Similarly all the arrows in the diagram have their interpretation. At the societal level one could consider the formal educational system and curricula, the capabilities and qualifications of the labor force, social and cultural attitudes to work, government policies affecting industry; in short, all those factors in the environment which may facilitate or inhibit the acquisition, maintenance and transfer of capabilities on each level.

The relevance to learning of the broader environment is most readily perceived when one considers either a company diversifying into an industry unfamiliar to it, or innovations pioneering a totally new field, or a company trying to start operations in an industrially underdeveloped country. Delaying or inhibiting factors in the last case might include:

1. Linguistic and cultural differences
2. The absence, or cost of creation, of physical and administrative infrastructure

3. Differences in natural environment: climate, terrain, resource endowments
4. Existing investment in incompatible equipment.

Planning of feasible trajectories for development requires consideration of sequencing which takes account of these links and dependencies--a point well discussed by Vietorisz (1974). On the other hand, in the industrially developed countries and for secondary industries, Keynes was able as long ago as 1933 to observe that:

> "Experience accumulates to prove that most modern processes of mass production can be performed in most countries and climates with almost equal efficiency",

though his observations failed to anticipate the extent of the scale economies which were to develop in such fields as cars, aero-engines or semi-conductors. The distinction between levels 2 and 3 (factory and company) is important: manufacturing economies of scale may be modest enough to allow many car assembly plants; but the development costs of new engines or gearboxes, and the creation of a global dealer and support network, may indeed reduce the number of companies to Agnelli's 1968 forecast of half a dozen in the world.

4.5 A Closer Look at the Learning Process

Returning to what is happening in the learning processes summarized by the "curve" of improving performance, it is predominantly in terms of the primary learning and plant modifications that the gains are made. The deliberate coding of the know-how is not generally made in great detail, perhaps no more than is required for specification of operations on a standard cost card. As volume expands and labor is recruited, or additional manufacturing centers are to be started for the same product, it becomes necessary to institute more systematic training programmes, and therefore necessary to make the best practice more explicit. At the same time, disciplines such as work measurement, method study, value engineering and production engineering are brought to bear on both the product and the process to achieve further gains in efficiency.

As experience accumulates, the capability has become developed in the following ways:

-- the primary skills of the experienced direct labor;

-- the physical equipment, now fully de-bugged, run in, tried and tested;

-- the experience of supervisory, ancillary, managerial and administrative aspects (e.g., maintenance requirements, appropriate working conditions, recording procedures, standard costs)--embodied in both people and written procedures;

-- training programmes for additional labor (experienced people, written procedures and appropriate materials);

-- blue-prints for the physical equipment.

These aspects of capability are not confined to the direct workforce, but may include suppliers of materials, components and services who will necessarily have been exposed to the learning process; a theme we return to in section 4.6.

The learning curve has been propagated almost as though it represented an inexorable law, that whenever cumulative output doubles, unit costs decline by x%, x being a constant characteristic of the product. More carefully, some industrialists stress that it represents the <u>potential</u> improvement in performance, under conditions of sufficient pressure. There is, however, something intrinsically implausible about continuing improvement in a wholly repetitious task: one can shear only a finite number of sheep in a lifetime, and presumably one's speed reaches a maximum after the first few hundred.

In manufacturing processes, however, few tasks of significant complexity are so wholly repetitious as may at first sight appear, even on the most mass-produced and apparently standardized product. For example, when the owner of a mass-produced car wants a spare part, he will often have to quote the year or even the engine or chassis number, indicating that there have been some changes during the production of the same standard model. Even within the same product and part there will have been many possibilities for minor changes in the manufacturing process--supplier changes, value engineering of the design, method study and work measurement applied to the assembly process, right down to individuals acquiring practice through the processes of primary learning.

Figure 3 represents what the "true" learning curve would look like, if anyone bothered to make the necessary detailed observations. Few research studies do, or can, go into the microscopic detail envisaged in Figure 3(b). However, in further research, it may be important to appreciate the stepwise nature of the learning. For instance, the earlier period in Figure 3(b) would be characterized by higher frequency of innovation, and a larger step size; the later periods, by lower frequency and smaller improvements. The frequency might be susceptible to management pressure, the inherent potential for improvement less so, except insofar as prior relevant expereince can be transferred, enabling production to start "well down the curve"--as though x thousand of the new product had already been made.

