Who Learns What? A Conceptual Description of Capability and Learning in Technological Systems

Cantley, M.F. and Sahal, D.

IIASA Research Report
December 1980

Cantley, M.F. and Sahal, D. (1980) Who Learns What? A Conceptual Description of Capability and Learning in Technological Systems. IIASA Research Report.

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

Mark F. Cantley
Devendra Sahal

RR-80-42
December 1980

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

FOREWORD

This report had its origins in a workshop on "Size and Productive Efficiency – The Wider Implications" held under the auspices of the Management and Technology Area at IIASA in June 1979. One author, Mark Cantley, was an organizer of that workshop; the other, Devendra Sahal, from the International Institute of Management, Berlin, was a participant. The workshop brought together for the first time economists, technologists, and social scientists to discuss the topic on an international basis. One recurrent theme in the discussion was the need to see decisions on scale within the dynamics of technological and economic development; in particular, questions of learning and the concept of the learning curve arose continually, until Professor Bela Gold was provoked to ask forcefully, "Who learns what?" This report attempts to answer that question.

Some assumptions about the expected pattern of future improvements in efficiency must be built into any planning process relating to a new plant. These assumptions are often built into "learning curves" as though improvements arise automatically with increasing cumulative production. There is confusion as to whether learning relates to the one producing unit, to the whole organization, or, indeed, to the industry. Delving into the subject, one discovers considerable chaos and misunderstanding beneath the beautiful simplicity of the learning curve. A great deal of further analysis and exposition is needed.

This report is concerned with a universal, practical problem inherent in industrial planning.

ALEC LEE
Chairman
Management and Technology Area

SUMMARY

In terms both of individual units and of groups or organizations, the evolution of technological systems has structural similarities to the evolution of biological systems. This paper thus makes use of Bonner's description of biological development: 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 technological fields. Examples from several industries illustrate technological developments. The pursuit of economies of scale exemplifies the parallelism with 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, stored on paper (or its equivalent), 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; in fact, the shift is from Darwinian to Lamarckian evolution. However, theoretical knowledge is important 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 underlie the phenomenon known as cumulative experience, manifest in the "learning curve." Learning, however, is a multilevel process, and levels are described as a basis for distinguishing the type of learning or information transfer characteristic of each level, answering the 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. An organization's capability is described in terms of a network of capabilities.

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

CONTENTS

1 INTRODUCTION

In this report we offer some concepts as a basis for describing or modeling the evolution of technological systems. Some of the ideas that we develop have been presented previously (Sahal 1979a, b, c). Others come from the program of research on "problems of scale" (Cantley and Glagolev 1978) undertaken at the International Institute for Applied Systems Analysis (IIASA).

In the concepts presented here, we identify common ground or relationships between 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. One objective of our work is to develop generalizations relevant to policy issues in technological systems. An example is the concept of progress function or learning curve. This generalization is not only well documented by empirical studies in many industries (Yelle, 1979, gives a comprehensive review) but is also promulgated with commercial success by consulting groups using it as the core of a strategy formulation framework (see Hedley 1976, 1977). Admittedly, while "learning" is much in vogue, the concept is often used with more breadth than precision. In the succinct statement of David (1970, p. 562):

> The application of the notion of learning by doing to account for the measured input efficiency growth of an aggregation of production units admittedly creates worrisome ambiguities about exactly what is being "learned" and by whom.

Indeed, the crux of the ambiguity in the notion of learning curve may be summed up in a single question: "Who learns what?" (Gold 1979). The applicability of the learning curve and the nature of learning constitute one focus of this report. We see it as essential, however, to set learning within the context of the general pattern of growth and change of capabilities that constitutes the evolution of a technological system. We hope gradually to clarify our usage of these terms; we deliberately pull together a variety of related or similar terms used for common phenomena. In demonstrating this underlying commonality, 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 interconnected 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 to understanding of systems other than those first considered that the abstraction justifies itself.

Von Bertalanffy's pioneering work on general system theory (1951, 1968) was rooted largely in his experience of biology, in his perception of underlying similarities of structure and behaviour between widely diverse biological entities. Of similarly fundamental importance was the work of the biologist Thompson (1917), now conveniently edited in Bonner's abridged version. Bonner himself built on the work of both of these pioneers and on his own extensive research to give in *Morphogenesis* (1952) a succinct statement of a general model of the development process in biological organisms. Although Bonner restricted his model to the field of biology, we find it remarkably applicable, at least as a starting point, to modeling technological systems. As Sahal (1979a) has published a description of this general theory of developmental processes, we shall begin by briefly summarizing it here; the authors cited have already thoroughly illustrated the theory through biological examples, which we may thus omit here. We shall then demonstrate its applicability to technological systems, consider some of the significant respects in which technological and biological systems differ, and ultimately derive policy implications for managing technological systems.

Bonner* separates development 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: *growth*, *morphogenetic movements*, and *differentiation*. Growth will be used here in the sense of an increase in matter; it involves the intake of energy and the storing of some of that energy by synthesis. . . may be reflected in changes in size or weight. . . . Morphogenetic movement. . . gives rise to

---

*Excerpts from John Tyler Bonner, *Morphogenesis: An Essay on Development*, Princeton University Press, copyright © 1952 and 1980. Reprinted by permission of Princeton University Press.

