Preliminary version.
Comments are welcomed.

The Economics and Management of Evolutionary Knowledge Diversification*

by

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Abstract

This paper elaborates on some theoretical issues in economics of knowledge and innovation linked to evolution in terms of growth, diffusion, diversification, relatedness, learning and strategic selection. Properties and idiosyncracies of technical and managerial knowledge and learning in particular and its implications are addressed. Growth and learning by interaction between agents, artefacts and areas of knowledge are addressed as well. Evolutionary knowledge diversification is shown to be conducive to economic growth under certain conditions. Empirical illustrations are given in the context of the firm, in particular a technology-based firm, its strategies and common organizational behavior.

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1. Introduction

Focussing on evolution in and of economies has implied an evolution of economics, with Nelson and Winter (1982) as no doubt a major evolutionary step. Focussing further on economies (of scale, scope, speed etc) in evolution (biological, technological etc.) implies the question whether evolution can be managed. Is 'management of evolution' in fact an oxymoron, an apparent contradiction to which meaning could after all be rendered?

The purpose of this paper is to focus on knowledge diversification in general, and technology diversification in particular, and its implications for economic performance and possible management thereof. This focus is then part of a broader focus on knowledge evolution and its implications for or interaction with economic evolution and the possibilities to influence or manage that interaction. In that connection the paper will raise some general theoretical issues in economics of knowledge/innovation and learning.

2. Concepts

In the diversity of notions of 'evolution' that naturally has evolved there are a few common surrounding conceptions. Thus, briefly (without going into a separate paper) evolution could be conceived of as a particular dynamic, stochastic process with a dominant continuous and endogenous component, leading to states that in some average sense are non-recurring and of higher "value", but without any clear (visible) centralized (in contrast to distributed) control. The process is by and large irreversible rather than stationary, path-dependent rather than ergodic, and its transient behavior is of primary interest.[1] In particular processes with a strong component of cumulation, such as learning, could qualify as evolutionary.

Thus, evolution is typically associated with innovation and progress (new, more valuable states are attained on average) and mainly continuous and directed change (on average).[2]

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[1]Steady state properties (if any) in the utmost long run are of interest to study as well but then from a theoretical point of view, which should not overshadow the study of transient behavior. A case in point is neoclassical and also endogenous growth theory that has focussed on steady state properties, and fruitfully so, but seemingly neglecting the admittedly much harder study of transient behavior, even apparently to the point of ignoring that some growth models are explicitly solvable (see Appendix.)

[2] Just as an example, a book on biological (paleontological) evolution gives a fairly broad definition (using 'trend' for a general phenomenon): "An evolutionary trend is a sustained, prevailing tendency in a phylogenetic progression". (Simpson, 1953, p.245). Nelson and Winter (1982, p. 10-11) says: ..."The broader

The essence of evolution is typically not associated with optimal control and equilibrium, at least not centralized optimization and long run equilibria.[3] Thus the notion of management as the act of influencing (without complete control) people to accomplish common objectives is somewhat at odds with the notion of evolution, at least as far as management is conceived of as involving optimization (even in severely constrained variants).

Essentially, management including entrepreneurship is represented in evolutionary economic theory, as represented by Nelson and Winter (1982), as embedded in organizational routines, a concept which in turn (with some deliberate stretching) also includes e.g. engineering decisions, activities directed towards innovation and strategic decision (or behavior) to the extent that they are regular and predictable in some sense. Viewed in this way management would primarily be interpreted as subjected to evolution, rather than evolution being subjected to management. Although, it is of course possible to view control variables as state variables instead, as done in Nelson/Winter-evolutionary theory (see Winter 1987), there is one important qualitative difference – control variables may very well be only piece-wise continuous, i.e. state variables (for physical systems) typically are evolving continuously. However, it is possible to talk about managing technological evolution in the context of an organization by employing a distinction between technology (being knowledge about engineering techniques in an ordinary sense) and management (being an appointed body of actors in an organization as well as a body of knowledge how to act in such a body).

It is equally possible to talk about managing managerial evolution in the context of the organisation.[4] Admittedly in so doing there is a smack of frivolous rationality at the same time as there is an opening for "infinite regress". (Cf. the saying "evolution is smarter than you think".) Nevertheless, the distinction between technology and management is important and will be made in this paper.

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connotations of 'evolutionary' include a concern with processes of long-term progressive change. ... although we stress the importance of certain elements of continuity in the economic process we do not deny (nor does contemporary biology deny) that change is sometimes very rapid. ... It is neither difficult nor implausible to develop models of firm behavior that interweave 'blind' and 'deliberate' processes.

[3] As pointed out by Nelson and Winter (1982) and others these concepts could be accommodated, although by stretching them so much that they more or less lose their core meaning.

[4] Just think about decisions to promote, demote, recruit and train managers, or to support teaching and research in management. See Granstrand (1982, 1989)

The concept of knowledge in general and technical knowledge in particular will be characterized below with reference to economically related properties, in an attempt to circumvent to some extent a morass of epistemological issues.

As to the concept of diversification finally, it will be used to refer to the process by which diversity of something is increased, or the range of something is extended (by deliberate management action or not). This ‘something’ is in this paper either products (or businesses), markets (typically geographic markets for the same product), applications (for the same product) and bodies (or areas) of knowledge, different technologies in particular, in the context of a firm. Knowledge diversification could also pertain to individuals. In either case it is a special case of learning, special since it presupposes some kind of partition or typology of knowledge (as done in Pelz and Andrews (1966) in their classical study of specialization and diversification by scientists and engineers).[5]

3. Empirical illustrations

3.1 Corporate cases

Diversification occurs at various levels in industry and the resulting diversity of firms and especially artefacts is actually bewildering, see e.g. Petroski (1994) and Sanderson and Uzumeri (1997) for good illustrations at product level. Figure 1 illustrates some types of diversification in the evolution of a particular firm.

5 Pelz and Andrews discover the puzzling phenomenon that individual scientists with a moderate diversity of mastered disciplines are most successful while engineers have two routes to success (in terms of productivity), strong specialization or strong diversification. A possible explanation is that engineers complement each other more through teamwork. The issue of optimal diversity and optimal selection at different levels is thereby raised.

