Brussels, November 1984.

NATURAL EVOLUTION AND TECHNOLOGICAL INNOVATION [♦]

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SYNOPSIS

A metaphor for the innovation process could be derived from analogies with the biological evolution.
The basil ingredients of the metaphor are the following:

- a process for generating ideas or inventions characterized by creativity and chance;
- a "storage container" where inventions can be accumulated;
- a "duct with an on-off valve" which connects invention storage to the selection device;
- a "selection machine" to test the inventions, accepting only those which are fitted to the “environment”.

The metaphor can be applied to understand different aspects of the complex technological innovation process, such as:

- the development of scientific knowledge;
- the diffusion of innovation in given product sectors;
- the long-term innovation changes in industrial sectors.

The technological innovation process can be viewed as a complex system arranging hierarchically different subsystems, each one having the characteristics of an “open system”. The metaphor suggests that each open system shows an intrinsic dynamic behaviour: it goes through a series of expansion of a logistic type followed by “catastrophic” changes. The interaction between the open subsystems (the basic research, the applied research-subsystem, etc.) in the global innovation process, is at the basis of the appearance of new innovation waves.

In respect to former interpretation of the long term (Kondratiev) waves, the metaphor suggests possible effects due to the penetration of scientifically based knowledge in the realm of empirically based knowledge, in line with a precise characterization of the “technological progress” (derived from the analogy with biological evolution), i.e.: the ability to manage increasingly complex structures, by means of an increasing ability to process information.

Speculative scenarios could be developed using the metaphor as an heuristic tool. The “progress” characteristics can be traced in the development of materials (the use of composite materials requires greater ability to process information), in products satisfying primary needs, such as automobiles (ability to interact with “intelligent” traffic control) and in services (new product opportunities coming from the diffusion of new complex infrastructure, such as telecommunications).

The metaphor could also be applied to address the problem of planning of R&D. The model of a rational approach on R&D planning - based on project-by-project selection to optimise some utility functions (the reductionist approach) - is far from being realistically applicable because of the intrinsic uncertainties in the R&D systems. It is especially so in time of large changes. A more holistic approach is suggested, that is based on the ability to grasp complex patterns emerging from the socio-economic-technical world.

[♦] Paper presented at the
R&D Management Conference “Can Europeans Manage The New Technology?”
Organised by Management Centre Europe, Brussels, 12 – 14 November 1984

The metaphor, by the general indications it gives on the patterns of the technological innovation process, will then help in developing the ability to grasp them. This will help to develop a base for R&D planning and decision making.

To show the case an example is given: the importance of considering the intrinsic time constants of the different technological subsystems (e.g. the time to design a product, the time to review the capital investments, etc .) and their interactions.

A first simple exercise is developed, concerned with the application of this general line of thinking to the problem of resource allocation in R&D. Another application of the metaphor is on the debate of the changing role of R&D in the company, when passing through a major technological crisis, which leads to a change of the technical system.

1. What cultural paradigm for R&D Managers ?

The prevailing cultural paradigm in physical sciences is that of the linearity of cause-effect, reversibility, determinism limited by our ability to have a detailed "microscopic" knowledge of cause-effect relationship, and - for complex systems - to know the "state of motion" of every one of its components. Macroscopic irreversibility is therefore considered as the result of the need to take a statistical view at macroscopic level. Complex systems might show collective modes in their dynamic behaviour as if they responded to finality. Nevertheless a perfect knowledge of the “microscopic state” of the system explains such collective modes. The typical case is that of the vibration of molecules on a string: considering each one as an elementary spring, one can set up the system of equations that describe the state of motions of all the molecules to find out that, after a transient period, they all will move according to a fundamental collective mode of vibration.

This cultural paradigm leads in philosophy to the so-called "reductionist approach" in the quest to develop the frontier of knowledge. No matter how complex is the system we are investigating the knowledge of its behaviour can be "reduced" to the knowledge of it's elementary components and their relationship.

The reductionist approach has pervaded all the natural sciences, including biology and social sciences. In economy the approach has resulted in the development of marginal theory with rational behaving operator. Today the biggest challenge for the reductionist approach is that of the understanding of the behaviour of human mind. Could such global pattern of behaviour as the origination of idea be "reduced" to the detailed understanding of the mechanism of the firing of neurons in the brain ?