As a rich example of a "learning" process in a "complex" task, consider the diagram Figure 4 in which Waddington (1973)

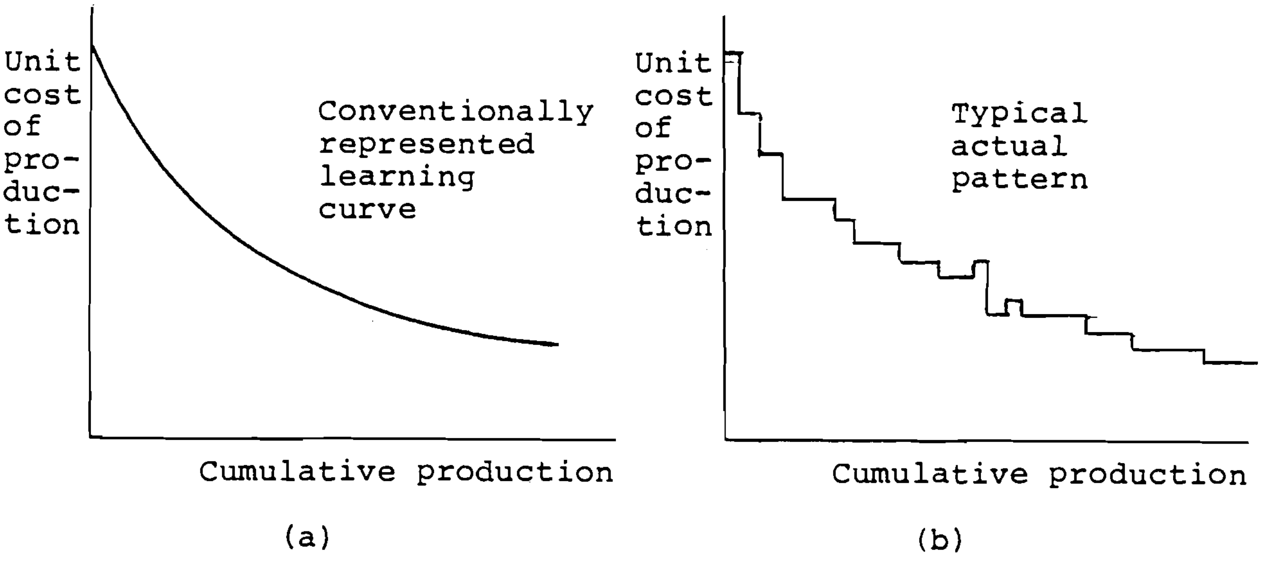

Figure 3. Conventional and Discrete Representation of Learning Curves.

summarizes the progressively increasing effectiveness with which German submarines were destroyed by British Coastal Command aircraft during World War II. The example is perhaps too rich, in that the submarines could also learn--they did do some experimentation, e.g., with staying surfaced and fighting back, and there was a technological battle of radio detection and listening devices. Basically, however, the U-boats were constrained by the requirements of their operational targets, their base location and the technology of their diesel-generators and batteries(obliging them to surface for a certain number of hours). Thus within the time-period covered, operational and tactical initiative lay largely with the attackers.

Given the serious and growing loss of British shipping due to the submarines, the <u>pressure</u> to learn was maximized. As Waddington describes the situation, organizational constraints on learning were minimized--innovative behavior was prized, and communication between pilots, senior officers and operational research scientists was extensive and uninhibited. Waddington identifies this aspect as one of the two most important lessons (the other being adequate staff) of the war-time experience, in his final summary:

> "...the entire development of the complex and interrelated body of scientific doctrine was guided at every step, not solely by the scientists who did the actual thinking and calculating, but to at least as large an extent by the senior Staff Officers whose needs the scientists were trying to serve. The relation between the scientists and Sraff was one of almost unblemished cooperation and trust. If this had failed on either side, Operational Research as Coastal Command knew it would have been impossible. If the scientists had not been taken completely into the Commander-in-Chief's confidence, if they had not sat in at his most professional and confidential conferences but had been fobbed off at lower level discussions, they would have learnt only too late of the importance of many of the subjects to which they made contributions of some