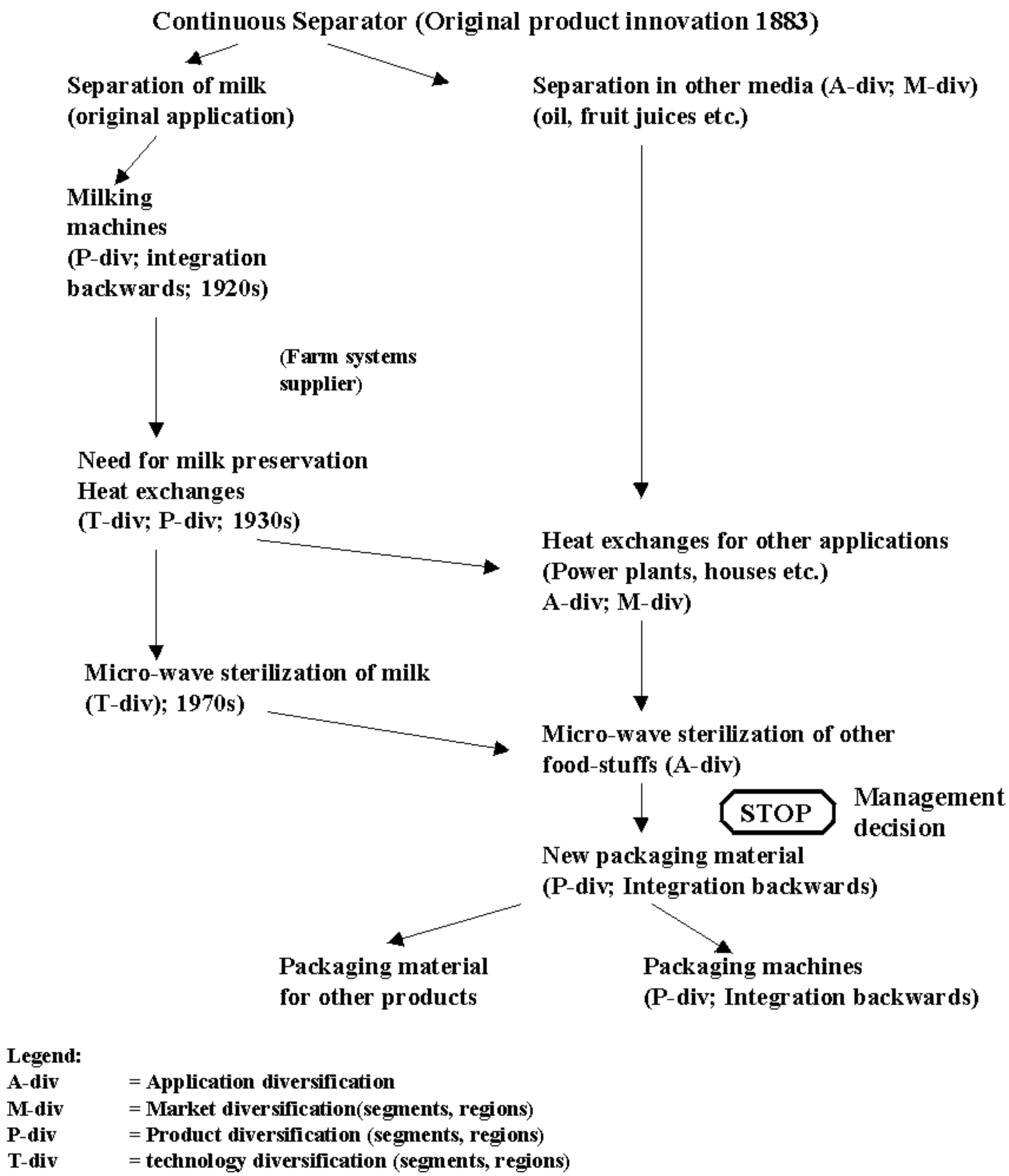

Figure 1. Diversification Tree (incomplete) – Case of Alfa-Laval AB

In a study (Granstrand 1982) of diversification in eight large corporations significant additions to the dominant technology of almost all corporations were found, e.g. generation shifts from carbide engineers to polymer technologists at KemaNobel (then merging into Akzo-Nobel); a series of generation shifts in electrical engineering from vacuum tubes to transistors to integrated circuits to microcomputers at Philips; chemistry, biology, electronics and systems engineering being integrated in mechanical engineering at Alfa-Laval; material scientists had been promoted at SKF; metallurgists and chemists had been added to the 'the mining people' at Boliden; biologists and mechanical engineers had been promoted at Iggesund (pulp and paper); a transition from chemistry to biology had taken place at Astra; and mechanical engineers had been supplemented by various other types of engineers at Volvo. These changes in the portfolio of technological competencies depended on external technological developments and internal conditions such as the rise of advocates or resistance among management and technologists.

Four different kinds of technology diversification were discerned. First, there was a diversification of competencies pertaining to the core technologies of a corporation, for instance, the differentiation of polymer technology or tribology. This was a kind of 'ordinary' specialization within a technology of decisive importance to the corporation. Second, there was a diversification pertaining to adjacent technologies. These adjacent technologies could concern supporting technologies such as automation technology in production, surface chemistry for lubrication in a part of a product or materials technology. Corporate R&D often diversified into adjacent technologies through an initial stage of perception of product problems followed by attempts to solve them by extending internal knowledge, often amateurishly, or hiring external R&D services. Third, there was substitution among different technologies, such as the transition from chemistry to biology in pharmaceutical research. Fourth, a new technology was 'picked up' because of its potential benefit to the corporation or because it will create new businesses (e.g., KemaNobel acquired polymer technology and Astra went into antibiotics).

The diversification into a new technology for new kinds of businesses was quite often evolutionary, with a progression over adjacent or substituting technologies. For example, the need to preserve milk led Alfa-Laval into heating and cooling, in turn leading to heat exchangers, microwaves, the preservation of other types of food and finally to a new packaging technology. Alfa-Laval then decided not to go into packaging. The concept of evolutionary chains is too simplified though; rather, technologies advance along some lines, may then rest until combined with some other technologies, and may then advance a bit further.

Any typology of diversification of technology and R&D is vague, since conceptions o a technology are diffuse and changing. Confluences and combinations occur. Strictly speaking, technology diversification should be considered to decrease if a combination of two technologies gains coherence and recognition. Many corporations encountered different environmental problems in the 1970s and developed counter measures in the form of corrective technologies. New competences had to be acquired, and perceptions of which technologies were adjacent and relevant changed rapidly. Thus the kind of technology diversification triggered by environmentalism is hard to classify. It may not even be considered a diversification at all after environmental technology became recognized as a specific technology . Measurement problems simply are difficult.

3.2 Diversification strategies for growth

Oskarsson (1993) explored if there were certain corporate diversification sequences that were associated with high sales growth. Observations of 57 large multinationals worldwide were classified according to sequences of diversification and specialization of technologies, products and markets. Four main patterns of strategic behavior were identified.

A Fourteen companies[6] followed a diversification sequence of first increased technology diversification, then followed by product diversification and market diversification in this or reverse order. These companies were called “aggressive diversifiers”.

B. Nineteen companies[7] followed a sequence of first increased technology diversification, then either product specialization or market diversification, or its reverse market diversification followed by product specialization. These companies were called “stick to the knitting” companies.

C. Five companies[8] followed a strategy sequence of increased technology diversification followed by product diversification concurrent with market specialization. These companies were called “market specializers”.

D. Eight companies[9] specialized both product-wise and market-wise and sometimes even technology-wise. These were called “defenders”.

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[6] 3M, Astra, ABB, Canon, Digital Equipment, Honda, Kyocera, Matsushita, Motorola, Nec, Sandoz, Sony, Toshiba, and Toyota.

[7] BASF, Bayer, Electrolux, ESAB, DuPont, Ford, Glaxo, General Motors, Hitachi, IBM, KODAK, Thone Poulenc, Pharmacia, L'oréal, Nobel, Ericsson, Unilever, Volvo and Xerox.

[8] Sumitomo, Sanyo, Merck, Nippon Steel and Siemens.

[9] General Electric, Aerospatiale, ICI, FAG, Thomson CSF, Olivetti, Texas Instruments and Philips.

Eleven companies had selected four other strategic sequences, all of them either growing slowly or declining. They had neither rapid increase or decrease in diversification, and therefore they will not b analyzed separately in the following analysis, besides that they are included in the total of 57 companies.

The “aggressive diversifiers” had significantly higher sales growth (in 1980-1990) and expanded their technology base, product base and market base significantly more.

