

Competition and endogenous technological change: an evolutionary model

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Summary: 1. Technological dynamics as a local-and-specific process at the firm level; 2. Sector-specific patterns of technological change; 3. Technical change and competitive asymmetries; 4. A simple evolutionary model.

This paper outlines a dynamic framework about relationships between technological change and competition among firms, one in which the rate of technological innovations is not taken as exogenously determined. The focus is on the "evolutionary" feature of competition and technological change: self-reinforcing mechanisms between technological investment and market occupancy play a crucial role in the analysis. The framework is developed as follows: section 1 deals with some local-and-specific features of technological dynamics at every firm level, whereas section 2 approaches some sector-specific features of technological change. The resulting view on technologically-related processes of competitive selection at the market level is summarized in section 3. Finally, section 4 presents a simple evolutionary model that attempts to highlight some of the aspects previously treated.

O presente texto delinea um arcabouço dinâmico sobre as relações entre mudança tecnológica e concorrência entre firmas, no qual a taxa de inovações tecnológicas não é tomada como exógena. O foco está nos caracteres "evolucionistas" da concorrência e da mudança tecnológica, ou seja, mecanismos de auto-reforço entre o investimento tecnológico e a ocupação de mercados cumprem um papel crucial na análise.

1. Technological dynamics as a local-and-specific process at the firm level

In the conventional economic literature, technology is usually presented as generally applicable "information", that is to say, as knowledge about the transformation of inputs into outputs — in productive, managerial and trade spheres — which can be fully replicated and reused, independently of time and space. Technology is identified as a set of relationships between "factors of production" and output levels which serves as a unique and general reference to "choices of techniques" by all firms. Technological change is defined as a shift of that "menu" of techniques.

From an opposite point of view, several empirical works have stressed the presence of *tacit* and *specific (idiosyncratic)* types of knowledge in any particular application of any technology (Nelson & Winter, 1977, 1982). By "tacitness" they mean some elements of knowledge that are both necessary for a minimally efficient use of each technology and embodied in the firm's routines and personnel. Consequently, that "tacit" knowledge cannot be acquired or transferred by means of handbooks or any other codifiable forms of knowledge transmission. That knowledge cannot be made "explicit" as in blueprints and thus cannot be perfectly diffused as either public information or private property. By an "idiosyn-

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cratic” or “specific” content they refer in turn to the fact that each materialization of generic and abstract principles of technology involves different conditions to become concrete — given the implausibility that contextual conditions be the same everywhere.

One can derive the following implications from those empirical observations:

Firstly, a fully complete transfer of technology is never attainable — either directly or indirectly between sectors or even intra-sectorally. Technology receivers inevitably get an information set not so complete as that one used by sources of transmission. Every technology transfer requires some development of tacit and specific technological capability by the receiver, however high or low be that content.

Secondly, technological dynamics is necessarily local and firm-specific. Whatever the weight of external sources in the firm’s process and product innovations, the latter correspond to a process of interaction between technical innovations and technological capabilities accumulated at the firm level. Technology is both an input and an output of the exercise of technological capabilities, since technical and technological changes come up simultaneously at the firm level.

The *learning* process (i.e., the accumulation of technological capabilities regarding operation and innovation activities) at the firm level has both internal and external sources as possible starting points:

— internally, R&D investment as well as informal learning (which includes the operation learning which accompanies the exercise of activities, such as the one depicted in traditional “learning curves”); and

— externally, there are flows of information of a public character (such as the ones coming from scientific breakthroughs), flows of information available as merchandise (coming from the same or other sectors, either disembodied or embodied in equipments or components), non-tradable technological spillovers (such as the information exchange between users and producers), and so on.

In any case, learning results from the cumulative process of interaction between external and internal sources at the firm level, process in which a tacit and idiosyncratic knowledge is inextricably present.

Thirdly, technological research at the firm level carries on a highly selective heuristics (Nelson & Winter, 1982). Directions in innovative efforts are not established at random since they refer to local and specific problems.

A commonly forgotten feature of innovative efforts is the fact that they are essentially problem-solving activities, dealing with “ill-structured” problems (Dosi, 1988:1,126): the set of available information by itself cannot provide perfectly clear-cut paths to solutions and the latter come along with some discovery and creation. It follows that there can be no perfect foresight about technical results of innovative activities, since there is no basis upon which to build a previous knowledge of all possibly resulting events, even less so as to attribute any probability distribution to them. One can thus find (*technological*) *expectations* and *uncertainty*, in an analogous manner as Keynes pointed out with respect to capacity-building investment, short-run pricing and production decisions, and so on.