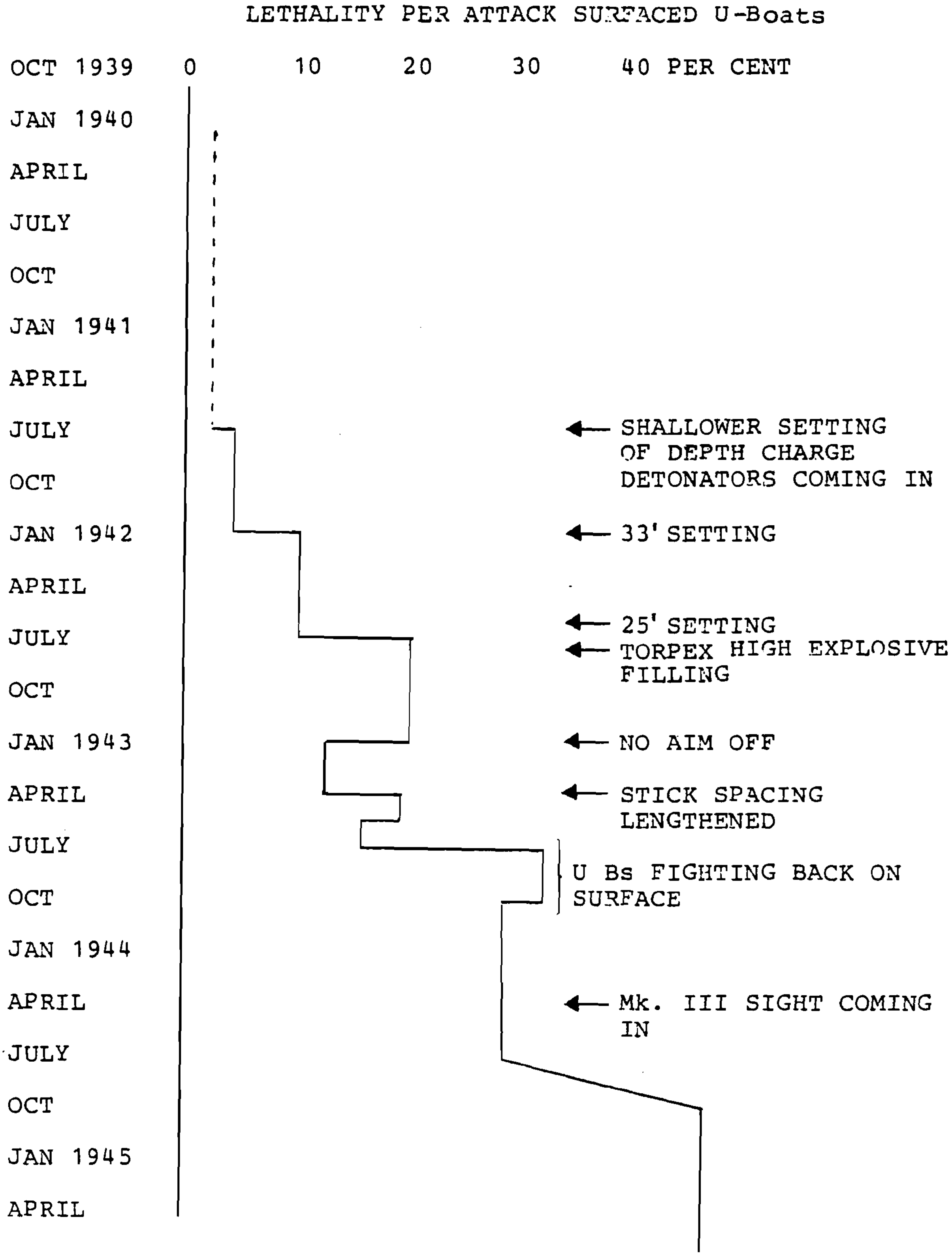

Figure 4. Percentage lethality of attacks against surfaced U-boats during the war.

Source: Waddington 1973

> value. Or again if the scientists had not spontaneously offered their views, as equals and not as mere servants of the Staff, many of their contributions would have been missed, since it is only the man trained in scientific thought who can see to which problems it can be applied. The credit for incorporating the scientists thus fully into the Command team belongs in rather small measure to the O.R.S. itself; beyond exercising a reasonable tact, there was little they could do about it. It was the readiness of the professional Air Force officer, given the lead by the Commanders-in-Chief, to acknowledge the value of the scientists' professional training, which alone made possible the whole success of Operational Research."