> 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 case material are exclusively biological, one can 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* 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.
>
> *De Beer, G.R. (1940) *Embryos and Ancestors*. Oxford: Oxford University Press.

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

Artists, engineers, and designers have long drawn on nature and biology for both general patterns and detailed techniques. Our aim is to draw structural parallels, and to consider 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 (1974, 1979). He criticizes the confusion between "size" and "scale," pointing out that "size" is increased by mere addition and accumulation (i.e., Bonner's "growth") but that an increase of scale properly implies redesigning the plant's form (i.e., Bonner's "morphogenesis"). On the question of scale, Gold states 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 that Bonner summarizes by the term "differentiation."

In the following section, we cite specific technological illustrations of this development theory. In Section 4, we turn our attention to "learning," which embraces processes of acquiring, storing, and transmitting capability. In considering these functions, we explore some significant differences between technological and biological systems.

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 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 examined the evolution of farm tractor technology from its genesis to recent years. During the turbulent competitive history of the industry in the US, many technological changes were introduced. Each new line of development eventually encountered a limiting process; in each case, however, the limit eventually could be overcome. As a striking example, technological evolution had reached a virtual standstill by the 1940s. Judging from the growth of the relevant measures of technology, such as fuel consumption efficiency, the ratio of horsepower to weight, and mechanical efficiency, the evolutionary process was at a dead end, with no prospects for further progress. A primary cause was an increase in the internal structural complexity of technology resulting from continually modifying an essentially unchanged form of machine design. New avenues of advance in technology were nevertheless found. In particular, the increased adoption of the three-point hitch for controlling integrated implements (recently developed after prolonged experimental effort) made it possible to simplify the overall form of the machine design and paved the way for considerable improvement in the farm tractor's capability. What seemed to be a permanent state of technological stagnation thus proved to be a mere interlude to further innovation.

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 1100 kV, another – electrostatic induction. We do not know at this time what problem will appear at voltages higher than 1500 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 show that, as size increases, not all functional capabilities increase in constant proportion. For example, surface areas increase as the square, and volumes as the cube, of the linear dimensions. Different functions bear different relationships to these geometric characteristics.

Over their 100-year technological evolution, fossil-fueled electricity generating plants have greatly increased in both physical and economic efficiency. During the postwar years, the advantages of larger scale plants were perceived and achieved, and the scale of unit ordered in the UK increased from 30 and 60 MW until 1950 to 200 MW by 1953 and 660 MW by 1966 (Abdulkarim and Lucas 1977). Similar development in the US and elsewhere achieved units with ratings in excess of 1000 MW. In summarizing this development, we should not oversimplify the engineering problems involved. In many cases, scaling up the physical size meant encountering 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. The transportability limit, being imposed by the environment, clearly is an example of Bonner's *external* constraints on growth.

On-site fabrication, the solution to this particular constraint, involves significant technical disadvantages. The quality and ease of assembly work achievable in a factory are 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).

Similarly, for chemicals, Woodhouse *et al.* (1974) give the following figures for olefin plants (quoted in Cantley, 1979, in a review of scale in ethylene plants):

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

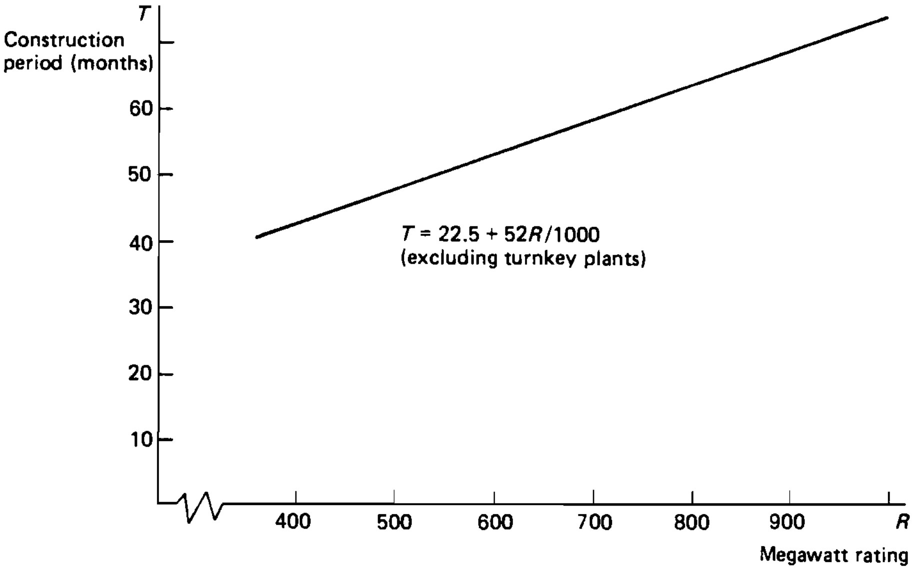

FIGURE 1 Scale of fossil-fired generating unit and construction time.
SOURCE: Fisher 1978.

These examples illustrate how the basic pattern of growth, originally pursuing efficiency by increasing size, encounters a succession of internal and external constraints. These constraints are overcome 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, pushing 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 (1977). (See Table 1.)