Canon was the company with the fastest growth of all the 57 companies between 1980 and 1990. Canon also followed an “aggressive diversifier” strategy, see Figure 2. A model of diversification in general is then given in Figure 3.

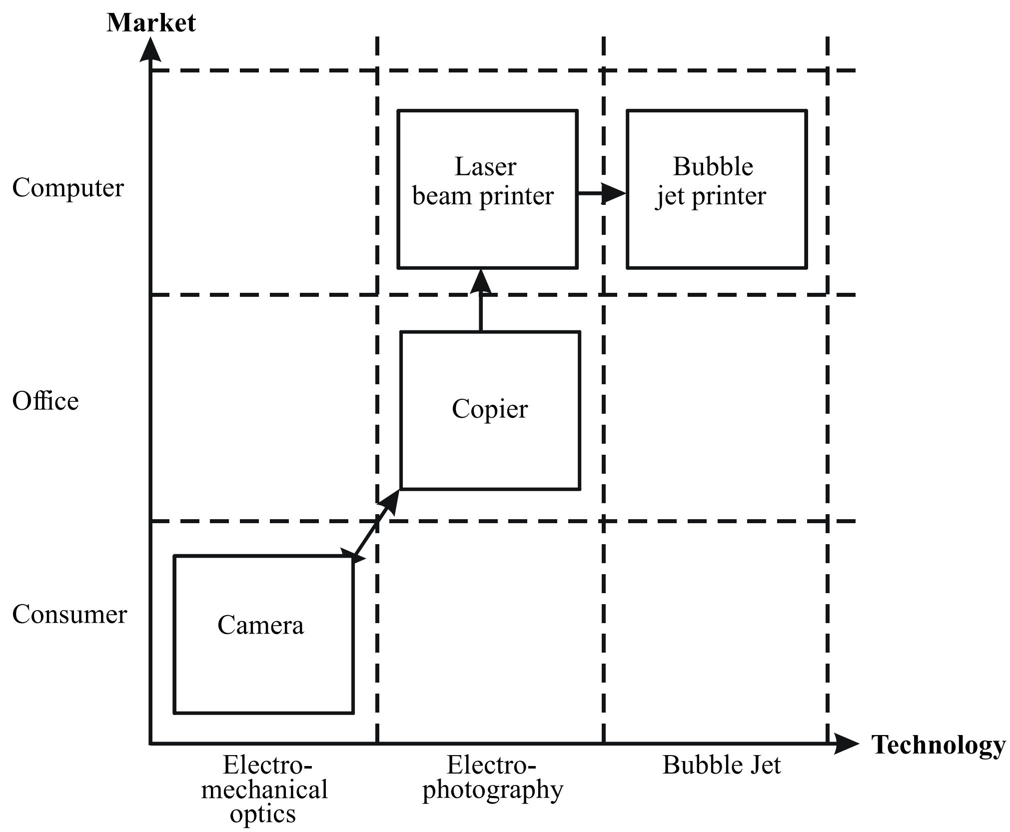

Figure 2. Canon's diversification trajectory.

Oskarsson (1993) tested a simplified and modified (due to lack of data on feedbacks) version of this model for 1980-1990 with results shown in Figure 4.

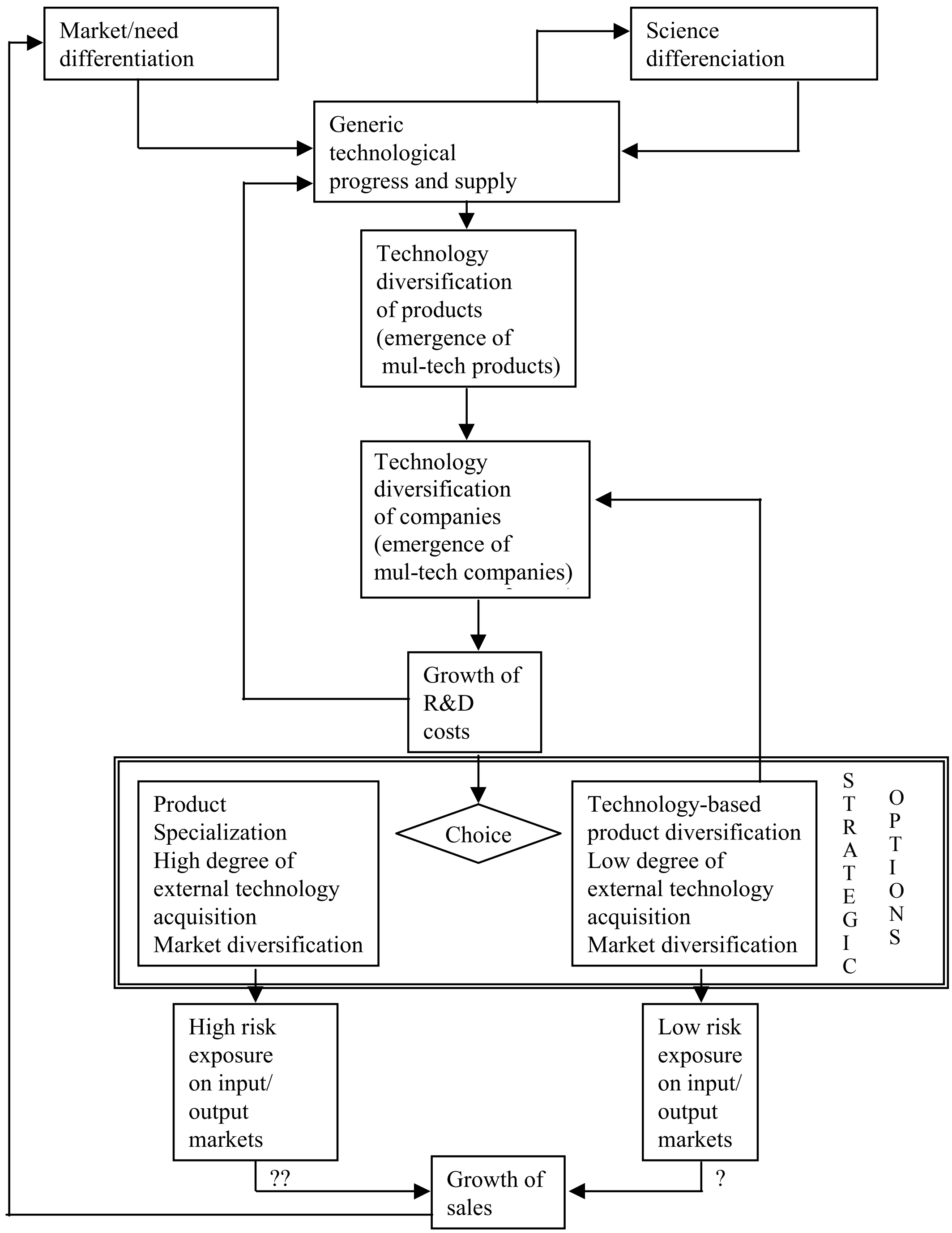

Figure 3. A Strategic Choice for Technology Managemant in "Mul-Tech" Companies

(Source: Granstrand et al., 1992)