If we replace the step-wise pattern of Figure 4 by a continuous curve, it might represent a generalization, but it is clear that we would be losing not only "random noise", but might also be losing specific understanding of the nature of the process.

So far, our discussion has tended to be conducted mainly in terms of manufacturing capability. It is at this level that most of the well-documented studies in the literature have reported and quantified learning effects. However, we have deliberately introduced Waddington's example of increasing effectiveness, not only because it illustrates in detail the stepwise nature of the process, but because the learning process here included a broad range of activities, from the pilots and crews in the aircraft, to the base commanding officers and strategists, and the operational researchers. It thus spans several of the levels of Figure 2, and the experience went further still.

The postwar diffusion of operational research in the U.K. reflects the conclusion, by those closely involved with it in the military context, that they had acquired or stumbled upon an approach and an outlook of wider applicability. Thus it is evidence of a learning process abstracted from the primary activity, upwards to levels 4 and 5 and horizontally between entities on these levels. Throughout industry and government, indeed enshrined in the customs of many societies both industrial and primitive, there is a widespread belief that age and experience do provide some accumulation of wisdom. The general validity of this assumption has not often been put to specific or empirical test; on a priori grounds, one might expect its validity to be very much dependent on the constancy of environmental conditions. But it demonstrates a belief in the acquisition through practice of general skills, having application beyond the specific contexts within which they were first acquired. This again represents transfer on the upward vertical arrows of Figure 2.

That this belief may be inappropriate for volatile environments is also well-documented, particularly where a rigid and formal organization becomes insensitive to the need continually to be receptive to changes in conditions. The belief of military chiefs in Britain, France and Poland, as late as the 1930s, in the superiority of cavalry over tanks, in spite of the available evidence, is a grim example (Liddell Hart, 1970).

The recognition of acquired capability in the Waddington case is most eloquently testified to by the Ministry of Defence's refusal to give clearance to his book, written in 1946, until 1973.

4.6 Networks of Capability

We now consider more carefully some characteristics of the nature of capability, and in what it resides. Its development is stimulated by need or incentive. It is maintained and increased by exercise, and can atrophy if not used. Capability in manufacturing almost any moderately complex product comprises a network of more specific capabilities, the finest elements of the network comprising individual people of specific skills, individual units of plant or their components, and stored information. Many--indeed most--of these elements will not be within the one organization; the network includes suppliers, and supplier's suppliers.

The specific capabilities could be listed; what gives them "network" form is their assembly in a specific configuration for a specific purpose--particularly, the purpose of manufacturing a certain class of products.

The network links could represent the flows between capability centers of materials of various kinds characteristic of this manufacturing activity; or the flows of information associated with this manufacturing. Where the information flows, so does the potential for learning.

Suppose we have a certain complex product, whose manufacture requires the manufacture and assembly of several components and sub-systems.

Each of these components or sub-systems is typically associated with one or more functions, and provides a specifiable level of performance of that function. It may also have physical, economic and other attributes.

If the whole product is changed--e.g., to produce higher performance or other changed attributes--this has to be achieved by changing one or more of the components or sub-systems. If we consider a wide range of possible types of change, we are likely to discover that changes in one component or sub-system require changes in another, rippling throughout a larger area of the network--though it will be inconvenient if minor changes create major disturbances. Indeed it would be an object of modular design to avoid this.

A diagram representing the connections can indicate which sub-systems are logically closely connected in the sense that a change in one usually or typically requires a change in the other. Figure 5 is a much-simplified example based on one author's experience of wire-drawing machinery. It is important in considering technological capability, particularly for complex manufactures, of this inherently network-like characteristic. Some of its significant implications are these:

- -- The technological capabilities of the firms in a country will be positively correlated by their common sources of bought-out services and materials, however much the managerial and design capabilities of the firms differ.
- -- It will be difficult to establish a complex high technology manufacturing establishment in an environment lacking the supporting services and supplies available in the original location.
- -- Technological development will require a trajectory in which the supporting infrastructure has the necessary coherence; insofar as the latter is lacking, the centers of development will have an isolated character, lacking linkage or integration in the host society, dependent on imported sources (of supplies, or skills), and both vulnerable to disruption (if sources are remote) and disruptive to the host society (through its imposition of unfamiliar and/or infeasible demands).