Since learning is a resource-consuming and costly process — the rhythm and intensity of which depend upon the firm’s decisions regarding information collection, R&D, labor

training and so forth —,¹ it constitutes a specific item in the firm's agenda for investment decisions. Investment in learning as such involves a double-sided dimension insofar as expectations and uncertainty are concerned: its return depends on both technological and economic results (Freeman, 1974; Nelson & Winter, 1977). Inasmuch as one can understand the adherence to "routines" as a possible rational attempt to safeguard against uncertainty — as developed e.g. by Davidson (1977) and other post-Keynesian economists — one can also realize how technological uncertainty may be a stimulus for the firm to stick to its more familiar "practices", namely its selective heuristics and local-and-specific technological capabilities.

On the other hand, actual or desired changes in the firm's performance and/or in competitive environment inflict a continuous tension between the relative safety provided by routines and the search for new ones. To this respect, the appraisal of technological and economic signs is subject not only to firm-specific expectations formation under conditions of uncertainty, but also to different degrees of confidence on those expectations and to different propensities to take risks. Any given set of observable signs common to all firms involved is liable to generate behavior diversity, not only because each firm's capabilities and routines are local and specific, but also because signs are interpreted in an idiosyncratic and possibly-changing way.

2. Sector-specific patterns of technological change

Selectivity in firms' heuristics regarding learning activities is tantamount to following a previous demarcation of relevant problems and of a pattern for research (i.e., of a limited set of technological possibilities and its expected developments). Whenever a minimum set of common features may be localized among ever local-and-specific learning processes and heuristics, one can stylize a "technological paradigm" — such as proposed by Dosi (1984,1988) in his analogy between science and technology evolutions.

A technological paradigm involves "a basic artifact to be developed and improved (such as a car, an integrated circuit, a lathe, each one with its own particular techno-economic characteristics)" as well as a corresponding "set of heuristics" (Dosi, 1988:1,127). The "basic artifact" must of course be understood as a tangible or intangible output which becomes the object of one or more technically-related productive processes and in which common or at least coherent directions of technological investigation are settled, with respect to its production and/or product characteristics.

Paradigms have different reaches, not only in terms of sectors and markets gathered as stages of the productive chain, but also regarding the set of users which have their (also selective) heuristics influenced by the techno-economic features of the basic artifact.

Certainly, in cases where scientific knowledge is relevant as an external source of learning, the former's abstract and ordered structure is also present in technological activity and evolution. On the other hand, it is worth recalling that the concreteness of the technological paradigm involves tacit and specific knowledge components, as well as lower degrees of articulation and codification, and strongly depends on capacities developed through experi-

¹ Informal learning is usually taken as something which follows time automatically. Nonetheless one must recall that that kind of learning depends upon quality of hired labor as well as on the levels of technological capabilities accumulated from the other sources which it interacts with.

ence. A paradigm lives through the technological diversity among firms in which the “basic artifact” is produced and used.

Technical progress generally corresponds to increasingly better answers to multiple technical and economic trade-offs established as the subject of innovative activities. For instance:

— the evolution of the “basic artifact” automobile proceeds upon its trade-offs concerning conflicting performance characteristics (comfort, fuel consumption, speed, and so on);

— an electronic component is improved within its trade-offs with respect to reliability, cost/performance ratios, and so forth;

— alternative processes of steel production represent distinct options regarding physical input-output relations, energy consumption and/or environmental damage;

— a consulting service firm searches for better responses to its trade-offs between speed and quality of the output, and so on.

In all those cases, technical change goes along as one or more “technological trajectories” defined by the paradigm — such as the “normal” development of scientific paradigms in Thomas Kuhn’s analysis.

Each paradigm has some degree of “technological opportunity”, that is to say a potential in terms of benefit and cost results stemming from innovative efforts according to methods and directions there established. That potential depends, among other things, on the limits which “physical laws” or “natural laws” impose to paradigmatic lines with respect to the trade-offs contained in its corresponding processes and products (Perez & Soete, 1988:41). On the other hand, the actual development along trajectory lines towards the exhaustion of that potential depends on its economic appraisal as an investment decision according to technological and economic expectations formed under conditions of uncertainty.