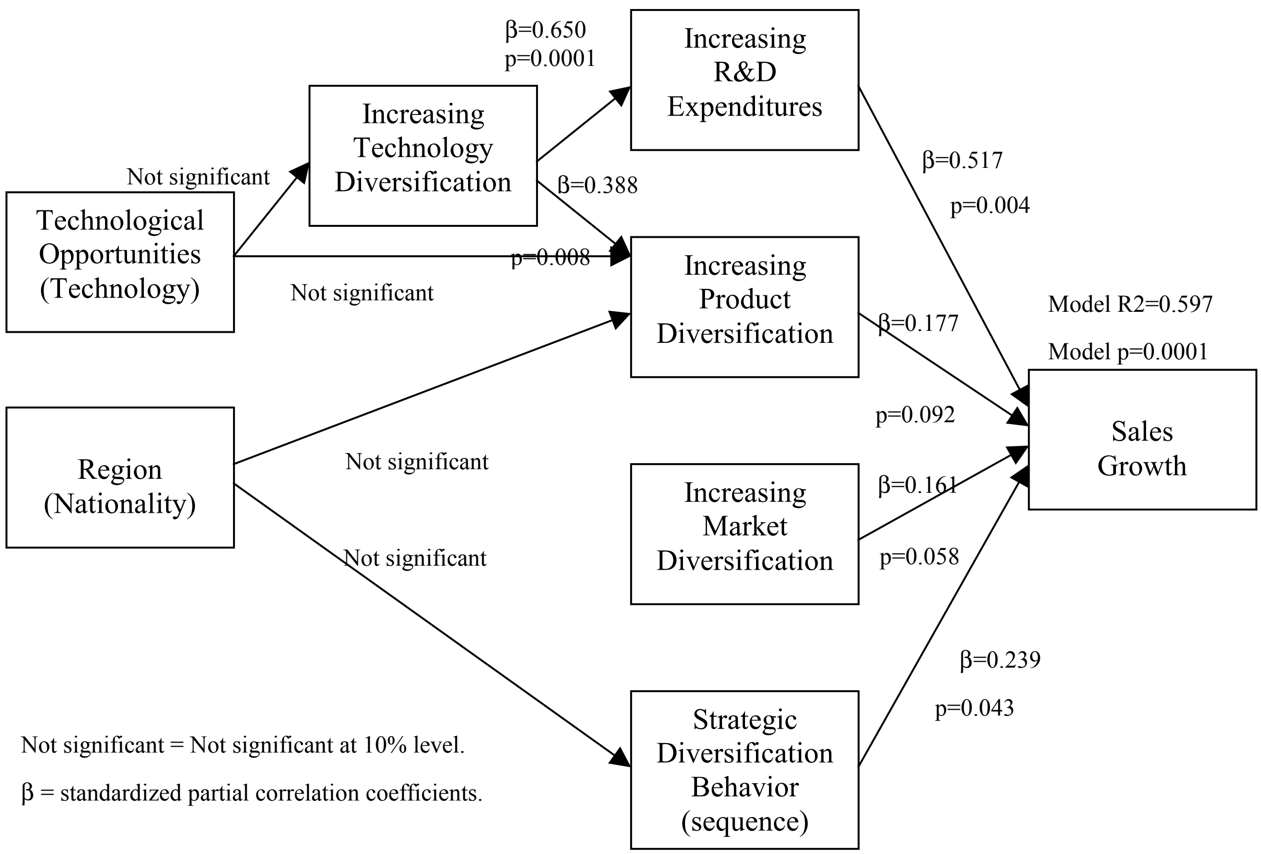

Figure 4. A test of a model for growth and diversification (N=55).

(Source: Oskarsson, 1993)

Technology diversification at firm level was thus an increasing and prevailing phenomenon in all three major industrialized regions, Europe, Japan and US. This finding has also been corroborated by Patel and Pavitt (1994).

Moreover, technology diversification was a fundamental causal variable behind corporate growth. This was also true when controlled for product diversification and acquisitions.[10] Technology diversification was also leading to growth of R&D expenditures, in turn leading to both increased demand for and increased supply of technology for external sourcing.

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[10] This finding has later been confirmed also by Gambardella and Torrisi (1997) for 32 of the largest European and US electronics firms.

These findings were not readily explainable in terms of received theories of the firm. Without going into detail about the pros and cons in using received theories to describe, explain and predict the behavior of technology-based firms, taking idiosyncrasies of technology into account, one can note that technology diversification does not feature at all in received theories. Moreover, most theories do not explicate the dynamics and heterogeneity of technology, and many restrict their focus to process technology.

4. Some theoretical issues

4.1 Biological vs technological evolution

(Most of the following is so far only an excerpt from Granstrand 1994b, pp. 456-460.)
It is well known how economics has drawn on mechanics and biology for analogies, and on mathematics for analysis and theory. Much debate has indicated the pros and cons in so doing, which cannot be reviewed here. Newton and Darwin have had profound impact not only on their disciplines but on the Western "Weltanschauung" on a broad scale, affecting many disciplines, not only economics. Biological analogies have been particularly "sticky" in social sciences, at least since Darwin, and have spurred heated disputes among social scientists.[11] Early advocates among economists include Veblen and Marshall, although on different grounds.[12]

In contemporary economics the transition from mechanical models to evolutionary approaches is long overdue, as Freeman [8] argues. Evolutionary economics is developing with Nelson and Winter [19] as one pioneering work accompanied by several others, e.g.

[11] Most evolutionary schemes in theories of societal development have some underpinnings from plant and animal biology. Exceptions and critics of this fashion include Jürgen Habermas and Anthony Giddens.

[12] Marshall's advocacy has a bit of historic irony. While making important contributions to economics under the influence of Newtonian thinking in mechanics, and Leibnizean thinking in mathematics, his marginalistic and formal utilistic approach triggered criticism by Veblen and the latter's advocacy of evolutionary and behavioral thinking (Veblen [24]). At the same time Marshall also advocated biological thinking and dynamic modelling and planned to continue his work with contributions along such lines but never came to realize his plans. One may also note that Veblen's advocacy of evolutionary economics is primarily a quest for dynamic considerations, as opposed to static ones, rather than a quest for using biological analogies. He saw the developments of biology from a taxonomic to a dynamic science, from Linné to Darwin, as a pattern for economics to follow.

the landmark work of Dosi et al. [6].[13] These developments are often spurred by criticism of the dominance of received orthodox theory, mostly referred to as neo-classical. The relation between neo-classical economics and evolutionary economics has similarities to (the young) Thomas Kuhn's depiction of paradigm shifts or substitution of theories in science, and also similarities to behavior in connection with substitution of technologies (including the "sailing effect"). Some argue that this is only on the surface and that the differences are reconcilable in principle; others argue that they are not, i.e. one has to make a strategic choice between neo-classical and evolutionary approaches in further research. There is a variety of criticism of neo-classical theory (e.g. of optimality and equilibrium concepts) and a variety of evolutionary approaches; see [6] and [21] for examples. Several approaches are inspired by biological analogies. At the same time, technology considerations in economics foster much evolutionary thinking in general.

It is then natural to make a closer scrutiny of what biology can offer economics in general and more specifically if technology is taken into account. A number of works have addressed this issue without reference to technology. There are outright advocates of biological analogies in economics like Marshall [17][14], Hodgson [13] and Hirschleifer [10]. The latter presents a comprehensive comparison of economic and biological systems, which has been further used and modified by Mark et al. [16], and which is comparable with Matthews [18]. A classic critique of biological analogies in economics is Penrose [20].[15] Saviotti and Metcalfe [21] include several papers on the subject and Freeman [8] gives a recent survey. Freeman advocates a seasoned view that economic and biological systems must be compared in order to identify similarities and differences, and that economics can learn something from biology but ultimately has to develop evolutionary

[13] For a historic survey of evolutionary economics, see [4].