In the chemical industry, disenchantment with large-scale plants has not yet been so clearly documented. However, long construction times lead to uncertainties in forecasting and planning for 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 when scaling up: as he points out, it becomes more appropriate, beyond a certain diameter, 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 factory-built modular construction of standardized units.

TABLE 1 Availability and forced outage rate by size groups, fossil-fired plant (figures are 10-year averages, 1964–1973).

Unit size (MW)	Average availability (%)	Average forced outage rate (%)
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	8.9
600 and larger	72.9	16.5

NOTE: Forced outage hours are the sum of full outage hours and equivalent full hours due to partial outage. The rate is expressed as the percentage of total hours less economy outage hours (periods when capacity is not required, due to load management).

SOURCE: Edison Electric Institute. Report on Equipment Availability for the ten-year periods 1964–1973 and 1965–1974. Copyright © 1977, Electric Power Research Institute.

In his recent paper, Fisher (1979) similarly concludes by arguing for a retreat from the maximum scale units and for concentration instead on developing and producing a standardized design that would benefit from the dynamic economies of scale of the learning curve.

The key concept of the "learning curve" in technological systems is that the group (company, factory) with greatest accumulated production experience can achieve the greatest production efficiency, presumably because it has had the largest number of opportunities to refine and improve both the product and the 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 discussed later in this report, but at this point two caveats should be noted. First, the successive improvements associated with cumulatively increasing experience will not happen inevitably; the experience creates the *potential* for improvement, but its realization depends on conscious effort. This is borne out by the available evidence in a number of areas. For example, it was widely believed that the initial availability and capacity factors of newly constructed nuclear power plants would be low but that performance measures would gradually improve because of accumulated production experience. However, this assumption proved to be largely illusory (Comey 1974). As another example, there is concern that the second phase in developing North Sea oil fields may prove as costly as the first, for want of requisite learning (see Economist, 10 February 1979). To a certain extent, this problem originates in the obstacles to transmitting learning from one context to the other. More generally, it is apparent that the dynamic scale effects do not always materialize. Theoretically, this is to be expected: while the learning curve has all the appearance of a deterministic model, it is a formulation of what is essentially a probabilistic phenomenon (Sahal 1979b).

Second, achieving success involves its own problems, frequently creating a complacency that reduces readiness to innovate because of the established technology's conditioning effect. When major challenges emerge from some unexpected direction, the initial response is typically redoubled effort within the familiar technology. Utterback (1978) and Utterback and Abernathy (1978) have documented this phenomenon in a number of industries. This is a good example of Kenneth Boulding's proposition, "Nothing fails like success."

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

4.1 Introduction

The biological mechanisms for storing and transmitting 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.) Gould (1979) neatly expresses this amplification of the capability for transmitting information in terms of a shift from the Darwinian to the Lamarckian model of evolution:

> Cultural evolution has progressed at rates that Darwinian processes cannot begin to approach. Darwinian evolution continues in *homo sapiens*, but at rates so slow that it no longer has much impact on our history. This crux in the Earth's history has been reached because Lamarckian processes have finally been unleashed upon it. Human cultural evolution, in strong opposition to our biological history, is Lamarckian in character. What we learn in one generation, we transmit directly by teaching and writing. Acquired characters are inherited in technology and culture. Lamarckian evolution is rapid and accumulative.

We should note, at least in passing, that our antithesis between biological entities, subject to natural selection, and human artifacts is blurred by the achievements of agriculture, today's plants and animals being the results of artificial selection and breeding. The distinction is further blurred by genetic manipulation, whose acceptance as a technology is well marked by the US Supreme Court's June 1980 decision to allow the patenting of an oil-slick-digesting bacterium engineered by General Electric. But the essential distinction is that both the old biotechnology of agriculture and the new biotechnology of recombinant DNA are intrinsically Lamarckian in the deliberate selection and transmission of desired and acquired characteristics.

In considering learning and the "Lamarckian" transfer or increase of acquired 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), be embodied in physical *plant,* or exist in combinations of these three. We shall use the term "primary" to describe learning that 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 through the visual and tactile senses, the sense of weight, balance, movement, and similar physical sensations. 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 that would significantly accelerate the basic process of learning to ride a bicycle. In learning to swim, the role of communicable information is higher: the arm and leg movements for effective propulsion can be described in ways that 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; where it is critical, it is partly coded and partly automated by providing 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. 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 – and hence 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 this 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. In principle, there is no reason 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, but also on the conversion of the information thus conveyed back into primary learning.

These points may appear obvious, the terminology overelaborate, for the familiar acts of learning. They are less obvious, however, when we consider such issues as technology transfer between industrialized and primitive societies, the design of policies and systems for technical education, or mid-career retraining for individuals. Fores and Sorge (1978) virtually go so far as 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 to *embodied* know-how in the form of physical plant or tools. The clear trend in manufacturing methods in industrialized societies has been towards the increased sophistication of equipment in terms of the amount of information-handling capability incorporated in physical form. Automation displaces not only 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; determining the extent of the adverse behavioral effects of "de-skilling" on the quality of work is beyond the scope of this paper, although it is potentially 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 postwar Japan's not merely learning from American technology but going on to improve on 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.