The alternative philosophical approach is the so-called “holistic approach”. Here the globality of the system enters as an irreducible characteristic in the behaviour of the-system. The analysis of the set of vibrations which composes a melody will never explain why just a small variation in one of the components will change a melody in a cacophony: the fact that small variations in the "microscopic" causes might have large effects, contradict the very basis of the physical sciences cultural paradigm. In recent years the question of the possibility to “reduce” the understanding of irreversible phenomena in thermodynamics to an intrinsically reversible microscopic world has been revised. First of all the “elementary” components of a thermodynamical system, the molecules are quite complex systems on their own, with a dynamic behaviour responding to their own internal time. Macroscopic irreversibility might therefore not simply be the results of the need to take the average over several molecules, but there might be an intrinsic microscopic irreversibility.

The difficulties to reduce the understanding of macroscopic behaviour to the microscopic one, are particularly evident during such "catastrophe change" as the transition of phase. Referring back for analogy to the case of the string, we could explain the macroscopic characteristic of a solid (e.g. elasticity parameters) assuming a certain “elementary model” of relationship among its constituent atoms. However, such an elementary model will not be able to explain the macroscopic characteristics of the same material when passed from the solid to the liquid state.

The conclusion we should derive, up to this point, to be of concern with our interest in the understanding of such a complex system as R & D is that at least one should consider that there are strong limits of validity when applying the reductionist approach. What cultural paradigm therefore for a R & D manager ?

2. Tools for complex system behaviour understanding.

When trying to understand the behaviour of complex system, there seems to be a fundamental asymmetry between understanding a given system behaviour using the power of analysis from trying to construct and predict future system behaviour using the method of synthesis. An interesting analogy of such asymmetry might be the one of the play of chess. At the end of a game, having taken note of all the successive moves, one could go backwards and analyse each preceding move finding reasonable explanation for each of them. Stopping the backward analysis at a certain stage and going forward by actual replaying, the game will very hardly reproduce the same sequence of successive moves. The backward analysis could have not helped much in trying to predict the sequence of the new game.

When dealing with system as complex as social system, whose elementary components are as difficult to reduce to an elementary model as are human beings, should we therefore renounce to use the power of analysis and of synthesis to help us to better manage the system, taking advantage of a better understanding of its behaviour ? Fortunately not. First of all we have seen, by analogy with other complex systems, that there are conditions, when the system is far from large or "catastrophic" changes, where the reductionist approach could be applied. We should not therefore disregard - as of no meaningful use - all the tools which have been suggested in the literature for a rational management of the R & D system (project selection, technological forecasting, etc...). But we should well be aware that the validity of the methods ceases completely in case of large transition in the environment of the enterprise (large economic crises) or internal to the enterprise (change of strategy, restructuring, changing role of the technology, etc.). The second question is: how can we detect if we are in a transition period or, better, can we predict when we will be in a transition period? And, furthermore, during such transition period are any methods available to help us in better managing the system by a better understanding of its behaviour?

It could help us in restoring a certain confidence that there might be a positive answer to such questions to analyse the case of complex physical system undergoing “catastrophic” changes or "bifurcation" changes due to changes in some parameters external to the system (environment changes).

An example of such a system is that of a laser. The external parameter is here the intensity of the light exciting the laser atoms. The dynamic mode of behaviour of the atoms is that of random secondary light emission up to a certain level of the external source intensity. Above such a level a sudden change in the dynamic behaviour of the system appears, all the atoms emitting secondary light according to a collective mode. The case can be treated mathematically. The interesting fact is that the same treatment can be extended to explain the behaviour of passing a bifurcation - because of changing in the environment - of several quite different systems both in the physical and biological sciences.

This analogy is exploited in a new discipline called synergetics.

The general description of the system behaviour is the following. Before of the "bifurcation", the dynamic behaviour of the system could be reduced to the combination of certain fundamental modes of collective motions (remember the case of the vibration of the string) whose explanation is reducible to the elementary relationship among the system components. The various fundamental modes can be arranged according to their time-constance. The one with the longer time constant tends to predominate: perturbing the system exciting shorter term modes will induce only temporary transient. The system is “attracted” to the longer-term mode. Approaching the "bifurcation" the longer term modes are the first to become “unstable” and the system transition could be described limiting

oneself to consider such modes. This permits a very strong simplification to the problem of studying the system behaviour across the transition. After the transition, new fundamental modes of behaviour develop which substitute the old ones.
The resulting recipe when trying to understand a complex system undergoing a transition because of environmental change, is therefore that to confine the analysis on studying the longer term mode of collective behaviour of the system.