A “radical innovation” — i.e., the emergence of some new product or process with techno-economic performance features so different from existing ones as to signify a discontinuity in the productive system — opens up a new paradigm and the corresponding trade-offs with respect to the characteristics of its “artifact”. Well-established trajectories of incremental innovations towards improvement/adaptation of processes and products tend to come up only after the new paradigm is settled.

That paradigm settlement will depend on its competition with existing paradigms, since it will appear with some (even if imperfect) substitutability with respect to the latter — except for those cases of extreme novelty. Selection among old and new paradigms will take place both on *ex ante* levels (when agents estimate subjectively the degrees of technological opportunities) and on the *ex post* level (through actual economic results coming from market processes).

Expectations of favorable technological opportunity are a necessary but not a sufficient condition for investment in accumulation of technological capabilities within a paradigm, since “appropriability” is required in order to allow innovations to become rent-generating assets. “Appropriability” conditions will vary from technology to technology, given specific properties of technological knowledge, artifacts, markets and legal environment which can

make difficult competitors' imitation (Dosi, 1988:1,139). Appropriability will express itself through time lags and differential costs of imitation relative to innovation.

Given the partial tacitness of technological knowledge, imitation is also a "creative process": the local and firm-specific nature of technological dynamics requires (re)search for imitation. Innovation and imitation — innovation and diffusion among firms — are not perfectly distinguishable, except for the fact that they are different moments with respect to constitution and dissolution of competitive advantages, as well as to technological divergence and convergence among firms.

In short, technology-specific estimated degrees of opportunity and appropriability constitute firm-specific and sector-specific inducements to technological investments and change. Market signals exert their influence (upon intensity and directions of innovative efforts) within the boundaries of prevailing paradigms and trajectories as well as according to the way by which they enter firms' expectative calculations.

On the other hand, as far as the rhythm and directions are concerned, technological development also keeps a "relative autonomy" in its relation with science — so that it is misleading to treat technology simply as a parameter derived from scientific advancements. In spite of increasing links between science and technology, the latter involves tacit and specific forms of knowledge, dealing with a particular sub-set of activities, and it does not evolve as a mere shadow of the former since its concreteness requires a properly economic calculation. Scientific knowledge continually opens up a multiple scope of potential paradigms which can acquire existence only after enduring a selection through "bridging institutions" (Freeman, 1974) as well as at the firm (*ex ante*) and market (*ex post*) levels. Science, technology and markets keep relative autonomy in their connections.

3. Technical change and competitive asymmetries

The firm-specific character of technological dynamics, the presence of technological and economic uncertainty in investment decisions associated with technological accumulation by learning, the selectivity in heuristics, as well as appropriability and cumulateness² of technological capabilities, all point to a particular view on relations between technology and competition among firms:

(a) Selectivity in heuristics leads to the search for improvements along prevailing technical lines rather than movements along "isoquants", even if that heuristics takes into account — within the technical boundaries of prevailing trajectories — some bias coming from original stimulus or restraint to technical change. This is in sharp contrast with the conventional view on production and technical change, according to which flexibility of production processes and full knowledge and access to a unique set of production possibilities allow for reversible choices within a common "menu" for all firms.

² The selective exercise of innovative activities along maintained directions results in accumulation of capacities within the latter. There is "cumulateness" whenever the probability of achievement of technological advances increases with the stage of that accumulation. The formulation of opportunity, appropriability and cumulateness as categories to deal with sector-specific patterns of creation/destruction of technological asymmetries among firms was originally provided by G. Dosi — e.g. Dosi (1984).

(b) Given irreversibility of learning and its cumulative character, the productive structure is best represented by fixed coefficients which move along time. At a particular slice of time there are one or more points corresponding to best-practice techniques, i.e. the technology frontier, rather than a well-behaved set of production possibilities. Through time, processes of technical improvements in best-practice techniques predominate over “static” factor-substitution processes (Dosi, 1988:1,145).

(c) Technological diversity among firms tends to originate technological asymmetries due to opportunity, appropriability and cumulateness. The firm-specific nature of technological-and-technical change allows for monopolistic/oligopolistic advantages, whether short-lived or not: higher or lower sustainability is what makes them different. In other words, firms can be ordered in a ranking according to their positions relatively to sector-specific technological frontier. The asymmetries thus classified change along time and are often unstable, but they are not necessarily unsustainable as it is proposed in the conventional neoclassical approach.