As an illustration of the importance of primary learning, it is interesting to note the emphasis placed by Pearson (1978) on the role of person-to-person communication in R and D groups:

> Most research shows that although mechanical information systems can be of help to people in R and D, a large part of the information used on a day-to-day basis is passed on by people.

Secondary learning is derived from primary learning via an intermediate recording stage; it is distinguished from it partly by being conducted separately in physical terms, but more importantly by emphasizing

- the development of *understanding*
- simplification, coding, and generalization
- the ability to store know-how and thus to *retain* learning

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. First, the lessons learned through practice are shown, through experimentation and investigation directed towards increasing understanding, to have wider applicability than the original context in which they were developed. Second, 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 secondary learning has a vital role to play in the acceleration, storage, and diffusion of technological learning, but it starts from and returns to the processes of primary learning. As Mao Tse-tung (1937) precisely expressed 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. By relating capability to cumulative experience, rather than to embodied know-how in the form of capital equipment, we recognize 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 previously quoted statement of Mao Tse-tung about knowledge and practice. Viewing capability and practice as inseparable has many implications for technological and industrial strategy. For example, a long-standing argument (used, for example, in the US by List and Carey in the mid-nineteenth-century debate on free trade versus protectionism (see Calleo and Rowland 1973)) is that a nation's industrial capability 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 are the fruits of acting – that productive power is "infinitely more important than wealth itself." Many countries, for example, might wish to take advantage of cheap imports – whether of oil, coal, food, or manufactured products – when available 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.

The dependence of capability on experience can be one of the strategic factors in those industries in which the growth of unit scale in the process plant, particularly in markets whose total growth rate is modest, dramatically reduces the number of available "learning opportunities," i.e., orders. Ball and Pearson's description (1977) of sinter plants in the UK is instructive – four orders in a decade, divided between three contractors. As they point out,

> To be able to tender for the largest complex plant the contractor requires experience to draw upon, and that experience cannot be acquired if the contractor fails to obtain orders. . . . This learning effect will give the first contractor to build the large plants a competitive advantage, since for subsequent orders his design costs are below those of his competitors.

4.4 Learning and Levels

Some of the confusion surrounding the discussion of learning curve – the "Who learns what?" question – may be removed by a more explicit consideration not only of the nature of the learning process, but also of the different *levels* on which it can occur. Following Cantley and Glagolev's (1978) discussion of the levels on which "problems of scale" may be considered, we distinguish

1. the *unit* level: a single piece of equipment, 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: all the firms within the industry (possibly within one country or market)
5. the *society* level: the wider society, within which the manufacturing and marketing of the goods takes place

Figure 2 summarizes these levels, with a typical member of each level lying within the next higher level – as, for example, one blast furnace within one steelworks of a steel company that 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 multinational industries, the figure serves as a framework for arrows representing information transfer or "learning." These are of three kinds:

1. The circular arrows represent learning occurring cumulatively over time within a particular entity on its own level.

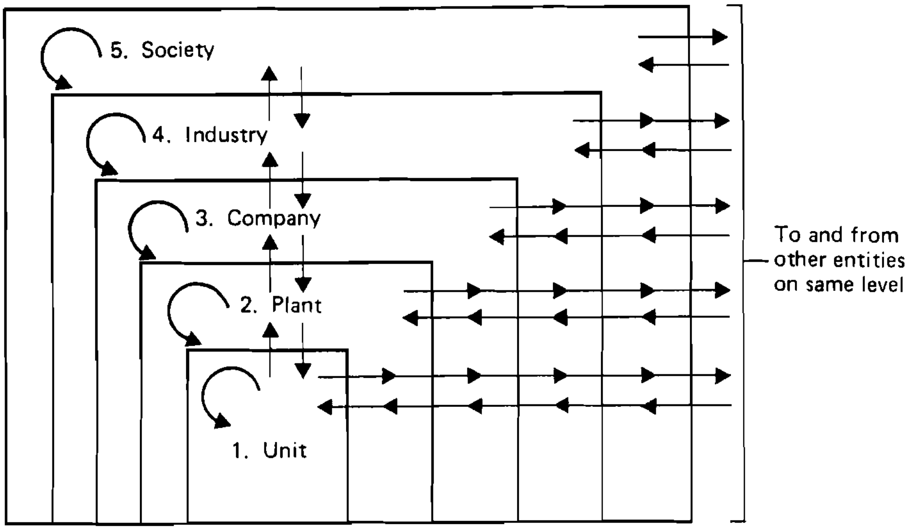

FIGURE 2 Levels and directions of learning or information transfer.

2. The vertical arrows represent transfer of information or know-how 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).

In spite of the diagram's oversimplification, the 43 arrows of Figure 2 represent the many different interpretations and answers that might be offered in response to the question "Who learns what?" Although the following examples of types of learning do not form an exhaustive list, they are represented on the diagram and are at least indicative. (The parallel arrows in opposite directions are different but symmetrical, in the sense that exporting differs from importing, although every export is someone else's import; learning is not identical to teaching.)

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, innovations (particularly process innovations), or both; these could include increases of scale.

The vertical arrow between levels 1 and 2 represents the acquisition, resulting from level 1 activity, of experience relevant to the supervisory, managerial, and technical support functions and to other services at factory level. Such staff could be transferred to other factories in the company, 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.