The relationship of the network character of capabilities to the concepts already introduced, of learning and multi-level information transfer, will be evident.

5. POLICY IMPLICATIONS AND ILLUSTRATIONS

5.1 Specialization and Flexibility

Primary learning at level 1 has close similarities to the biological model of specialization of function for increase of efficiency in the individuals of a species. Survival and prosperity also depend upon the joint behavior of the species in its living activities, and the evolution of patterns of

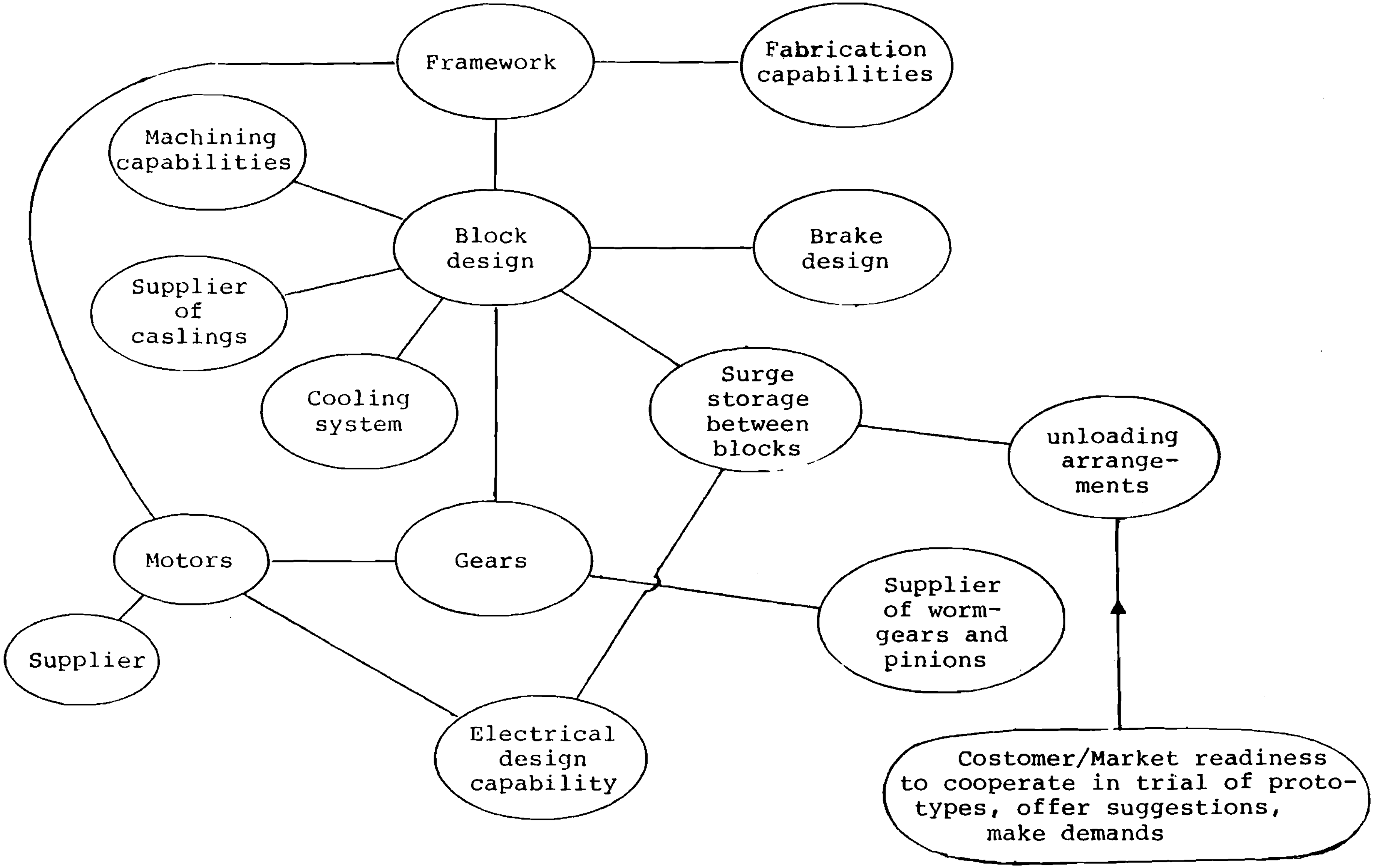

Figure 5. A simplified network of some of the elements of capability required in the manufacture of wire drawing machinery.

societal behavior corresponds to the "learning" behavior of technical or social systems from level 2 upwards, in the terms of Figure 2.