Following Dosi et al. (1990:88), let us take an n -dimensional space defined by n inputs to represent the techno-productive structure of a homogeneous-product sector, where the physical output/input relation is measured by the distance from the origin. The technical evolution of each firm within its own pattern will correspond to a discrete set of period-specific points reasonably ordered around a ray coming from the origin, the direction of which represents the firm’s trajectory. If all firms are crossing similar trajectories one would find — at each moment of time — each firm as a point in a period-specific set in which distances express degrees of asymmetry. The absolute and relative positions of firms will evolve as a result of technological opportunity and innovative/imitative search by each one.

The asymmetric configuration of productive efficiencies will also reflect, at each slice of time, static economies of scale in production which can be made possible by prevailing technologies — the appropriation of which will be related to market shares held by each firm. Furthermore, one can add non-technological asymmetries, such as preferential access to some inputs and/or market shares, as well as pecuniary economies of scale in advertising, marketing, distribution and so forth. In any case, the local and firm-specific accumulation of technological capabilities may play a crucial role in a dynamic evolution of levels and dispersion in productive efficiencies, whatever the degree to which the process is associated to equipment vintages, R&D activities or other sources of learning.

Degrees of asymmetry express themselves as a dispersion in monetary costs, with the latter reflecting differences in productive efficiency in the use of each input as weighted by each corresponding input price. Product differentiation in turn may be conceptually incorporated by converting differences in performance regarding product characteristics to a single dimension, by using some market-defined weight.³ Innovational search by each firm is a strategic attempt to alter market structures in its favor by creating or diluting asymmetries.

(d) Technological asymmetries (which are part of the market structures at each moment of time) and firms’ strategic decisions (which are conditioned but not determined by the for-

³ One must not forget that within a paradigm and its trade-offs product differentiation corresponds to differences in performance with respect to a certain set of techno-economic characteristics which make the paradigm unique.

mer) interact and make up an evolutionary trajectory, one which is *ex ante* indeterminate — or rather multideterminate —, since expectations and uncertainty in the choice of strategies preclude any unique determination of structure upon firms' conduct and performance. *Ex post* changes in market structures and firm performances will result from absolute and relative intensities of firm-level learning processes (the effective results from search) and from market-level selection.

Technological investment by firms as an economic decision implies that it is intertwined with the other dimensions of investment decisions (such as finance and productive capacity). Furthermore, technological opportunity, appropriability and cumulateness are all appraised and ultimately realized in a firm-specific idiosyncratic way. Therefore, those three attributes of each technological paradigm/trajectory are compatible with multiple paths of structure-strategy interaction.

4. A simple evolutionary model ⁴

Technological learning

Let $L_i(t)$ represent the level of technological capabilities of firm i at time t , assuming that the multidimensionality of technological capabilities and product-and-process innovations can be represented in a one-dimensional way. $L_i(t)$ corresponds to the stock of technological knowledge which increases with accumulated R&D activities and captures the integrated notion of technological experience and learning processes highlighted in section 1. The rate of technical progress (technological learning, accumulation of technological capabilities) of the firm is given by the time derivative dL_i/dt , which is an increasing function of the current amount of R&D input, denoted by $RD_i(t)$. Formally:

$$dL_i/dt = f(RD_i(t)) \tag{1}$$

where $f'(\cdot) > 0$ and $f''(\cdot) < 0$. The concavity of the function can be rationalized as a type of "Penrose-effect" (Penrose, 1959) in R&D at each period of time, namely, decreasing physical returns of further R&D upon a given stock of accumulated R&D experience.

One may notice that technological opportunity and cumulateness — along selective heuristics at the firm level and, when adequate, corresponding technological trajectories and paradigms at the sector level — are respectively captured by $f(\cdot)$ and $f''(\cdot)$. In the case of substantial divergence between opportunity and cumulateness at each firm level, the arguments for f might be accompanied by corresponding firm subscripts.