The case of drastic or “catastrophic” system transition due not, or not only, to environmental change, but to internal changes in their component subsystems (the revolution bottom-up instead of top-down) is less amenable to a formal treatment. Nevertheless the observation of very different open-systems (i.e. systems that interact with the environment exchanging energy, matter and information) shows that they have a common type of dynamic behaviour: the system increases in complexity exploiting the potentiality of its present structure up to a point, where it undergoes a catastrophic change from which it emerges with a new structure, the basis for a new expansion period.
The theoretical underpinning of such a statement is lacking - at a difference with the case of physical system under environmental change - and the model can be considered only an heuristic tool. Its validity is based on the analogy, in the description of behaviour of quite different complex open-systems.
To describe the model one could refer to a given open-system which is the best studied, whose pattern of development could then be taken as a paradigm. Such a system is that of biological evolution and we refer to it as a metaphor for the understanding of the change in the technological system, i.e. technological innovation.

3. Why the biological evolution metaphor

A description of the metaphor, the basis for the comparison with the biological evolution, and the use of the metaphor to derive some general conclusion on the technological innovation system behaviour is given in the paper “Applying the biological evolution metaphor to technological innovation" [1]. The remarks above are here given as an introduction to that paper to stress the need of a new frame of thinking for R & D manager, which does not discard the rationalistic approach of R & D planning and management, but sets severe limits to its use. There are historical times when the most appropriate quality of a R & D manager is that of analysis and there are other times where a more global, intuitive, synthetic approach is needed. How many of the difficulties of getting the most out of R & D investments are related to out-of-phase R & D management characteristics?

To better understand it, let us assume that management performs the role of an instrumentation and control (IC.) system. It is possible, for an IC. system - notwithstanding the time delays between detecting the signals from instrumentations and operating the actuators - to maintain the system in dynamic equilibrium (homeorhesis) when the input variables increase uniformly. When the external variables suddenly change, then the delayed response of the instrumentation and control system will produce an oscillatory behaviour.
This naive metaphor stresses the point that a man-made instrumentation and control system behaves rationally: it takes the signals, it elaborates them predicting future states of the system and, according to some optimisation rule, it produces feedback actions. To design a control system that avoids large oscillations in case of large input changes, it is a difficult art.
One should be able to design the “logic” of the control so that it changes behaviour during

[1] *Futures, December 1983, p. 463*

fast transients, from a rational to an “irrational” or better, a different level of rationality. As a matter of fact, adaptive control systems that have an internal learning system capable to recognize patterns are developed.

This need to change behaviour is recognized also in the economic system: when large economic changes characterize the prevailing mode, then Schumpeterian economists emerge to emphasize the role of the entrepreneur, capable to deal with high uncertainties, with respect to the classical economy concept of the rational operator as a profit maximizer.

4. The case of decision making for R & D investments.

While in the accompanying paper the biological evolution metaphor is exploited to get general ideas on the technological innovation process we will use here not so much the specific metaphor but the basic change in "cultural paradigm" to discuss the case of decision making on R & D investment.

Uncertainties are intrinsic to the economic system but it is the more so the more one moves back from market to production, to development, to research. Even in the case that the general economic situation is predictable and the company is following a steady growth course of development, it is difficult for the company management to behave rationally with respect to research projects, especially when dealing with radical research projects. In other words, to look at research projects for their profitability - as with capital investment projects - and decide in a well balanced strategic plan how much of the available resources should be allocated to research projects on the basis of the expected contribution to long term company growth.

As a matter of fact, it seems that the game of project-by- project resource allocation in research is seldom played at the different echelons of the company management hierarchy.

The top management might be satisfied with having delegated to the research management level this rational behaving approach.

We do not enter here into a detailed discussion to what an extent this actually happens.

In any case, top management with all its strategic staff support has a direct responsibility with respect to research, i.e. that of deciding the total amount of resources that are devoted to research and development.