However, learning at all levels can diminish capability in two other potentially significant respects. Firstly, as physical plant becomes progressively more specialized, by definition it is becoming less capable of being used for any other type of production.

Secondly, by processes of habituation, the human responses at all levels from direct labor to supervisory and managerial are likely similarly to become strongly attached to the products, processes and systems in which they have invested time and effort. These achievements are the demonstrable output of their efforts and justification for their status, and they may therefore naturally become increasingly reluctant to abandon them, and resistant to radical innovation.

Tha capability to respond to environmental change includes both taking advantage of change, by appropriate adaptation or development to suit the new situation; and minimizing the damage caused by change. Many words have been used for the latter ability--resilience, robustness, defensive flexibility--by authors in a variety of disciplines. In the context of high technology systems of which high performance and reliability are demanded, a useful term and concept is that of the reversionary modes of operation of the system. For example, in navigation systems for air transport, several methods of establishing position are typically provided. If the normal or preferred mode breaks down, this redundancy enables the crew immediately to switch to an alternative. Even if two or more failures occur, the crew can still revert to other procedures and are trained to do so. Similarly pilots are trained to cope with many emergency conditions such as the failure of one or more of the engines on a multi-engine plane.

In manufacturing organization, there are many ways in which flexibility in the face of shocks can be consciously developed: second sources for all key supplies (i.e., redundancy in the capability network--sound ecology), stockpiles of essential components and supplies. The development of flexibility in manufacturing capability tends to be antithetical to the processes of specialization involved in learning. The capability is likely to reside at a level above the specialist operations of the product-line.

The need to develop flexibility, reversionary modes of operation and the like is determined mainly by the characteristics of the external environment. One can contrast two species and two sets of environmental characteristics as shown in Figure 6. For simplicity, we suppose some single measure of performance related to survival, such as food-gathering efficiency.

At the level of the organization, a discussion of how to describe, and what constitutes, strategic flexibility would lead naturally into the literature of strategic planning and management. Ansoff (1965), in particular has used the grid shown in Figure 7, in three modes.

	Environment characteristics	
Performance characteristics	Stable	Prone to sudden change
Group A High variance (therefore more individuals away from the optimum)	Can survive, but inferior to B in total performance	Higher prospect of adaptability and survival
Group B Low variance, around optimum	Ideal	Risk of catastrophic collapse

Figure 6. Illustrating the relationship between performance capability and the characteristics of the environment

1. As a "capability profile", it can be used as a framework for giving an objective view of an organization,
2. In the context of a specific product-market, it can be used to specify the "competitive profile" of the industry--by reference either to ideal standards, or to the existing firms in this sector,
3. By super-posing the "capability profile" of the company on the "competitive profile" of the industry, the succession of comparisons highlights the strengths and weaknesses of the firm in relation to the product-market under consideration.

While this type of analysis will clearly tend to be dominated by physical plant capabilities and locations and financial resources, both the plant and the existing skills

Skills and resources Functional area	Facilities and Equipment	Personnel skills	Organizational capabilities	Management capabilities
General management and finance				
Research and development				
Marketing				
Operations				

Figure 7. Grid of competences, for assessing capability of firm, competitive profile for an industry, or firm's strengths and weakness

Source: Ansoff 1965.

of personnel represent the physical and human forms of know-how. Thus at its broadest, the processes of learning are seen as central to the processes of survival and strategy. The strategic significance of a weak information strategy will be illustrated by example in the following section.

5.2 On "Learning by Doing" and the Pursuit of Understanding--A Historical Counter-Example

All learning originates in practice, through the forms we have termed primary learning and transmission. If this is viewed as the only form of effective learning, it can become a blind alley. Barnett (1978) has documented the profoundly debilitating consequences of Britain's neglect of formal technical education during the nineteenth century. The neglect was repeatedly recognized by successive commissions of enquiry, such as the Schools Enquiry (Royal) Commission in 1868:

> "We are bound to point out that our evidence appears to show that our industrial classes have not even the basis of sound general education on which alone technical education can rest."