At organizational level, the history of the large US corporation's growth has been explained in terms of the evolutionary advantage conferred by faster or better information transfer within a unified administration than could be achieved between independent entities (see Chandler 1962, and Temin's 1978 review of Chandler 1977). This implies learning at level 3, subsequently propagated to levels 4 and 5.

Similarly, all the arrows in the diagram have their interpretation. At the societal level, one could consider the formal educational system and curricula, capabilities and qualifications of the labor force, social and cultural attitudes to work, government policies affecting industry – in short, all environmental factors that may facilitate or inhibit acquiring, maintaining, and transferring capabilities on each level.

After drafting Figure 2, we discovered a remarkably similar figure in the very different context of *The Active Society,* a major work by the American sociologist, Amitai Etzioni (1968). He describes the "Dimensions of a Macro-Sociology of Knowledge" as follows:

> 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 transferring 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.

The societal environment's relevance to learning is most readily perceived when one considers a company diversifying into an industry unfamiliar to it, innovators 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 the following:

- linguistic and cultural differences
- the absence or cost of creation of physical and administrative infrastructure

- differences in natural environment: climate, terrain, resource endowments
- existing investment in incompatible equipment

Planning feasible trajectories for development requires consideration of sequencing that takes these links and dependencies into account – a point well discussed by Vietorisz (1974), who includes the following questions in his concluding list of primary criteria for technological choices in project evaluation in developing countries:

- What does the project (technical alternative) contribute to institution building? Does it stimulate new skills, new capabilities, new organization?
- Does it lead toward technological autonomy or a perpetuation of dependency, especially on mother companies in foreign countries?
- Does it contribute toward technological integration? Does it help to tie together universities and research institutes with producing enterprises?

Moyes (1979) has usefully illustrated questions of technology transfer from Oxfam case material. He points out that most so-called appropriate/alternative technology organizations start with the technologies of the rich and seek to adapt them for the poor and argues that it might be preferable to help people acquire the skill to improve their own technology or to adapt for themselves the imported technology; local knowledge of local conditions is usually best. This is the transition problem between secondary and primary learning.

> Appropriate technology (which may be simple, intermediate or high) can be developed by outsiders (i.e., people who are not going to use it), but it can only be transformed by insiders – by the people who are going to use it and benefit from it. Failure to appreciate this is a major reason why the very poor do not use more technology.

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, gains are made, as Moyes points out, predominantly in terms of primary learning and plant modifications. 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 as additional manufacturing centers are to be started for the same product, it becomes necessary to institute more systematic training programs and therefore 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 developed in the following ways:

- the primary skills of the experienced direct labor
- the physical equipment, now fully de-bugged, adapted, 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 programs for additional labor (experienced people, written procedures, and appropriate materials)
- blueprints for the physical equipment

These aspects of capability are not confined to the direct work force but may include suppliers of materials, components, and services, who will necessarily have been exposed to the learning process; this is a theme to which we return 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 prudently, some industrialists stress that it represents the *potential* 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 as wholly repetitious as they may at first 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(b), rather than the conventional Figure 3(a), 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

---

*But see Hudson (1980) for progress on the development of robot sheep-shearers!

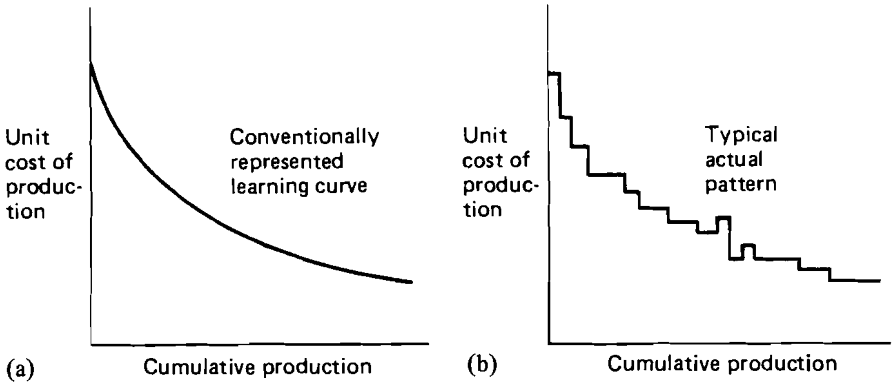

FIGURE 3 Conventional and discrete representations of learning curves.

instance, the earlier period in Figure 3(b) would be characterized by higher frequency of innovation and a larger step size; 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 experience 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 Figure 4, in which Waddington (1973) 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 in fact experiment (with remaining surfaced and fighting back, for example), and there was a technological battle of radio detection and listening devices. 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 *pressure* 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. In his final summary, Waddington identifies this aspect as one of the two most important lessons (the other being adequate staff) of the wartime experience:

> . . .the entire development of the complex and interrelated body of scientific doctrine was guided at every step, not solely by the scientists