[14] See also Hodgson [12] on Marshall's advocacy of biology. An often-cited passage of Marshall is: "It [economics] is a branch of biology broadly interpreted." His preceding sentence (in the margin) is also interesting in this context, however: "But economics has no near kinship with any physical science." (Marshall [17] p. 772, see also p. xiv, Vol. I.) One should not go too far in interpreting this ad verbatim but one may at least observe that an implication of Marshall's two propositions is that the perspectives, methods and developments of all physical sciences are remote from both economics and biology. Contradictory or not, one value of Marshall's propositions rests with their clear provocation of further studies of the issue.

[15] Penrose focuses her criticism on differences between firms as organizations and biological systems. Such criticism is still valid, perhaps even more so, for R&D organizations.

theories of its own.[16] Such a view seems particularly relevant for economics of technology, a view that has also been forwarded by De Bresson [5]. Such views do not, of course, exclude similarities between biological and technological systems (see also [23]).

It is then also natural to compare technological systems with biological systems, and draw implications from the type and degree of similarities and dissimilarities between economic and biological systems. This task must be left for further research. However, the hypothesis is forwarded here that technology considerations weaken the applicability of biological analogies in economics and present some idiosyncratic features to evolutionary economics and its modelling. As a starting point for probing this issue, Table 1 displays some differences between biological and technological systems, differences which also serve to point out the caveats of biological analogies in economics of technology.[17] Such caveats are particularly important when analogies, being non-perfect, become mathematized and economics runs the risk of being carried too far away from its empirical grounds by the forces of mathematics. Mathematics and biology in themselves will certainly continue to develop together in many interesting ways, e.g. in the area of dynamic modelling. But some of these ways may be misleading for economics, as important differences may be suppressed in the abstraction process.[18] One possible guard against such risks, which are aggravated by low empirical falsifiability, is to have a more general and flexible theoretical framework such as a more general systems theory and to critically evaluate biological analogies. This is by no means to argue against evolutionary theorizing, quite on the contrary.

[16] Conversely, biology has to, and does, develop evolutionary theories of its own. This does not preclude applications of economics in biology, e.g. those under the label 'bioeconomics' related to environmental protection. Interdisciplinary work clearly must go beyond the use of analogies.

[17] A reflection near at hand, not least after the discovery of discontinuous genes by Roberts and Sharp, is that genetic technology will in fact change biological systems in the future in ways that will create new similarities with technological systems.

[18] Concepts that originally have been empirically grounded may often be redefined theoretically to increase generality. At the same time the specific empirical features of the concepts become disguised.

Table 1. Examples of Differences between Biological Systems and Technological Systems[1]

Biological systems[2]	Technological systems[2]
Heterosexual reproduction in general	"Promiscuous" reproduction and practically unlimited recombinations of both knowledge and artefacts
Finite life of specimen	Almost infinite life a possibility for artefacts and the rule for knowledge[4]
Spontaneous mutation[5]	Invention by design, not only by default or serendipities
Regular life cycle stages of development of specimen (birth, growth, stagnation, death) and species (formation, propagation, exclusion, extinction)[3]	Irregular and erratic appearance of stages of development

Notes:

1 The exposition of differences is not meant to rule out the possibility of similarities, but to indicate some limitations to the use of biological analogies in economics, deriving from technology. Needless to say, a techno-economic system, which includes human actors and therefore intersects with a biological system, should display some similarities, e.g. certain types of purposeful behavior and competition for scarce resources.

2 It is not obvious what the relevant comparisons are. But this, too, contributes to the scepticism about the value of the analogy.

3 Life cycle conceptualizations tend to creep into economics with a certain ease, e.g. regarding the evolution of firms, products, technologies and industries, perhaps essentially based on the need to divide a temporary process into stages. By its very nature a temporary process has some feature of rise and fall, or emergence and disappearance, since it is temporary. Many times, however, the analogy with a life cycle breaks down when carried further.

4 If knowledge is taken to correspond to genes and different product areas (rather than individual, physical products) correspond to different species the analogy is strengthened but still deficient.

5 The 1993 Nobel Prize winners in medicine and physiology, R. Roberts and P. Sharp, discovered in 1977 what appears to be a powerful biological evolutionary mechanism for higher organisms besides mutation, based on combinations of different segments of genes (so-called splicing). This evolutionary mechanism in turn seems to strengthen to some extent the analogy between biological and technological evolution. That would particularly be the case when splicing is used artificially in bio-genetic engineering. Thus, the strength and usefulness of an analogy may change over time as a consequence, and often as a cause as well, of new discoveries. Similarly, modern physics, which is vastly different from classical mechanics, offers new sets of analogies, although again limited, with its discoveries cast in various stochastic and dynamic frameworks, which are also basically evolutionary.

Nelson and Winter (1982) exposes a balanced position, and have borrowed basic ideas from biology (p. 9) but "emphatically disavow any intention to pursue biological analogies for their own sake, or even for the sake of progress toward an abstract, higher-level evolutionary theory that would incorporate a range of existing theories." (Nelson and Winter 1982, p. 11.) In stark contrast with (contemporary) biological theory the Nelson/Winter economic theory is "unabashedly Lamarckian" (p.11). At the same time their three basic concepts for their evolutionary theory of economic change, i.e. organizational routines, search and selection environment, are explicitly tied to basic biological concepts. Thus, Nelson and Winter (1982) let routines be the counterpart of genes and routine-guided, routine-changing processes – modeled as searches – be the counterpart of mutations in biological evolutionary theory (Nelson and Winter 1982, p. 14,18,134) and a selection mechanism in the economy function as the counterpart of natural selection of genotypes in biology (Nelson and Winter, p. 17).

So given, the (ever-changing) similarities and differences between economic, technological and biological evolution, and the after all fairly strong association between economic and biological evolutionary theory, where can biological analogies lead us into wrong terrain?

It is admittedly a formidable research agenda to develop more realistic and useful dynamic economic models. There are barriers (not necessarily fixed) to observation and computation, but far down the road. Evolutionary theory, biologically inspired or not, has inspired a much needed dynamizing of economic modelling. Attention to technological innovations has been a major vehicle on this journey, but it is perhaps overly burdened by a baggage of biological analogies, perhaps containing useful fuel at the start?[19]

4.2 Representing knowledge, technology, management and learning

Much has of course been said on various concepts, properties, characterizations and representations of knowledge (including information) and learning (growth of knowledge) with various perspectives and little if anything can be said without being disputed. (One

[19] In avoiding throwing out the baby it must be recognized that the state of mathematical modelling of e.g. complex systems dynamics with millions of 'small' feedback loops will most likely be advanced significantly as a result of the efforts being currently devoted to biological sciences in the recognition that they will replace physics as a major engine of scientific progress.

can be sceptical about everything except scepticism.) General knowledge properties apply to technical knowledge (i.e. technology) as well as managerial knowledge as special cases. However, in addition there are some important special properties. Thus, technical knowledge has specifically strong links to physical artefacts (products, materials), to sciences, especially natural sciences and their methodologies, to purposeful functionalities, and to common systems for its operationalization and codification. In addition novel, useful and non-obvious technical knowledge is patentable more or less worldwide.[20]