Even limiting the present discussion to this apparently simpler issue of the global resource allocation to R & D, one can still question to which extent this decision could be taken rationally, if it is not possible, at least at the level where the decision is taken, to analyse the return of R & D considered as an investment.

The holistic approach reintroduces a certain degree of rationality by assuming that the different echelons of an hierarchical management system decide on the basis of the <u>patterns</u> of information and signals <u>that emerge from the system</u> at their corresponding level.

Typically, at the top of the company one pattern that emerges is that of the research intensity (measured, f.i., by the ratio of R & D expenditure to company sales) characteristic, at a certain moment of time, of the industry in which the company operates.

R & D as an investment is therefore a less analytical project-by-project concept and a more synthetic one.

The capability of that high level rational behaviour, based on synthesis perception, is more evident then the patterns are stable and the management has learned to grasp them along the course of company history.

But when environment suddenly changes, the old patterns are no more valid for decision taking and the new ones are not yet emerging. Talking of R & D as an investment, and therefore relaying on some kind of rational management behaviour in time of large business change is therefore an hope- less exercise ?

As we have remarked above, a simplification on the task comes from the possibility to concentrate the attention to the basic mode of behaviour of the system. It is increasingly necessary, in that case, to understand the general mechanism that underlay the research-production interaction or, more in general, the innovation process. By understanding the basic mechanism one might be able to predict the emergence of future patterns, and how to learn not only reading its own system history but also that of different industry systems.

For instance, the fact that a sector whose technological development was mainly based on the development of empirical knowledge - such as e.g. the automotive sector - becomes more and more a scientific knowledge intensive sector (see, e.g., the ability to predict the combustion behaviour in an engine chamber) should induce to look at the prevailing pattern of R & D investment (such as the ratio of R & D expenses on sales) in sectors (such as, e.g., the aerospace sector) where the scientific knowledge is diffused as the basic determinant of innovation well before than in the automotive sector.

Let us proceed further by considering as a significant global mode that characterizes the R & D system, the R & D yearly spending intensity (R & D expenditure to sales). Such a mode shows a quite stable behaviour within a given industrial sector. Referring to the sector case is therefore a first guideline for decision making providing the sector is far from major technological transitions.

But even if this condition is satisfied, one company case differs from the other. How to proceed ?

Let us consider the total company expenditures or “investments” which are concerned with the general problem of assuring the company growth, such as: R & D, capital investment, publicity, personnel training, etc.

First of all we are f aced with the problem of finding the optimal subdivision among R & D and all other investments. To understand the “optimisation” problem let us for a moment imagine that the total resources available are unlimited not necessarily then, an increase in the absolute spending on R & D or on the other investments will produce an increased growth, averaged on the years, for the company. For instance, the capability to profit from R & D and capital investments the so-called “technological opportunity", varies from company to company, from an industrial sector to another. Increasing R & D expenditure, beyond certain limits, will therefore result in wasting money.

The situation can be best pictorially synthesized. as in Fig. 1.

Using as one coordinate the R & D intensity and as the other co-ordinate the sum of all the other investments intensities, one can imagine to plot curves of iso-opportunity, i.e. the locus of points that conceptually will produce the same opportunity to grow for a company varying the absolute amount of investments and the relative allocation between R & D and other expenditures. Curve A-A might be characteristics of a given industrial sector and B-B of another. The optimisation problem corresponds to that - giving a fixed amount of total intensity, say a - of how to best subdivide such total amount between the two investments. The solution is the tangent point of the straight line a-a to the curve A-A, of co-ordinates (p,q), being p + q = a.

A first target for a corporate R & D strategy is therefore to "grasp" the pattern of iso-opportunity for their company at a given time. From the general behaviour of the innovation process we should expect that such pattern, varies with time and company history: f.i., a company operating under licence in a national market (curve A’-A’) will have not only smaller total resources available, say a', but the optimal allocation will see a lower value for R & D intensity. The growing of the company with increasing profitability and total resources available say a’’, might mean a shifting to another iso-opportunity curve (A’’-A’’), but without changing the relative allocation between R & D and non R & D investments. Changing of technology, such as towards more flexible manufacturing, will tend to increase the product oriented innovation opportunity therefore changing the iso-opportunity pattern (curve A '''-A''') towards a relatively higher R & D intensity.