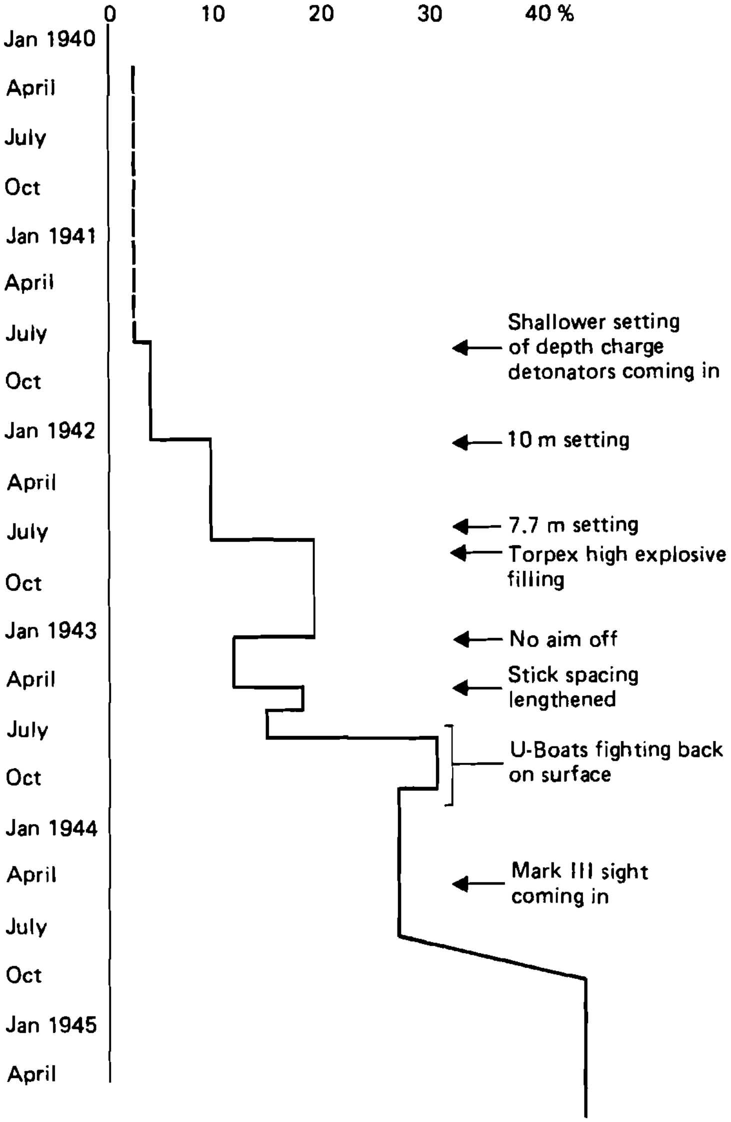

FIGURE 4 Percentage lethality of attacks against surfaced U-boats during World War II.
SOURCE: Waddington 1973.

> 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 Staff 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 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 stepwise pattern of Figure 4 by a continuous curve, it might provide a simpler mathematical model, but it is clear that we would not only be losing "random noise" but might also be losing specific understanding of the nature of the process.

Our discussion thus far has been primarily in terms of manufacturing capability. Most of the well-documented studies in the literature have reported and quantified learning effects at this level. 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 there included a broad range of actors, from the pilots and crews in the aircraft, to the base commanding officers and headquarters strategists, and the scientists of the operational research section. It thus spans several of the levels of Figure 2, and the experience went further still.

The postwar diffusion of operational research in the UK reflects the conclusion, by those closely involved with it in the military context, that they had acquired or stumbled on 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 on these levels, age and experience are the appropriate routes to the 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

---

*From Waddington 1973. Reprinted by permission of the estate of the late C. H. Waddington.

validity to be 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 available evidence to the contrary, 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 by 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 found within one organization; the network includes suppliers and suppliers' 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 various materials characteristic of this manufacturing activity or the flows of information associated with this manufacturing. Where the information flows, so does the potential for learning.

Let us suppose that we have a certain complex product whose manufacture requires the manufacture and assembly of several components and subsystems.

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

If the whole product is changed – to produce higher performance or other changed attributes, for example – the change must be achieved by changing one or more of the components or subsystems. If we consider a wide range of possible types of change, we are likely to discover that changes in one component or subsystem 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.

In considering technological capability, particularly for complex manufactures, it is important to recognize this inherently network-like characteristic. Some of its significant implications include the following:

- 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 demands that are unfamiliar, infeasible, or both) (Vietorisz 1974).

The relationship of the network character of capabilities to the previously discussed concepts of learning and multilevel information transfer will be evident from the discussion that follows.

5 POLICY IMPLICATIONS AND ILLUSTRATIONS

5.1 Specialization and Flexibility

Primary learning at level 1 has close similarities to the biological model of functional specialization for increased efficiency in the individuals of a species. Survival and prosperity also depend on the joint behavior of the species in its living activities, and the evolution of patterns of 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. First, as physical plant becomes progressively more specialized, it is by definition becoming less capable of being used for any other type of production.

Second, 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 the justification for their status; they may therefore naturally become increasingly reluctant to abandon them and resistant to radical innovation.

The 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. Authors in a variety of disciplines have used many words for the latter ability – resilience, robustness, defensive flexibility. 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 multiengine plane.

In manufacturing organization, flexibility in the face of shocks can be consciously developed in many ways, such as second sources for all key supplies (i.e., redundancy in the capability network – sound ecology) and 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 Table 2. For simplicity, we suppose some single measure of performance related to survival, such as food-gathering efficiency.