Apart from general qualitative conceptualizations and classifications of technologies (such as mechanics, electronics, core, enabling etc.) and features (such as generic, radical/incremental etc.), a number of more formalized representations of technology appear in economics. Thus, technologies can be represented by random variables, production functions, various technical performance variables, and certain economic variables (e.g. hedonic prices). Technological change and learning could then be represented as changes in these proxy variables or simply by a time or clock variable. The standard learning curve reflects variable unit cost reductions as a result of numerous small process technology improvements, leading to faster work operations, less material needed and so forth (i.e. learning by doing or more specifically by producing.) Numerous small product technology improvements could be attributed to learning by doing as well, with learning by using and learning by producing as special cases. These product technology improvements are then reflected in hedonic prices (see e.g. Trajtenberg 1990).[21] This type of more gradual techno-economic improvements basically result from interaction between bodies of knowledge embodied in agents and products during a diffusion process, thus intertwined with an innovation process (cf. the notion of learning by interaction by Lundvall.) With a mapping (or rather a many-to-many correspondence) between technologies and realizable technical performance over time (absolute time or "production clock time") state-of-the-art and learning proxied by levels and changes in technical performance, enable a representation of learning in the technology space, in turn enabling introduction of concepts such as directions and trajectories of learning in the technology space.

[20] Recently increasingly liberal court and patent office practices especially in the US, allows for more general knowledge with only weak links to technology (as we know it) to be patented.

[21] Standard references are to pioneering works of Arrow (1962) and Rosenberg (1982) but the pioneering works of Sahal (1980, 1981) need to be recognized as well, in which technical performance is explicitly regressed upon installed base and cumulative production

Thus, in representing technical knowledge and learning the distinction and mapping between a technology space and a technical performance space for observable, measurable artefacts is important (although not necessary since growth of e.g. patents, publications and people might be used as indicators of knowledge and learning as well.) However, in representing managerial knowledge and learning, including organizational routines, the link to observable artefacts is far less clear, the knowledge is less codifiable and not patentable (apart from some software and business method embodiments). How to do this formally must be left an open issue here. There are attempts and possible approaches e.g. in the area of evolutionary algorithms or more specifically genetic algorithms. Nevertheless, it is important to recognize the impact of managerial learning on other types of evolution. For example, in face of radical innovations destabilizing market and industry structure, an increasing ability to manage technology transitions over a series of them would increasingly mitigate their disruptive effects and thereby contribute to stabilizing the industry. More generally, to the extent that technology is manageable and important to economic growth and evolution technology management is important to economic growth and evolution (see further Granstrand 1982, 1989). New technologies (like ICTs) also enable better managerial performance. Thus, management as a heterogeneous body of knowledge bodies grows, diversifies and interacts but in a far more elusive manner for formal representations.

4.3 Growth, diffusion and diversification of knowledge

4.3.1 Homogenous knowledge growth models[22]

There are numerous models (e.g. simple ones as logistic, exponential or combinations thereof) of growth (of populations, capital stock, markets, sales, etc.) and diffusion (of information, innovations, diseases etc.) which have been applied to knowledge, then treated as a homogenous entity, typically linked to (embedded in) countable products or individuals. Also, studies of growth on a particular parameter T in terms of best or average practice in some technical performance is often using this type of models. In fact, if T is modelled as a result of cumulative learning by using and/or producing as in Granstrand (1991, 1994), the well-known S-curves obtain as a result of unimodal growth or diffusion

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[22] The term homogeneous refers to knowledge being undifferentiated in the models, i.e. only one type of knowledge is being considered. Some of the growth models are in addition homogenous differential equations.

rates of corresponding products. The traditional learning curve of the form $C_N = C_1N^{-\lambda}$ for the direct unit variable cost C_N of producing the Nth unit then corresponds as a special case to a T-performance curve. Alternatively an S-shaped T-curve obtains (on average) from a unimodal intensity parameter of a non-stationary Poisson process of incremental innovation “arrivals”, in turn resulting from a unimodal (single-peaked) R&D investment pattern over time, in turn resulting from the empirically common “routine” to budget R&D as a constant fraction of sales, given that sales growth is unimodal as in a well behaved product life cycle model. (This then corresponds to a constant saving rate version of an endogenous growth model with an addition of declining growth due to e.g. substitution). However, it must be emphasized that beautifully S-shaped T-curves are far more common in literature than in reality. This is e.g. due to irregularly varying ‘sizes’, clustering and speed of implementation of the underlying innovations. It must also be emphasized that there are generally many technical performance parameters for a given product, all evolving in different ways as a result of a mix of ‘by-product’ learning and managed external technology acquisition and in-house R&D.

Multidimensional evolution of technical performance then allows for product differentiation, multiple engineering optimizations (engineers after all attempt to optimize designs as a matter of routine), multiple equilibria and heterogeneity of the underlying technology bases.[23]

4.3.2 Heterogenous and interactive knowledge models

It should go without saying that knowledge (information, ideas) is intrinsically heterogenous (as is labor). In fact the essence of knowledge growth is that a new ‘piece’ of knowledge is ‘added’ to the ‘stock’ of knowledge without being identical to any piece previously existing in the stock.[24] Different pieces of bodies of knowledge are moreover interacting with each other. Growth in one knowledge area impacts growth in another and a diversity of interacting areas evolves. How could such growth and diversification of knowledge be modelled in an evolutionary (dynamic) way? This is largely raised as an open issue here with a brief exposé of some available formalized and therefore simplified approaches.

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[23] The term ‘underlying’ then presupposes a correspondence between a set (base) of technologies necessary for realizing certain levels of technical performance at a given point in time.

[24] Note how a phrase like this invites to think about knowledge as countable things.

Let us first in the abstract assume we account for knowledge heterogeneity by a decomposition of the knowledge space into say n areas and represent our knowledge by a vector of x of knowledge proxies assumed to vary continuously differentiable over time t. In general, dynamic interactive knowledge growth (or change) could then obviously be modelled in general as $\dot{x} = f(x,t)$ or if time enters just ahistorically $\dot{x} = f(x)$ for some functions f. This system could be approximated by a Taylor expansion of f. The simplest case of a linear system (i.e. linear dynamics) $\dot{x} = Ax$ (with A a matrix capturing the positive, negative or absent interactions of knowledge growth in different areas) is well studied and generally explicitly solvable with series of exponential functions as solutions, whose transient behavior is by and large dominated by the growth rate corresponding to the largest real part of the eigenvalues of A (exceptional cases apart).

The next-to-simple case of quadratic expansion of f is able to capture much more of dynamic interaction but is generally not explicitly solvable, however. Many modelling approaches fall in this quadratic category and could thus be seen as special approximations without necessarily invoking any analogies to models of biological population interaction. An example of the latter is the n-species model of population interaction:

$$x_i = a_i x_i + \sum_{j=i}^{n} b_{ij} x_i x_j , i = 1,2,...,n$$

Let us then for the sake of illustration assume just two interacting bodies of knowledge, i.e. x = (x_1, x_2). A quite general specification is then in form of the Kolmogorov growth equations:

$$\begin{cases} \dot{x}_1 = x_1 f_1(x_1 x_2) \\ \dot{x}_2 = x_2 f_2(x_1 x_2) \end{cases}$$

which by linearizing reduces to general Lotka-Volterra (GLV) equations

$$\begin{cases} \dot{x}_1 = x_1(a_1 x_1 + b_1 x_2 + c_1) \\ \dot{x}_1 = x_2(a_2 x_1 + b_2 x_2 + c_2) \end{cases}$$

with constants a,b,c.