Each firm's technological capabilities will be partially non-transferrable, whereas the remaining stock of knowledge might "spill-over" to other firms, either as private property or not. Letting aside the possibilities of technology transfer as a commodity, we assume β to

⁴ The following model is largely based on that developed by Maggi (1993) with respect to technological gaps and international trade.

represent a fixed proportion of $L(t)$ that is liable to be diffused and non-appropriated, i.e. $0 \leq \beta \leq 1$. In a two-firm sector, equation (1) becomes:

$$dL_i/dt = f(RD_i(t)) + \beta [L_j(t) - L_i(t)] \quad \text{if } L_i(t) < L_j(t) \quad (1')$$

$$dL_i/dt = f(RD_i(t)) \quad \text{if } L_i(t) > L_j(t)$$

Market occupancy

In the two-firm sector ($i = a, b$), where $m_i(t)$ stands for each firm's market share at time t , we necessarily have $m_a + m_b = 1$. We assume that the market share of each firm will be a function of:

(a) the technology differential between the two firms:

$$\text{diff } L(t) = L_a(t) - L_b(t)$$

(b) and the non-technological cost differentials due to non-technological asymmetries mentioned in section 3:

$$\text{diff } C = C_a - C_b$$

That is to say:

$$m_a(t) = g [L_a(t) - L_b(t), C_a - C_b] = g [\text{diff } L(t), \text{diff } C] \quad (2a)$$

$$m_b(t) = g [L_b(t) - L_a(t), C_b - C_a] = g [-\text{diff } L(t), -\text{diff } C] \quad (2b)$$

where the partial derivatives of g with respect to $\text{diff } L(t)$ and $\text{diff } C$ are respectively positive and negative. Note also that $g [-\text{diff } L(t), -\text{diff } C] = 1 - g [\text{diff } L(t), \text{diff } C]$. The second derivative of g with respect to $\text{diff } L$ might also be seen as negative, given some user stickness to product diversification.

The total profits of each firm are assumed to be an increasing function of its corresponding market share:

$$P_i(t) = h [m_i(t)] \quad (i = a, b) \quad (3)$$

where $P'(\cdot) > 0$ and $P''(\cdot) < 0$. The concavity of the function may be seen as due to some increasing "sales effort" which must be incurred in order to augment market share in spite of cumulative technological advantages.

Technological investment

Given the market growth and the evolution of market shares one knows that part of the firm's profits will necessarily be addressed to investments in production-related fixed and working capital. Adhesion to routines with respect to investment in technological capabilities under prevailing lines, as well as to financial leverage, is denoted here by a link between $RD_i(t)$ and $P_i(t)$ such as:

$$u \cdot RD_i(t) = k_i \cdot P_i(t) \quad (i = a, b) \quad (4)$$

where u stands for unit costs of R&D activities and k is a fixed proportion of current total profits that is devoted to technological investments by each firm.

Equations (1'), (2a), (2b), (3) and (4) make up a 8-equation differential system that implicitly defines the time path of eight variables: dL_a/dt , dL_b/dt , RD_a , RD_b , P_a , P_b , m_a and m_b . The system can be reduced to (we omit the time argument):

$$D = (dL_a/dt) - (dL_b/dt) \quad (5)$$

$$D = f \{ k_a/u \cdot h [g (\text{diff } L, \text{diff } C)] \} - \\ - f \{ k_b/u \cdot h [1 - g (\text{diff } L, \text{diff } C)] \} - \beta \cdot \text{diff } L$$

For each combination of (diff L , diff C), there will be dynamic equilibrium insofar as market shares and profit levels are concerned if and only if $D = 0$. Otherwise, diff L will be changing and m_a , m_b , P_a and P_b therewith.

Let us examine three possible scenarios, all of them including a non-technological cost advantage of firm b relative to firm a :

1. Complete technological appropriability ($\beta = 0$)

Figures 1a, 1b and 1c display the dynamics of interaction between technological leads/lags, profits and market shares, and the accumulation of technological capabilities at both firms. The concavity of and the symmetry between the dL_i/dt are derived from the concavities of f , g and h and the constancy of k_i . Notice that $dL_a/dt = dL_b/dt$ at some diff $L > 0$, given some non-technological cost advantage of firm b , and that all of the argument would be kept the same whatever the level of diff C (including zero) by simply shifting the vertical axis.

L^* represents an unstable dynamic equilibrium. Unless diff $L = L^*$ the market will be increasingly occupied by one of the firms: a or b depending on whether the former manages to compensate for diff C , e.g. by some radical innovation through which it obtains some favourable leap in diff L . Technological opportunity, appropriability and cumulateness lead to ever increasing market concentration along selective processes, the direction of which can only be altered by new radical innovations.