For example, Group A could be illustrated by African populations containing the gene which (if present in both parents) leads to sickle-cell anemia in the offspring; this disadvantage has not led to the gene's elimination by natural selection because the gene offers greater resistance to malaria. Where malaria has been eradicated, the incidence of the gene is predictably declining (e.g., among the population of African origin in the US), this element of "flexibility" no longer having any advantages to offset its "cost."

At the level of the organization, a discussion of how to describe, and what constitutes, strategic flexibility leads naturally into the literature of strategic planning and management.

An analysis of the elements of strategic capability will clearly tend to be dominated by physical plant capabilities and locations and by financial resources, but both the plant and the existing skills of personnel represent the physical and human forms of know-how. In the broadest sense, then, the processes of learning are seen as central to the processes of survival and strategy.

TABLE 2 Illustration of the relationship between performance capability and the characteristics of the environment.

Performance characteristics	Environment 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

The strategic significance of a weak information strategy is 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 viewed as the *only* form of effective learning, this 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.)

Other countries' more deliberate development of formal technical education – for example, 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 social prestige of institutions responsible for technical education and with the processes of secondary learning. As another Royal Commission commented in 1884 about 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 both from employers concerned with the secrecy of their processes and from trade unions concerned with the protection of their crafts, practical instruction was to be excluded from technical education. After seven attempts, the Technical Instruction Act reached the statute book in 1889. 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 to, qualitative change and the broader context. As part of the process of sharpening perception of technological change, we suggest 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. This is the basis and objective of technological forecasting.

Other points following from our analysis include (1) the desirability of incorporating a technological dimension in strategic decision making and (2) the need for a quantitative and structured perception of one's local competitive and strategic position.

The policy applications of improved understanding of the processes of technological innovation, improvement, and learning exist at each level, as follows. (Items 1 and 2 are in fact better viewed as a continuum than as intrinsically different.)

1. Improving the operational efficiency of producing an existing product.
2. Planning and controlling development effort on introducing "new" processes and products.
3. Making strategic choices of direction in developing 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 that collectively constitute the capability to operate in the chosen sector. Item 3 may be interpreted, *mutatis mutandis,* 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 supranational grouping
   - world society

Clearly, however, the structures for organizing efforts and coordinating them vary enormously between these eight groupings.

Conflicts between these functions will probably arise, the strategic desirability of abandoning a sector conflicting with the tendency of those operating within it to seek resources for improving their performance.

At societal and indeed at global level, we may expect a changing balance between the strategic significance of *capability* and of *natural resources.* 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. Such global long-term studies as the Organisation for Economic Co-operation and Development (OECD) "Interfutures" (1979) suggest that the developed industrial countries can maintain their position, employment, and living standards only 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 that 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 advantage in years of experience or cumulative output will see this initially wide performance difference diminish to insignificance. If the leader stagnates in technological complacency, he will be overtaken.

A more stable and sustainable long-term pattern will be achieved by developing the capability to create the sophisticated products and services of a rich life-style from widely available common and renewable resources. The long-term future will depend on such capabilities as genetic manipulation and biotechnology rather than on indefinitely continuing discoveries of convenient resources. The latter are inexorably diminished by exploitation, whereas information, capability, and education are amplified by their propagation and use. The long-term balance of advantage thus returns to capability.

REFERENCES

Abdulkarim, A. J., and N. J. D. Lucas (1977) Economies of scale in electricity generation in the United Kingdom. Energy Research 1:223–231.

Anonymous (1979) North Sea oil: learning curves. Economist, 10 February, 270(7067):110.

Anson, D. (1977) Availability of Fossil-Fired Steam Power Plants. Electric Power Research Institute Special Report. FP-422SR.

Ball, D. F., and A. W. Pearson (1977) Influence of increasing size of metallurgical plant on process-contractor economics. In Advances in Extractive Metallurgy. London: Institution of Mining and Metallurgy.

Barnett, C. (1978) The Human Factor and British Industrial Decline: An Historical Perspective. London: Working Together Campaign.

Bertalanffy, L. von (1951) Problems of general system theory. Human Biology 23:302–312.

Bertalanffy, L. von (1968) General System Theory. New York: George Braziller.

Bonner, J. T. (1952) Morphogenesis: An Essay on Development. Princeton, New Jersey: Princeton University Press.

Calleo, D. P., and B. M. Rowland (1973) America and the World Political Economy: Atlantic Dreams and National Realities. Bloomington and London: Indiana University Press.

Cantley, M. F. (1979) The Scale of Ethylene Plants: Background and Issues. WP-79-43. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Cantley, M. F., and V. N. Glagolev (1978) "Problems of Scale" – The Case for IIASA Research. RM-78-47. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Chandler, A. D. (1962) Strategy and Structure: Chapters in the History of the American Industrial Enterprise. Cambridge, Massachusetts and London: MIT Press.

Chandler, A. D. (1977) The Visible Hand: The Managerial Revolution in American Business. Cambridge, Massachusetts: Harvard University Press, Belknap Press.

Comey, D. D. (1974) Will idle capacity kill nuclear power? Bulletin of the Atomic Scientists, November:23–28.

David, P. A. (1970) Learning by doing and tariff protection: a reconsideration of ante-bellum United States cotton textile industry. Journal of Economic History 30:521–601.