In case $c_1>0$, $b_1<0$, $a_1<0$, $c_2<0$, $a_2>0$, $b_2<0$ the GLV-system reduces to the classical predator-prey model, modified with a crowding effect (represented by a_1 and b_2), still not explicitly solvable in time space (but in phase space, however) with cyclicity, equilibria and stability properties well understood (see e.g. Samuelson 1971 and Freedman 1987).

This classical model represents decreasing returns to growth, while with positive a_1 and b_2 increasing returns obtained. Such a version may be used to model competing technologies (or species). f_1 and, f_2 then correspond to market potential (or biopotential), a_1 and b_2 are inhibition (crowding) coefficients, b_1 and a_2 are competition coefficients and the c's capacity coefficients. Depending upon these coefficients competition may dominate, leading to substitution, or inhibition may dominate with market size primarily limiting growth. Typically oscillating behavior obtains in the classic LV-model and its applicability to knowledge growth at first glance appears limited , at least to growth of disembodied, unscrappable knowledge. Nevertheless, the Lotka-Volterra type of model is the most wellknown and in some sense the most simple family of models of population interaction with a number of modified (incl. perturbed) versions and applications, not the least in technological forecasting. Most of these latter applications concern technological substitution as a special case of interaction. With an initially dominant technology on a market (or say theory in a population of scholars), a new potentially superior technology with a fraction x_2 of the market may outcompete (substitute) the initially dominant technology, commanding a market share x_1, according to the classical one-variable Fisher-Pry (logistic, Pearl, Bass) model as a very special LV-case:

$$\begin{cases} \dot{x}_1 = -kx_1x_2, k > 0; x_1(0), x_2(0) > 0 \\ \dot{x}_2 = -kx_1k_2 \end{cases}$$

This type of modelling could then be extended to multiple substitution analyses as done by Marchetti (see e.g. Nakicenovic and Grübler 1991). The new technologies could moreover be assumed to arrive stochastically but partly endogenously as radical innovations (or speciations) over time, constituting a piecewise deterministic process of interactive diffusion and learning processes on both demand and supply side (see Granstrand 1994).

In this modelling approach both Schumpeter's principle of (total) creative destruction and the principle of competitive exclusion in biology applies, the latter saying that similar species are unlikely to coexist when competing for common resources and only the most 'fit' one will survive.[25]

However, complementary or mutually cumulative knowledge interaction has been far less studied than knowledge, competition and substitution (as has complementary, symbiotic or cooperative growth in biology as well as cooperative games in economics for some strange reason). The GLV-modelling as well as Kolmogorov-modelling offer some possibilities, however apparently not much studied (see Freedman 1987). In general there is a (possibly time dependent) mix of competing and complementary interactions[26].

A particular type of competitive/cooperative mix of interactions is studied in Granstrand and Lindmark (1995) where technologies decomposed hierarchically in a tree compete on the same levels while growth of a technology at a lower level ("a trunk technology") boosts growth of its branching technologies. (For example, wireless telephony compete with wired telephony and on the level below opto transmission competes with electro transmission for wired telephony an analog radio signal processing competes with digital, while wired telephony 'cooperates' with opto- and electrotransmission and wireless with analog and digital radio signal processing. The resulting models have combinations of linear and/or logistic dynamics, which are explicitly solvable.

A similar case in principle obtains when a design or performance limit (constraint) presents a bottleneck and an enabling technology pushes the limit and spurs growth of the constrained technology. This model applies interaction between technology and science as well for that matter, as when a new instrument (e.g. a telescope or a high speed camera) enables new observations (e.g. in astronomy or metallurgy) and concomitant with knowledge growth improvements in instrument technology are fed back through learning by using (cf von Hippel 1976, Rosenberg 1982).

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[25] Volterra developed the original model of competitive exclusion (with positive vectors a,b,c,x): $\dot{x}_i = (b_i - (a^{\mathrm{T}} x) c_i) x_i$ for the ith species.

[26] This is empirically well recognized as well, e.g. as in the 'sailing effect' when an old technology grows as a response to growth of a new one until some design limit is reached and substitution come into dominance as the overlap between the two technology bases decreases over time (i.e. their distance to each other increases). Innovations represent as a rule a mix of knowledge enhancement (growth) and knowledge destruction (substitution).

Other examples of enabling technologies are gateway technologies between incompatible standards, information compression technologies (e.g. MPEG, JPEG) enabling higher transmission capacity, and technologies for codification in general enabling diffusion.[27] If different types of skilled labor is used as knowledge proxies (as done in some recent EGT-models, distinguishing e.g. between R&D workers or explorers and exploiters, see e.g. Dosi and Orsenigo 1994), different knowledge laborers such as gatekeepers, 'pollinators', generalists and integrators play an enabling role.

It is well-known that bottlenecks attract resources and the appearance of an enabling technology could be endogenized through resource allocation mechanisms, including "routine" or rule-of-thumb budgeting based on some measure of performance, possibly subjected to saturation and reallocation. Obviously laws of nature may then enter as stiff constraints, possibly discovered through R&D, then eventually terminating itself.

Thus there are a number of dynamic modelling approaches, including (with overlapping labels) original, industrial dynamics models developed and applied by Forrester, Roberts and others, simulation models, stochastic evolutionary models (as in Nelson and Winter 1982 modelling interaction between innovative and imitative R&D), endogenous growth models and optimal control models. Each of these modelling approaches is applicable to modelling of growing and interacting bodies of knowledge but much remains to be done, particularly regarding complementary growth rather than competition and substitution (selection).

5. Diversification, innovativeness and economic growth

Sources of heterogeneity (diversity) of knowledge are both exogenous and endogenous. Knowledge is intrinsically heterogeneous in the first place as mentioned. But knowledge hetero geneity represented by a conceptualized decomposition of knowledge into areas (bodies, fields, disciplines, classes etc.) is partly reflecting an exogenous reality (assuming it exists) being searched and researched, partly reflecting a cognitive or social construct where conceptualizations and reconceptualizations may change the heterogeneity (diversity) without necessarily changing the underlying "content". Competition between

[27] Note that knowledge is not once and for all tacit and its codification is a partly R&D driven dynamic (evolutionary) process.

individual scientists typically lead to dispersion and nominal and real differentiation, while formation of professional subcultures in science and technology typically lead to formation of specific codes and knowledge boundaries acting as (imperfect) repellants to search behavior. A discovered new piece of knowledge, new at subpopulation level, is always bundled with some new and somewhat codified knowledge about what is not known, thereby carrying the seed for further search and diversification. As the boundary regions gradually become undersearched, due to subcultural formation rather than solely due to exogenous lack of fertility, and knowledge in different areas become differently coded, the potential yield of boundary search and crossing, combining and integrating knowledge from different complementary areas, gradually increases. This is one then way to explain why more radical innovations appear as interdisciplinary combinations of different bodies of knowledge.