All the above remarks are very qualitative and serve only to the purpose of defining the heuristics of the R & D allocation problem at corporate level.
One could proceed a step forward and, supposing to have defined the optimal R & D intensity value, say p, to ask how to optimally subdivide it between, e.g., applied research and development or between R & D oriented to product innovation with respect to R & D oriented to process innovation.
For a given company, at a given time of its history, different research iso-opportuníty patterns apply. One can pictorially describe the optimisation problem as in Fig.2. The variability of the iso-opportunity curves in the Rescarch-Development plan is much more sensitive to: the typical business product cycle, the exogenous variables such as macro-economical cycles, the invading new technologies, etc ...

Though very qualitative, as an heuristic tool, we suggest that it might be useful to discuss the R & D Corporate strategy making use of the biologic innovation metaphor with the help of the innovation process model described in the paper referred to at pag.5 and reproduced here in Fig. 3. For instance, when the “selection valve” opens in accordance to the various innovation clocks, it will help management to make explicit the needed temporarily shift towards more development type activities at corporate research centres., even if they usually are designed to play a major role on long term research.

5. Conclusive remarks.

At this point of the state of the research, the message that can be given is only of a qualitative nature.
The very first important objective of the reflections so far is to induce a change of attitude in the research manager. This might, as an important by-product produce a reduction of the gaps that often develop between the corporate officers responsible of general planning - that are used to a rationalistic approach - to the scientists themselves, who know how often irrational, full of intrinsic uncertainties and not amenable to planning is the research.