Etzioni, A. (1968) The Active Society: A Theory of Societal and Political Processes. London: Collier-Macmillan and New York: the Free Press.

Fisher, J. C. (1978) Size-dependent Performance of Subcritical Fossil Generating Units. Palo Alto, California: Electric Power Research Institute.

Fisher, J. C. (1979) Optimum size of subcritical fossil-fueled electric generating units. Paper presented at IIASA workshop, Size and Productive Efficiency – The Wider Implications, 26–29 June. In Buzacott, J. A., Cantley, M. F., Glagolev, V. N., and Tomlinson, R. C., eds., Scale in Production Systems. Oxford: Pergamon Press. To be published.

Fores, M., and A. Sorge (1978) The Rational Fallacy. Discussion paper. Dp/78-84. Berlin: International Institute of Management.

Friedman, G. (1977) Large petrochemical plants are using tomorrow's concepts. Oil and Gas Journal, 12 December:80–84.

Gold, B. (1974) Evaluating scale economies: the case of Japanese blast furnaces. Journal of Industrial Economics, September:1–18.

Gold, B. (1979) Scale, technological change and economic effects: some empirical bases for revising prevailing concepts. Paper presented at IIASA workshop, Size and Productive Efficiency – The Wider Implications, 26–29 June. In Buzacott, J. A., Cantley, M. F., Glagolev, V. N., and Tomlinson, R. C., eds., Scale in Production Systems. Oxford: Pergamon Press. To be published.

Gould, S. J. (1979) Another look at Lamarck. New Scientist 84(1175):38–40.

Hedley, B. (1976) A fundamental approach to strategy development. Long Range Planning 9(6):2–11.

Hedley, B. (1977) Strategy and the "business portfolio." Long Range Planning 10(1):9–15.

Hudson, Paul (1980) Technology brings home the wool harvest. New Scientist 87 (1218): 768–771.

Lee, T. H. (1977) The case for evolutionary optimization. In Future Strategies for Energy Development: A Question of Scale. Proceedings of Oak Ridge Universities Conference, Tennessee, October 1976.

Liddell Hart, B. H. (1970) History of the Second World War. London: Cassell.

Malpas, R. (1978) As reported in "Plant-after-next" will use much less energy. Financial Times, European Energy Report, 20 June.

Mao Tse-tung (1937) On Practice. Peking: Foreign Languages Press.

Moyes, A. (1979) The Poor Man's Wisdom: Technology and the Very Poor. Oxford: Oxfam.

Musgrave, P. W. (1964) The definition of technical education, 1860–1910. Vocational Aspects of Secondary and Further Education 16(34):105–111. Reprinted in Musgrave, P. W., ed. (1970) Sociology, History and Education. London: Methuen.

Pearson, A. W. (1978) Review of selected information transfer studies. Paper presented at the NATO Advisory Group for Aerospace Research and Development (AGARD) Technical Information Panel's Specialists' Meeting, Paris, 18–19 October. To be published.

Sahal, D. (1978) Evolution of Technology: A Case Study of the Farm Tractor. Discussion paper. Dp 78-99. Berlin: International Institute of Management.

Sahal, D. (1979a) A theory of evolution of technology. International Journal of Systems Science 10(3):259–274.

Sahal, D. (1979b) A theory of progress functions. Transactions of American Institute of Industrial Engineers 11:23–29.

Sahal, D. (1979c) Recent Advances in a Theory of Technological Change. Discussion Paper. Dp 79-11. Berlin: International Institute of Management.

Spencer, D. L. (1970) Technology Gap in Perspective. New York: Spartan Books.

Temin, P. (1978) Chandler's *The Visible Hand.* Bell Journal of Economics 9(1):297–303.

Thompson, D'A. W. (1917) On Growth and Form. Abridged edition (1969) by J. T. Bonner. Cambridge: Cambridge University Press.

Utterback, J. M. (1978) Business Invasion by Innovation. MIT report. CPA/wp-78-13. Cambridge, Massachusetts: Massachusetts Institute of Technology, Center for Policy Alternatives.

Utterback, J. M., and W. J. Abernathy (1978) Patterns of industrial innovation. Technology Review 80(7):2–9.

Vietorisz, T. (1974) Diversification, linkage and integration focus in the technology policies of developing countries. Pages 57–77, Transfer of Technology for Small Industries. Paris: Organisation for Economic Co-operation and Development.

Waddington, C. H. (1973) O. R. in World War II: Operational Research Against the U-Boat. London: Elek Science.

Woodhouse, G., D. Samols, and J. Newman (1974) The economics and technology of large ethylene projects. Chemical Engineering, 18 March: 72–85.

Yelle, L. E. (1979) The learning curve: historical review and comprehensive survey. Decision Sciences 10(2):302–328.

THE AUTHORS

Mark F. Cantley was a research scientist at the International Institute for Applied Systems Analysis, Laxenburg, Austria from January 1978 to October 1979. He is now with the "FAST" team (Forecasting and Assessment in the field of Science and Technology) in Directorate-General XII (Research, Science and Education) of the Commission of the European Communities, Rue de la Loi 200, Brussels, Belgium.

Devendra Sahal is a research fellow at the International Institute of Management, Platz der Luftbrücke 1-3, D-1000 Berlin (West) 42.