Figure 1a

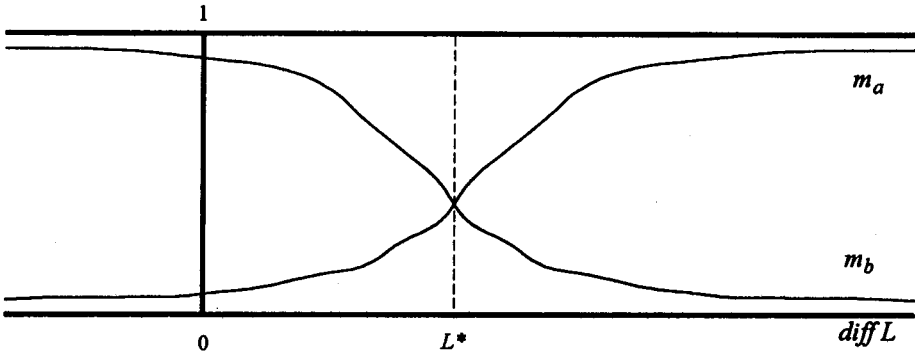


Figure 1b

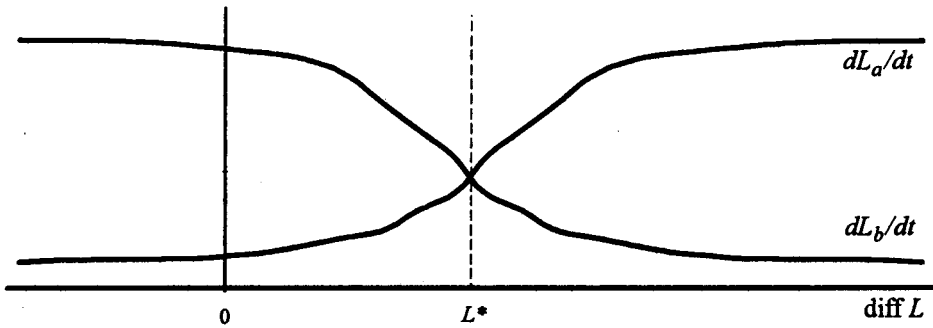
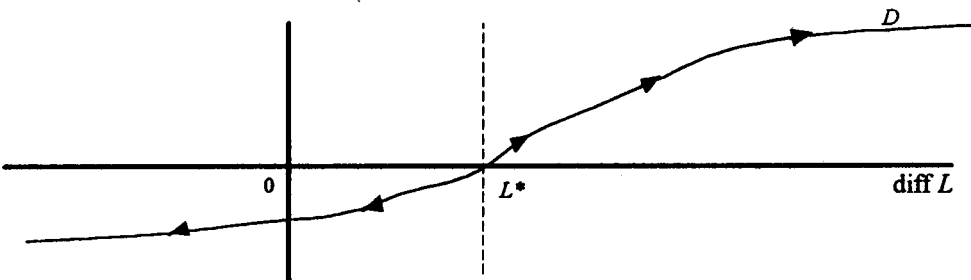


Figure 1c



2. Slow technological diffusion ($\beta > 0$ but below some critical value β^*)

In order to find the values of $\text{diff } L$ for which $D = 0$ in this case, we draw dL_a/dt , dL_b/dt and $(dL_b/dt + \beta \cdot \text{diff } L)$ in figure 2a. The presence of non-technological cost differences is no longer trivial in the case of $\beta > 0$.

It is easy to see that if β is small enough, $D = 0$ at three moments, as shown in figures 2a and 2b (points d_0 , d_1 and d_2). Notice that as β increases, $(dL_b/dt + \beta \cdot \text{diff } L)$ shifts leftwards and that, after some threshold level (β^*), it ceases to cross dL_d/dt for positive levels of $\text{diff } L$. Furthermore, d_0 approaches but does not reach $\text{diff } L = 0$. In turn, on the positive side of $\text{diff } L$, the distance between d_1 and d_2 shrinks and the former swallows the latter when $\beta = \beta^*$.