These warnings did not lead to effective action, because they ran counter to the prevailing philosophy of liberal individualism and self-help. The "learning by doing" philosophy was expounded by the "Economist" (1850):

> "...the education which fits men to perform their duties in life is not to be got in school, but in the counting-house and lawyer's office, in the shop or the factory." (Quoted by Barnett.)

The more deliberate development by other countries of formal technical education--for example in the Swiss and German polytechnics-provided a much sounder basis for continued development of industrial or technological capability. It linked the primary learning in the factories with the facilities and the social prestige of institutions responsible for technical education, and the processes of secondary learning. As another Royal Commission commented in 1884 of the German polytechnic system:

> "To the multiplication of these polytechnics may be ascribed the general diffusion of a high scientific knowledge in Germany, its appreciation by all classes of persons, and the adequate supply of men competent, so far as theory is concerned, to take the place of managers and superintendents of industrial works. In England there is still a great want of this last class of person."

The history of British technical education, by contrast, shows it much slower to develop (see Musgrave 1964). Under pressure from both employers concerned with the secrecy of their processes, and trade unions concerned with the protection of their crafts, practical instruction was to be excluded from technical education. After seven attempts, in 1889 the Technical Instruction Act reached the statute book. It was concerned with

> "...instruction in the principles of science and art applicable to industries, and in the application of specific branches of science and art to specific industries or employments. It shall not include teaching the practice of any trade or industry or employment..."

Fortunately as the Bryce Commission reported in 1895 the Department of Education was "liberal rather than strict in its interpretation".

5.3 Implications for Strategy

One of the recurrent themes in the history of industrial strategy is the failure to recognize, or indeed to be alert for, the qualitative change, and the broader context. As part of the process of sharpening perception of technological change, we have suggested that there is value for the users or developers of any technology in seeking to identify its "law of growth", its limitations, and the likely future or ultimate need for morphogenesis and differentiation.

Other points following from our analysis would include the desirability of incorporating a technological dimension in strategic decision-making, and the need for a quantitative and structured perception of one's local competitive and strategic position. Elements of this are of course already widely published, as illustrated for example by Ansoff's "capabilities profile"; but it is equally easy to point to continuing example of strategic neglect.

The policy applications of improved understanding of the processes of technological innovation, improvement and learning exist at each level, as illustrated below.

1. Improving the operational efficiency of production of an existing product.
2. Planning and controlling development effort on the introduction of "new" processes and products.

1 and 2 are in fact better viewed as a continuum, rather than intrinsically different.

3. Making strategic choices on directions of development of an organization's activities. This encompasses maintaining present positions, abandoning some old ones, and entering new ones. When we speak of "positions" or "activities", we mean not only "product range" and "market sector", but the whole spectrum of functional abilities which collectively constitute the capability to operate in the chosen sector--i.e., the network of Figure 6.
4. Item 3 may be interpreted, <u>mutatis mutandis</u>, at many organizational levels:
   -- the operating group within a factory
   -- the whole factory
   -- the multi-plant company
   -- the multi-company conglomerate

-- the industry
-- the country
-- the supra-national grouping
-- world society

although clearly the structures for organizing efforts and co-ordinating them vary enormously between these eight groupings.

It is not only possible but probable that there will be conflicts between these functions--the strategic desirability of abandoning a sector conflicting with the tendency of those operating in it to seek resources for improving their performance within it.

At societal and indeed at global level, we may expect a changing balance between the strategic significance of <u>capability</u> and of <u>natural resources</u>. The balance is currently shifting from the former towards the latter; as time goes on, capability becomes more widespread and commonplace on a broader range of skills; while natural resources diminish, and become of increasing value and scarcity. Global long-term studies such as the OECD "Interfutures" (1979) may indicate that the developed industrial countries can maintain their position, employment and living standards by continuously maintaining a lead in high skill, high technology new products. On the other hand, insofar as these are characteristic potential outputs of any society which has moved itself far enough down the cumulative experience curve of education and development, one may observe a feature of such curves. Two competitors initially separated by one's having a finite initial advantage in years or output will see the initially wide performance difference diminish to insignificance. If the leader stagnates in technological complacency, he will be overtaken.

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