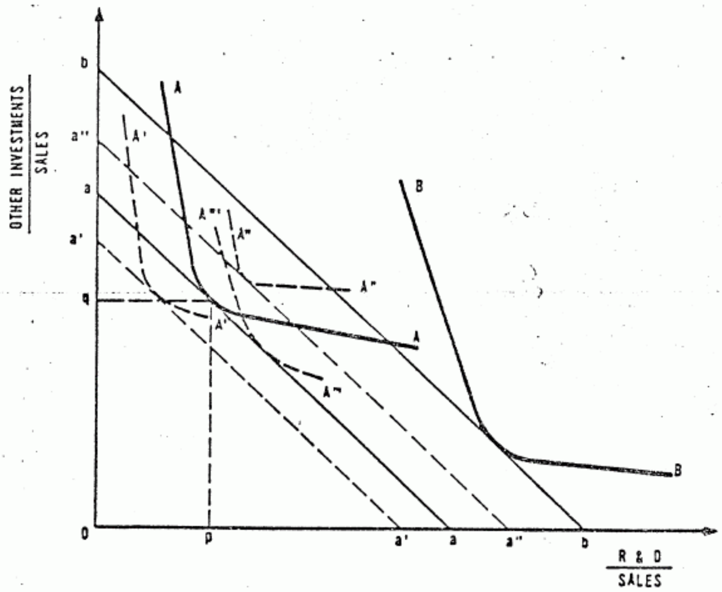


Fig. 1 - OPTIMAL RESOURCE ALLOCATION BETWEEN R & D AND OTHER INVESTMENTS

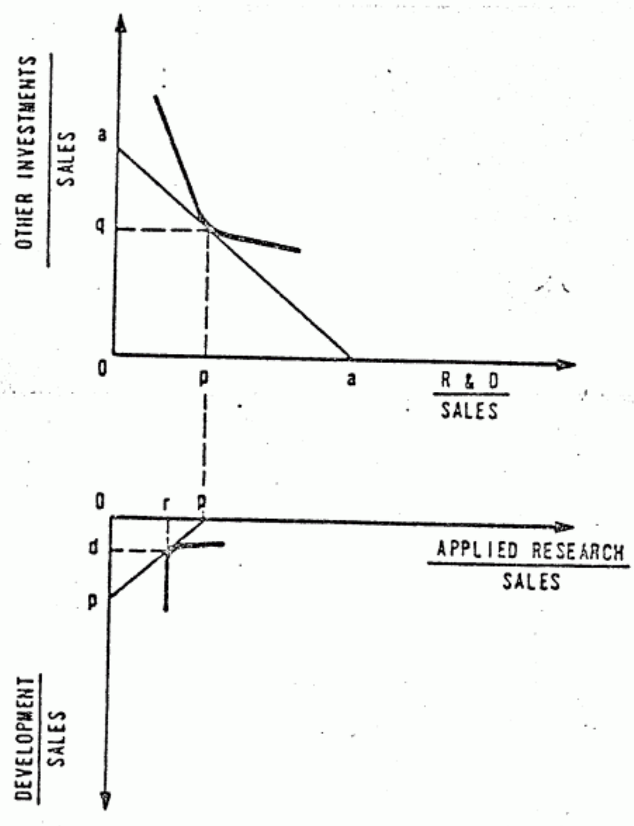
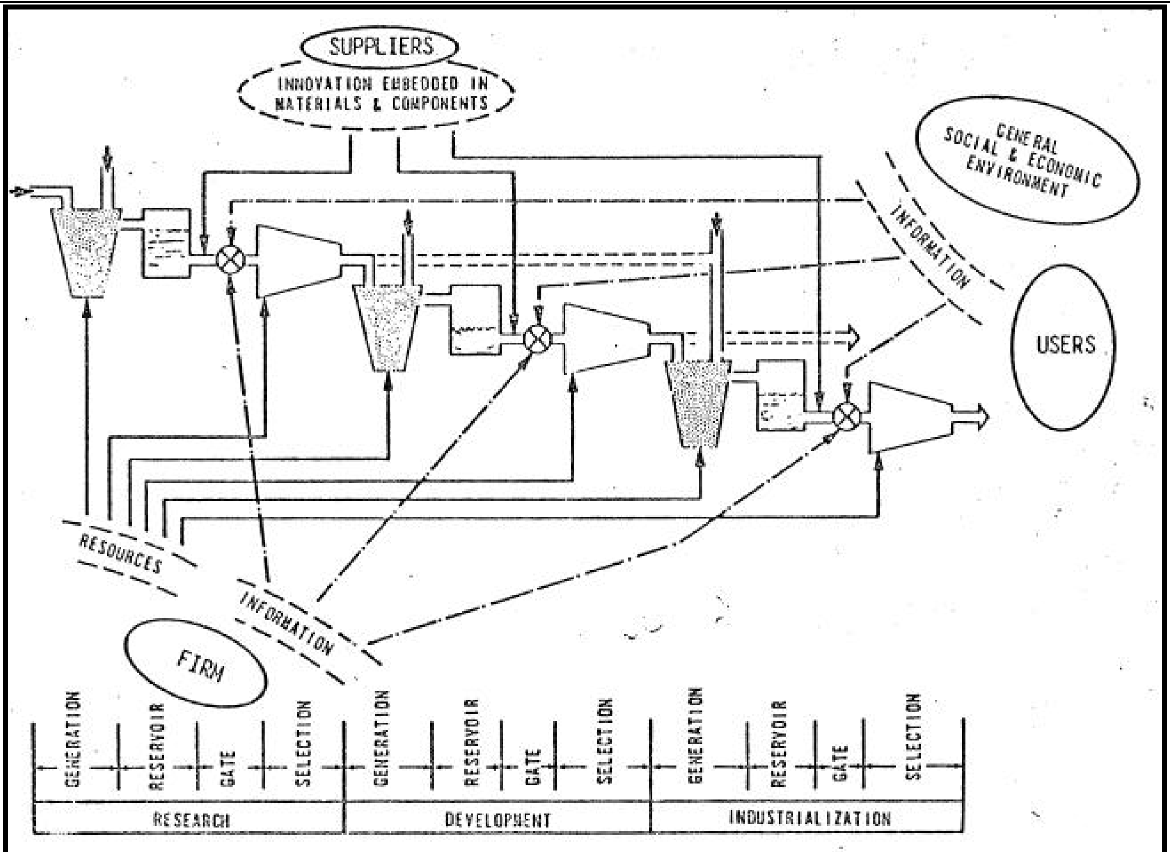


Fig. 2 - OPTIMAL ALLOCATION OF R & D RESOURCES BETWEEN APPLIED RESEARCH AND DEVELOPMENT



ig. 3 - A MULTISTAGES GENERATION SELECTION MODEL FOR THE INNOVATION PROCESS