In the context of a firm, how is strategic search and selection of "winning technology combinations" done among the rapidly growing combinatorial possibilities arising from diversification? Two main types of search processes appear to be employed and then in a dialectic rather than concurrent fashion as described in the empirical section (and more in detail elsewhere, e.g. Granstrand 1998). The first could be called *product related technology diversification* (or at a more general level problem *related knowledge diversification*), meaning briefly expressed that new technologies are searched (explored) and possibly integrated (acquired, absorbed) into the technology base for a given product. This process is mainly driven by demand side and economies of scope considerations, leading to enhanced technical performance along existing trajectories related to customer (user) utility and cost plus possibly new functionalities (i.e. opening up of entire new sub-spaces in the technical performance space).

The second process could be stylized as a kind of reversal to the first, that is for a given technology base (knowledge base), new product opportunities are searched and possibly integrated into the product base of the firm. This process is mainly driven by supply side (resources) and economies of scale considerations, and could be called *technology related product diversification* (or *knowledge related problem diversification*). During this process needs for still more new technologies in entering a new product area may become clear, thus leading to embedded sub-processes of the first kind (and vice versa). After having entered a new product area, search of the first kind may be initiated again. A similar reasoning applies to the relation between technology and application diversification, with an interplay between ‘demand pull’ and ‘technology push’ considerations. Thus a dialectic process evolves, possibly also at several levels.

Although there are cases (as in Canon) of concurrent product/technology diversification (perhaps increasingly so according to Cantwell and Piscitello 1996), some sort of sequential diversification dominates. This could be explained by reference to successively binding resource constraints (sequence of bottlenecks), especially constraints on managerial resources (including attention span), learning speed limits and learning economies associated with sequences of specialization and integration. There are also more standard financial explanations in terms of the need to smooth investment expenditures and risks[28]. After all a firm is institutionally designed to evolve fairly continuously in financial terms, and management tries to steer the firm away from bankruptcy or take-over, functioning as an absorbing barrier on its downside.

What then could explain the economic growth apparently stemming from diversification? Reference to economies of scale and scope has already been made. Reference to economies of speed is also possible to the extent that adequate intra-firm technology transfer is faster than external technology acquisition (which is not always the case in a large corporation). Some locational economies (“economies of space”) could also accrue, e.g. for a large corporation having units for R&D and technology acquisition located in technology diversified (multi-technology) regions.

More detailed explanations obtain with reference to the nature (characteristics) of different technologies being integrated in the technology bases of products and firms. Generic (multi-product, general-purpose) technologies clearly offer economies of scale in technology related product diversification if adaptation costs are moderate (see e.g. Bresnahan and Trajtenberg 1995). Enabling technologies offer economies of scope (in a broader sense than just being a special case of economies of scale) as touched upon in the previous section[29]. Joint product/process technologies (such as FMS and genetic engineering) improve both performance and cost of a product, thus giving leverage to the

[28] A particular type of explanation is by means of rationalization theorems, showing the existence of circumstances under which sequential investments in different types of diversification is optimal (similar to “bang-bang” control behavior).

[29] Qualifications such as ’generic’ and ’enabling’ are more specifically characteristics that could appear jointly in a particular technology depending upon how technologies are defined and classified.

cost/performance parameters guiding customer purchasing decisions[30]. More technology characteristics could of course be referred to. Inherently some technologies and technology combinations simply offer more opportunities than others and the nature of the richness of the opportunity set is uncertain and dynamic, thus making any characterization of particular technologies in such terms uncertain and dynamic.

In product related technology diversification typically more technologies are added than scrapped (substituted) as empirically observed, while a portion is kept from time to time (more so for less radical innovations). Thus, economies of scale and scope (complementarities) illustrated above dominate over any economies associated with substitution. In addition the scrapping cost might be high due to organizational resistance (inertia) and agency problems. The cost of adding technologies can also be considerable, e.g. through higher costs of coordinating different new technologies and their associated subcultures. (Note the empirical association of higher R&D costs and technology diversification).

In this way, product related technology diversification and its reverse could be analysed and its impact on innovativeness, R&D growth and sales growth (if not profit growth) could be explained. It is finally worth emphasizing that even in the absence of product diversification, technology diversification may have positive impact on sales growth.

[30] It is worth noting that the strong separability of strategies of differentiation and cost leadership, advocated in Porter's work on generic strategies, apparently assumes away the existence of such technologies. This is not true to reality, however (see e.g. Oskarsson and Sjöberg 1994).

Appendix

Transient solutions to some growth models

The classical Solow growth model (see e.g. Romer 1996 or Aghion and Howitt 1998) is:

$$\dot{k} \quad = \quad sf(k) - (n+g+\delta)k \qquad \text{(eq. 1a)}$$

where:

- k = K/AL with K = capital, L = labor and A = knowledge (interpreted as effectiveness of labor)
- s = investment (savings) share of output Y(t)
- n = labor growth rate ($= \dot{L}/L$)
- g = knowledge growth rate ($= \dot{A}/A$)
- δ = depreciation rate ($= (sY - \dot{K})/K$)
- f = intensive-form production function

Output Y(t) at time t is then assumed to be determined by a function F of capital, labor and knowledge, i.e. Y(t) = F (K(t), A(t), L(t)). With a Cobb-Douglas specification of F, i.e. $Y=K^{\alpha}(AL)^{1-\alpha}$, $\alpha\in(0,1)$, eq. 1a becomes:

$$\dot{k} \quad = \quad sk^{\alpha} - (n-g+\delta)k,\ \alpha\in(0,1) \qquad \text{(eq. 1b)}$$

With constant (exogenous) parameters s,n,g and δ, equation 1b becomes a Bernoulli type of equation which is explicitly solvable. The solution is:

$$Y(t) = \left(\frac{s}{n+g+\delta}(1-e^{-\delta t}) + \frac{Y(0)}{A(0)}^{\frac{1-\alpha}{\alpha}} \cdot e^{-\delta t}\right)^{\frac{\alpha}{1-\alpha}} A(t) \qquad \text{(eq. 2)}$$

where $\lambda \equiv (1-\alpha)(n+g+\delta)$.

Thus (with c an abbreviated constant):

$Y \propto (1-ce^{-\lambda})^{\frac{\alpha}{1-\alpha}} A$

Several versions of growth models are similarly explicitly solvable. For example (cf. Romer's model of 'endogenous technological change', Romer 1990), with time t subscripted for simplicity, a_L denoting fraction of labor employed in R&D and B a shift parameter:

$$\begin{cases} \dot{A}_t = B a_L L_t A_t \\ \dot{K}_t = s K_t^{\alpha} ((1-a_L) L_t A_t)^{1-\alpha} \\ \dot{L}_t = n L_t \end{cases}$$

(eq. 3)

which gives:

$$\begin{cases} A_t \propto \exp\left(\int^{t} B a_L L(\tau) d\tau\right) \\ K_t \propto \left((1-a)\int^{t} s((1-a_L) L(\tau) A(\tau))^{1-\alpha} d\tau\right)^{\frac{1}{1-\alpha}} \\ L_t \propto \exp(nt) \end{cases}$$

which gives (with c an abbreviated constant):

$$\begin{cases} A_t \propto \exp\left(B a_L L_0 e^{nt}/n\right) \\ K_t \propto \left[\int^{t} \exp(n\tau) \exp(c \cdot \exp(n\tau)) d\tau\right]^{\frac{1}{1-\alpha}} = \\ \qquad = \left((nc)^{-1}(\exp(ct) - \text{const.})\right)^{\frac{1}{1-\alpha}} \\ L_t \propto \exp(nt) \end{cases}$$

(eq. 4)

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