Figure 2a

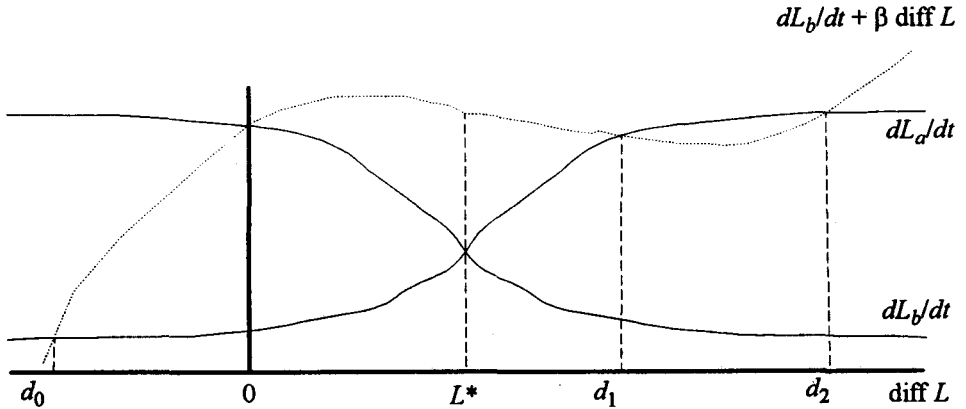
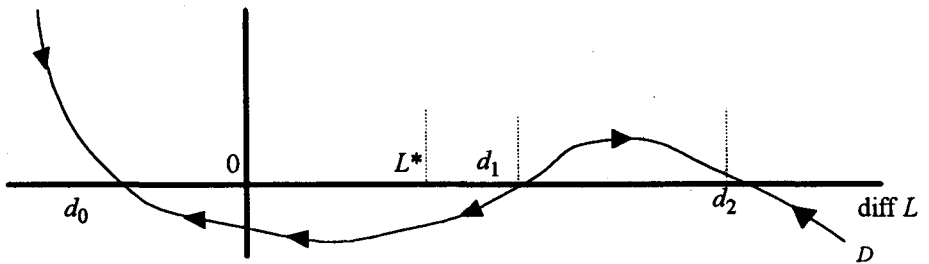


Figure 2b



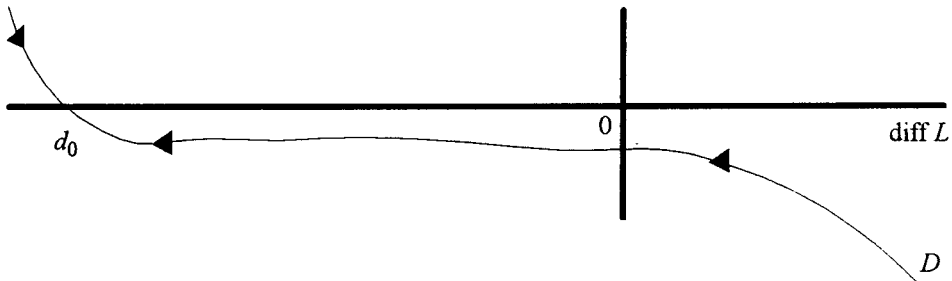
In the case of slow technological diffusion ($0 < \beta < \beta^*$) (figures 2a and 2b) there are three possible dynamic equilibrium positions: an unstable one (d_1), a stable higher market share for the firm with a non-technological cost advantage (d_0) and a stable higher market share for the firm with a non-technological cost disadvantage (d_2). It all depends on the initial technology gap as well as on further leaps (shocks) in $\text{diff } L$.

The multiple-equilibrium system presents path-dependence and “hysteresis”, a property of the interaction between competition and technological change that was emphasized in the previous sections of this paper. One can also observe that the equilibrium market-structure positions suppose some “strategic” organizational routines as defined by the k_i in the technological investment functions (the financial-leverage strategy, technological expectations regarding physical results from R&D activities, and so on).

3. Fast technology diffusion ($\beta^* < \beta < 1$)

This case is represented in figure 3. The curve corresponding to $(dL_b/dt + \beta \cdot \text{diff } L)$ in figure 2a has shifted leftwards enough to leave a unique stable dynamic equilibrium at the left side of figure 3 (d_0), one that will be as closer to $\text{diff } L = 0$ as the non-technological cost advantages of firm b are lower. In the case of low technological appropriability, if one of the firms has a static cost advantage, the market structure tends to feature a steady-state technology gap in favour of that firm, as well as a higher market share for the latter. Fast technology diffusion makes market occupancy to depend on non-technological asymmetries — in an opposite way to the first scenario (maximum technological appropriability).

Figure 3



Finally, we might also introduce the notion of “life cycle of technologies” (Canuto, 1992): the coefficient β tends to be low immediately after radical innovations and rise as technological capabilities under prevailing trajectories approach “maturity”. If the selective process does not fully operate at the beginning — as implied by the concavity of $m_i(t)$ in our model — the market structure might evolve successively within scenarios 2 and 3.

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